VALORISATION OF WASTE CHICKEN FEATHERS: PRODUCTION OF HIGH-VALUE MATERIALS

by

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Submitted in fulfilment of the academic requirements of Doctor of Philosophy

in Chemical Engineering

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15 February, 2018

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Chemical Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Howard campus, Durban, South Africa. The research was financially supported by: the Ethiopian Government; the Waste Roadmap Programme of the Department of Science and Technology, South Africa; and the Thermodynamics Research Unit, Chemical Engineering, UKZN.

The contents of this work have not been submitted in any form to another University and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE
DECLARATION 1: PLAGIARISM

I, Tamrat Tesfaye Yimer, declare that:

(i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;

(ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;

(iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

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DECLARATION 2: PUBLICATIONS

Chapter 3 Decontamination and pre-treatment of waste chicken feathers

1. **Tesfaye, T.,** Sithole, B., and Ramjugernath, D. 2017. Valorisation of waste chicken feathers: optimisation of decontamination and pre-treatment with bleaching agents using response surface methodology. Published in *Journal of Sustainable Chemistry and Pharmacy*.
2. **Tesfaye, T.,** Sithole, B., and Ramjugernath, D. 2017. Optimisation of surfactant decontamination and pre-treatment of waste chicken feathers by using response surface methodology. *Journal of Waste Management,* **72**, pp. 371-388.

Chapter 4 Characterisation of chicken feathers

3. **Tesfaye, T.,** Sithole, B., Ramjugernath, D. and Chunilall, V., 2017. Valorisation of chicken feathers: Characterisation of physical properties and morphological structure. *Journal of Cleaner Production,* **149**, pp. 349-365.
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5. **Tesfaye, T.,** Sithole, B., and Ramjugernath, D. 2017. Valorisation of chicken feathers: Characterisation of mechanical, thermal and electrical properties. Submitted to *Journal of Cleaner Production*.

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1. Making smart use of the world excess chicken feather waste, CSIR news, Oct 19/2015.
2. UKZN ‘Chicken Man’ could be on to new uses for feathers, The Mercury newspaper, Oct 23/2015.
3. Seeking good uses for chicken feathers, Cape Times News, Oct 26/2015.
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2. Valorisation of chicken feather: current status and future prospect, Poster presentation, Emerging Researchers Symposium (CSIR), Pretoria, South Africa, Oct 8/2015.
3. Valorisation of chicken feather: current status and future prospect, Oral presentation, Ethekwini-University research symposium (MILE), Durban, South Africa, April 08/2016.
4. Valorisation of chicken feather: Characterisation of physical properties and morphological structure, Poster presentation, NRE science week (CSIR), Pretoria, South Africa, April 05/2016.
5. Valorisation of chicken feather: Characterisation of physical properties and morphological structure, Oral presentation, 66th Canadian chemical engineering conference, Canada, Oct 23/2016.
6. Valorisation of waste chicken feather, Oral presentation, South African Waste Road Map Program, Johannesburg, South Africa, Feb 14/2017.
7. Grace Kakonke, Tamrat Tesfaye, Germain Ntunka and Bruce Sithole, Oral presentation, The South African Institution of Chemical Engineers (SAIChe), Durban, South Africa, August 30/2017.
8. Fagbemi Olajumoke Deborah, Tesfaye, T., Sithole, B., and Ramjugernath, D., 2017. Valorisation of chicken feathers: Utilisation as a binder in the forest products industry. The South African Institution of Chemical Engineers (SAIChe), Durban, South Africa, August 30/2017.
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11. Grace Kakonke, Tamrat Tesfaye, Germain Ntunka and Bruce Sithole, Oral presentation, College of Agriculture, Engineering and Science Research Day (CES), University of KwaZulu-Natal, Durban, South Africa, Oct 26/2017.
12. Valorisation of waste chicken feather, 4 min Business competition, UKZN InQubate, Durban, South Africa, Oct 26/2017.

ACKNOWLEDGMENTS

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Now is the time to write the last section of my study with a great privilege. Thanks to GOD for helping me to pass through this difficult time.

Undertaking this PhD has been a truly life-changing experience for me and it would not have been possible to do without the support and guidance that I received from a large number of people. I would like to express my deepest gratitude to my supervisor Professor Bruce Sithole, for his guidance and continuous support throughout and beyond the scope of this research. I owe special gratitude to my co-supervisor, Professor Deresh Ramjugernath, and am very grateful for his constructive advice and financial support.

To the Biorefinery Industry Development Facility team at the Council for Scientific and Industrial Research (CSIR), the Researchers, Senior Researchers and my fellow postgraduate students, it has been a long and eventful journey. This work would not have been possible without their constant input and advice. I would also like to thank Dr Viren Chunilall, Mr. Navan Gounden, Associate Professor Magdi Gibril, Dr. Prabashni Lekha, Mr. Jonas Johakimu, and Mom Elsie for their assistance in the laboratory at Biorefinery Industry Development Facility. To the administrative staff in the CSIR-NRE, as well as at the UKZN School of Chemical Engineering, thank you very much for all your assistance.

I gratefully acknowledge the funding received towards my PhD studies from the Ethiopian Institute of Textile and Fashion Technology, Bahir Dar University, Bahir Dar Ethiopia; The Republic of South African Department of Science and Technology (DST) Waste Road Map Program; and Thermodynamics Research Centre, University of KwaZulu-Natal, Durban, South Africa for their financial support. I am also deeply grateful for the National Research Foundation KIC award and JW Nelson scholarship for the financial support for the participation in international conferences.

Lastly, it will be impossible not to make use of this opportunity to thank all my beloved ones for supporting me spiritually throughout writing this thesis and my life in general.

Without their love, enduring support, understanding, words of advice and courage, thoughts, patience and perspective, this study would never have reached the final stages. A sincere and hearty thank you, strangely feels vastly inadequate.

Kind regards

Ozithobayo

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TAMRAT TESFAYE YIMER

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ABSTRACT

Environmental concerns, rapid oil consumption, increased demand for fuel due to rapid increment in urbanisation, depletion of non-renewable resources, the high price of oil and limited oil reserves with consumer demand is driving research into cheap, biodegradable, sustainable, renewable and abundantly available green materials. Reducing waste materials through reuse has in the recent past contributed to sustainable manufacturing in many manufacturing industries. Recycling of waste biomass reduces the price of raw materials and eases human pressure on the environment by alleviating the threat of depletion of oil resources. Recycling/recovering of waste biomass is also an important aspect to protect human ecological environment and realise the full utilisation of resources, especially the recycling and utilisation of waste biological polymers. Due to their high yield, low cost, and excellent biodegradability increasingly more efforts are being invested in beneficiation of agricultural and animal wastes.

The poultry industry is an important contributor to the GDP of countries worldwide. For example, in South Africa the industry processes more than $1x10^9$ broilers chickens per annum and contributes 21 % of all agricultural production and 43 % of all animal products to the country's GDP. About 5-10 % weight of a chicken is due to feathers, hence the poultry industry generates a significant amount of waste feathers that need to be disposed of. Globally, around $58x10^9$ chickens are killed per year generating an annual production of $40x10^9$ kg waste chicken feathers. South Africa contributes about $258x10^6$ kg chicken feathers/annum and this number is continually increasing year-after year. With the development of large-scale poultry farming, the treatment of large amounts of chicken feathers has become a long-standing problem. Most of the feathers generated are disposed of in landfills, incinerated, and buried, with a small percentage being converted into low-grade animal feed and fertiliser. Unfortunately, landfilling, incineration and burial lead to environmental concerns with potential health risks to human and animals. Conversion of this waste to low-grade animal feed and fertiliser is an energy intensive process and is accompanied by significant health and environmental impacts. Considering the rising cost of disposal, reduction in available landfill space, and increasing environmental concerns, research is urgenlty needed on developing innovative recoverying/recycling technologies which could potentially consume a significant amount of waste chicken feathers.

This dissertation is concerned with development of routes for beneficiation of waste chicken feathers. Waste chicken feathers from poultry meat processing industries are sticky, odoriferous and unfit for further valorisation since they are coated with offal fat, blood, grease, preen oil, debris, sand and processing water. Prior to possible valorisation pathways, waste chicken feathers require decontamination to reduce the amount of microbial contamination to allow for safe handling of the feathers. Thus, effective decontamination procedures were developed and evaluated to effect this. The objective was to assess various decontamination strategies, thereby identifying the optimised independent variables, namely, chemicals, concentrations, number of treatment stages, contact time and temperature, using statistically designed experiments.

Following this, the feathers and feather fractions (barbs and barbules) were characterised for their physical, chemical, mechanical, thermal, electrical properties and morphological structure in order to identify possible avenues for valorisation of waste chicken feathers. Physical properties of the feathers were ascertained by measurements of fibre length, fineness, density, diameter, aspect ratio, colour, dimensional measurements, ash content, moisture content, and moisture regain. The morphological structures of the feathers were studied by scanning electron microscope, and the fine detailed analysis of the topographical structures was determined by atomic force microscopy. Thermal properties of feathers were ascertained by thermogravimetric analysis and differential scanning calorimetry. Four probe testing experiments were used to study the electrical properties of the feathers. Mechanical properties of the feathers were studied by mechanical testing and dynamic mechanical analysis. Chemical properties of the feathers was studied by proximate analysis, ultimate analysis, chemical resistance, burning test, FTIR, X-ray diffraction, SEM-EDS, elemental analysis, swelling property and hydrophobicity.

The results of the detailed characterisation and tests conducted on the whole feathers and feather fractions revealed a myriad of possible routes for beneficiation of waste chicken feathers indicating that they could be used as a valuable raw material for applications in various industries including textiles (yarn production, filler for winter clothing, nonwoven production, cationisation of fabrics, regenerated keratin nanofibre, sizing agent, and leather treatment and production), pharmaceuticals, cosmetics, bioenergy, paper, binder, biomedical engineering, construction, automotive and aeroplane industries.

The feathers and feather fractions were then used to test production of some of the products identified in the preceding paragraph. These included:

- Replacement of wood pulp in paper manufacture: the results showed that increasing replacement of wood fibre with feather fibres in a paper sheet resulted in increased tightness, tear strength, tensile index, breaking length, stretch, and tensile energy absorption of the results paper sheet. However, the bursting index decreased whereas the air permeability improved. This could potentially open up a new avenue for the use of waste chicken feathers in manufacture of speciality papers that can tolerate high humidity conditions e.g., packing products.
- Use of feather barbs for yarn production and technical textile applications. Physicochemical, mechanical, and morphological characterisations indicated that feather barbs exhibited the following properties: hollow honeycomb structure, insolubility in organic solvents, solubility in alkaline conditions, low density, hydrophobic behaviour, high slenderness ratio, high flexibility, spinnable length, fineness, good mechanical properties, and high flexibility. These are unique properties that are not found in any other natural or synthetic fibres – the implication being that chicken feather bars are ideal for yarn production and textile applications
- Production of bioplastic films from keratin extracted from chicken feathers and waste mango/avocado seed starch as food packaging materials. The aim of this study was to develop green biofilms from waste avocado seed starch and waste chicken feathers keratin. With increasing starch content, the flexibility, solubility, dissolution, moisture regain, and moisture content of the biofilms increased, whereas the tensile strength property decreased. The results demonstrated that chicken feather keratin can be used as a raw material in the manufacture of different hygiene products, (e.g., superabsorbent materials for diaper products); in tissue engineering; in wound dressings; and in the pharmaceutical industry (e.g., as drug delivery and/or transdermal drug delivery system).
- Clean-up of oil spills in water streams to replace the conventional costly and synthetic adsorbents. The results showed that chicken feather fractions have a very high oil adsorption capacity (up to 16.21 g of oil/g of chicken feather) and a relatively fast rate/uptake time (10 min) for adsorption of liquid oils. Oil spill removal efficiency increased with increase in contact time. More than 85 % of

the adsorbed oil by chicken feather fractions could be recovered. Thus, waste chicken feathers show very attractive and promising absorption/desorption properties for oil spill clean-up applications to replace unfriendly polymer based adsorbents due to their high oil absorption capacities.

This dissertation reveals that there are significant potential benefits in implementation of "cleaner production" in poultry meat processing industries. Specifically, beneficiation of waste chicken feathers will reduce the environmental impact of this waste organic load to generate additional value streams that could be of major economic benefit to the industries.

Outputs from this work include: seven papers that have been published in high impact peer-reviewed journals; two that have been accepted for publication; one conference proceeding; and three more papers that have been submitted for publication in peer-reviewed journals.

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CHAPTER 1

INTRODUCTION

1.1. GENERAL OVERVIEW

The potential of significant environmental benefit and consumer demand for eco-friendly and green materials lead to developing biobased alternatives using the biorefinery concept (Al-Salem et al., 2009). More attention has been paid to agricultural by-products due to their high yield, low cost, excellent biodegradability and low pollution impacts (Russ and Pittroff, 2004). Recycling of waste biomass is an important aspect to protect the human ecological environment and realise the full utilisation of resources, especially the recycling and utilisation of waste biological polymers (Beretta, et al., 2013; Marshall and Farahbakhsh, 2013). Recycling of waste natural polymers can reduce the price of raw materials, but also alleviate the depletion of oil resources, and also ease the human exploitation of the environment. The most abundant natural polymers based on renewable, plant and microbial resources are polysaccharides (cellulose, starch, keratin and chitin) and protein resources (Beretta et al., 2013). These biological resources can be recycled, with the production of biodegradable materials, instead of synthetic polymer materials applied to many areas of human life, e.g., keratin is widely used in products that is prevalent in skin and skin derivatives due to its special molecular structure can be used in cosmetics and pharmaceutical industries (Russ and Pittroff, 2004; Beretta et al., 2013).

Increasing population and economic growth worldwide has caused an enormous increase in waste production (Martelli et al., 2006). Waste management in the food industry poses problems in environmental protection and sustainability (Russ and Pittroff 2004).

Nature is surrounded by high-performance materials that can be studied to exploit them as sustainably sourced raw materials for innovative technologies as mandated by the Green Economy. More than $58x10^9$ chickens are killed every year across the world producing more than $90x10^9$ kg white meat to meet customer demand. This results in generation of about $40x10^9$ kg of waste poultry feathers as a by-product from commercial poultry meat processing abattoirs. The Republic of South Africa is ranked the top in

Africa and among the top 20 poultry producers in the world. Hence it is among the top producers of waste chicken feathers. Considering the rising costs of disposal, reduction in available landfill space, and increasing environmental concerns, research is critically needed on innovative recycling technologies which could potentially consume a large amount of virtually waste poultry feathers and make a significant contribution to the circular economy.

1.2. CONTEXT OF RESEARCH

As the economic status of a country or race increases, there is usually a shift in its diet and nutrition to include a greater percentage of tasty and well-balanced protein from animal sources. With all of the natural advantages of animal food products, there still remains a great quantity, often in excess of 40 %, of animal by-products that sometimes have rather unusual physical and chemical characteristics that are not part of the normally consumed steaks and roasts. Poultry meat is now of great importance in the consumer market due to great demand by a rapidly increasing population. Thus, the opening of large-scale poultry processing slaughterhouses greatly increased from the 1980s (EL Boushy et al., 2000). As a result, large amounts of organic solid by-products, which are considered to be industrial organic wastes, are generated from poultry slaughterhouses. Poultry meat processing industry waste can be defined as solid waste comprising of feathers, soft meat, legs, fats, viscera, deboning residue, head, carcases, dead on arrival skin and bone, and various liquid wastes such as blood and liquid effluents (EL Boushy et al., 2000). Poultry producers sell meat and the most profit is generated from the breast meat. However, the meat only represents about 60 % of the weight of the chicken. The rest is comprised of feathers, blood, fat, and other non-saleable parts. Fat is a useful lipid molecule that can be converted to fuel such as biodiesel or hydrocarbon chemical intermediates. Feathers, blood, bones, dead birds on arrival, soft meat, head and skin are all proteins. These organic solid wastes are characterised by high total solid (TS) contents above 10–15 % that are mainly composed of animal proteins and fats. These organic solid wastes need to be strictly managed according to governmental legislation (Department Environmental Affairs: Republic of South Africa, 2015).

USA, Brazil and China are the largest poultry producers in the world with South Africa, Egypt and Nigeria being the largest in Africa (Compassion in World Farming, 2013). On a world scale, it is estimated that 40×10^9 kg of chicken feathers are produced from the slaughter of more than 58×10^9 chickens (Compassion in World Farming, 2013; USDA Foreign Agricultural Service, 2014). In South Africa, statistics from 2013 indicate the presence of more than 179 large scale chicken abattoirs in the country. These poultry farming activities generated more than 528×10^6 kg of feathers (DAFF, 2014). Similar to the rest of the world, solid waste management is currently a crucial issue in the Republic of South Africa.

These wastes give rise to environmental concerns, guided by legal requirements and contemporary best practices, such as the Zero Waste Initiative in South Africa. The copious mass of poultry feathers produced annually is viewed as a low value by-product of the poultry industry and the most commonly proposed methods for its management are burning in incineration plants, burial in landfills, or recycling into low-quality animal feeds, with the last one being the least option of choice. Current traditional disposal techniques of poultry waste (incineration, burial, landfilling and composting) are energy intensive, naturally resistant to deterioration and allow the wastes to persist in the environment for decades, they take up landfill space, and result in emission of unpleasant odours. In addition, they produce 50 times more CO_2 release than the coal industry and large quantities of other greenhouse gases (GHG). All this increases air pollution and can negatively impact environmental health if environmentally sound management and best practices are not implemented. Apart from polluting the soil, water or air environments, the large amounts of discarded waste poultry feathers causes various human ailments including chlorosis, mycoplasmosis and fowl cholera arising from feather waste. Currently, South Africa is plagued with the avian flu virus crisis. Concerns over these issues discourage beneficiation of the wastes as animal feed. Thus, disposal of rendered poultry products becomes an expensive problem that drives up the cost of poultry in supermarkets. The disposal of waste in an economically and environmentally acceptable manner is a critical issue facing most modern industries. These materials represent a massive amount of solid waste that should be properly managed to avoid environmental damage and loss of important raw materials for use in development of new valuable chains from the waste.

1.3. RATIONALE AND SIGNIFICANCE

The poultry meat processing industry is an important contributor to jobs and the GDP of South Africa. However, its environmental impact has grown considerably due to its generation of large amounts of waste including feathers. Without proper treatment, this waste may pose severe health risks and cause emission of unpleasant odours and environmental pollution. Although regarded as a waste material, poultry waste may be considered a valuable source of financial income if processed properly. Currently, poultry feathers are renewable protein resources, inexpensive, and abundantly available keratinous biomass, but with limited applications. This dissertation will entail detailed analysis and characterisation of waste chicken feathers to ascertain, develop and demonstrate possible beneficiation pathways for the waste into high value products and to support the Waste Research Development and Innovation Roadmap strategy, Department of Science and Technology, Republic of South Africa.

1.4. RESEARCH QUESTIONS

The research contained in this thesis aims to address the following research questions

Can the poultry industry benefit from valorisation of chicken feathers?

The poultry processing industry generates a large amount of feathers as a waste product. For example, over $40x10^9$ kg of chicken feather "waste" is generated by the United States of America poultry industry alone every year. Feathers represent 5-10 % of the total weight of mature chickens and are comprised of mainly protein matter (~ 90% keratin). This waste represents a significant disposal problem for the industry as it pollutes the environment. Presently, feathers are considered as "waste" because their current uses are marginally economic and their disposal is difficult. Their utilisation is difficult due to their having a very rigid protein structure. This then leads to the question: can the protein matter be converted into high-value products? Such conversion will solve the disposal problem and generate extra income for the poultry processing industries due to creation of new industries to process the feathers.

Can high valuable products be obtained from waste chicken feathers?

The concept of biorefinery and the circular economy requires the utilisation of waste biomass for the production of high-value materials. Chicken feather waste is classified under animal fibre which is the main source of a biodegradable polymer called keratin protein (about 91 %). It is recognised in the beneficiation space that a polymer rich in protein, like keratin, has the potential to replace petroleum-based materials in the manufacture and production of a wide variety of industries. Thus chicken feathers can be used as a raw material for a plethora of industries including textile (as a source of sizing agent, regenerated fibres, nonwoven fabrics, superabsorbent fabrics, geotextiles, yarn, filler for winter clothing, and binder in textile printing), paper production, bioplastics, cosmetics, pharmaceuticals, bioenergy, composite manufacturing, etc.

1.5. AIM AND OBJECTIVES

The general aims of the following work are to conduct a detailed analysis and characterisation of waste chicken feathers and use the data to develop and demonstrate that high value products and materials can be beneficiated from waste chicken feathers. The specific objectives were as follows:

- Development and formulation of appropriate and effective decontamination and pre-treatment procedures for waste chicken feathers.
- Characterisation of the decontaminated waste chicken feathers to ascertain the effect of decontamination and pre-treatment procedures.
- Characterisation of the decontaminated waste chicken feathers to assess their physical, mechanical, chemical, thermal, electrical properties, morphological and fine detail structures.
- Identification of potential beneficiation routes for valorisation of waste chicken feather in line with their ascertained properties.
- Demonstration of production of possible materials and products from waste chicken feathers.
- Assessment of properties and qualities of the materials and products from waste chicken feathers.

1.6. MAIN CONTRIBUTIONS OF THIS WORK

The following are the contributions: -

- Information and data on detailed analysis and characterisation of waste chicken feathers
- An effective technology for decontamination and pre-treatment of waste chicken feathers
- Reports on chemical, mechanical, thermal, electrical and physical properties of chicken feathers
- Demonstrations of possible beneficiation routes of waste chicken feathers:
    - Source of green oil sorbent
    - Production of lightweight materials
    - Replacement of wood fibres in paper production
    - Production of bioplastics for possible use in food packaging
- Proposals for further research to be conducted by two PhD and two MSc students

1.8. ORGANISATION OF THE THESIS

The layout of the thesis is according to publication outputs. The publication outputs include those have been in print, are in press and have been submitted for publication in high impact peer-reviewed journals. Each chapter is mostly self-contained, containing a brief introduction for the motivation of the study through literature, materials and methods, results and discussion, and conclusions.

Chapter 2 consists of a literature review on background information on the poultry meat processing industry, description of the poultry rendering process, information on quantities of waste chicken feathers, characteristics and problems with chicken feathers, current methods for disposal of the waste, and methods for beneficiation of the waste. The review also touches on waste management and legislation of the poultry meat processing industry in the Republic of South Africa.

Chapter 3 focuses on research undertaken to develop decontamination and pre-treatment technologies for waste chicken feathers. Various surfactant and inorganic chemicals were used. Two peer-reviewed publications have emanated from this work.

- **Tesfaye, T.,** Sithole, B., and Ramjugernath, D. 2017. Valorisation of waste chicken feathers: optimisation of decontamination and pre-treatment with bleaching agents using response surface methodology. Punlished in *Journal of Sustainable Chemistry and Pharmacy*.
- **Tesfaye, T.,** Sithole, B., and Ramjugernath, D. 2017. Optimisation of surfactant decontamination and pre-treatment of waste chicken feathers by using response surface methodology. Published in the *Journal of Waste Management, DOI: 10.1016/j.wasman.2017.11.013.*

Chapter 4 focuses on the characterisation of waste chicken feathers after decontamination to identify possible beneficiation routes of feathers. Three peer-reviewed publications emanated from this work.

- **Tesfaye, T.,** Sithole, B., Ramjugernath, D. and Chunilall, V., 2017. Valorisation of chicken feathers: Characterisation of physical properties and morphological structure. *Journal of Cleaner Production,* **149**, pp. 349-365.
- **Tesfaye, T.,** Sithole, B., Ramjugernath, D. and Chunilall, V., 2017. Valorisation of chicken feathers: Characterisation of chemical properties. *Journal of Cleaner Production,* **68C**, pp. 626-635.
- **Tesfaye, T.,** Sithole, B., and Ramjugernath, D. 2017. Valorisation of chicken feathers: Characterisation of mechanical, thermal and electrical properties. Submitted to *Journal of Cleaner Production*.

Chapter 5 is concerned with development of demonstration products for valorisation of chicken feathers. Five publications and one conference proceeding have emanated from this work.

- **Tesfaye, T.,** Sithole, B., Ramjugernath, D. and Chunilall, V., 2017. Valorisation of chicken feathers: a review on recycling and recovery route-current status and future prospects. *Journal of Clean Technologies and Environmental Policies*, **19**, pp. 2263-2275.

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Chapter 6 summarises the entire dissertation, the various findings drawn, and recommendations for future work.

A schematic showing the research plan of the detailed proposal is shown in Figure 1.1.

Papers

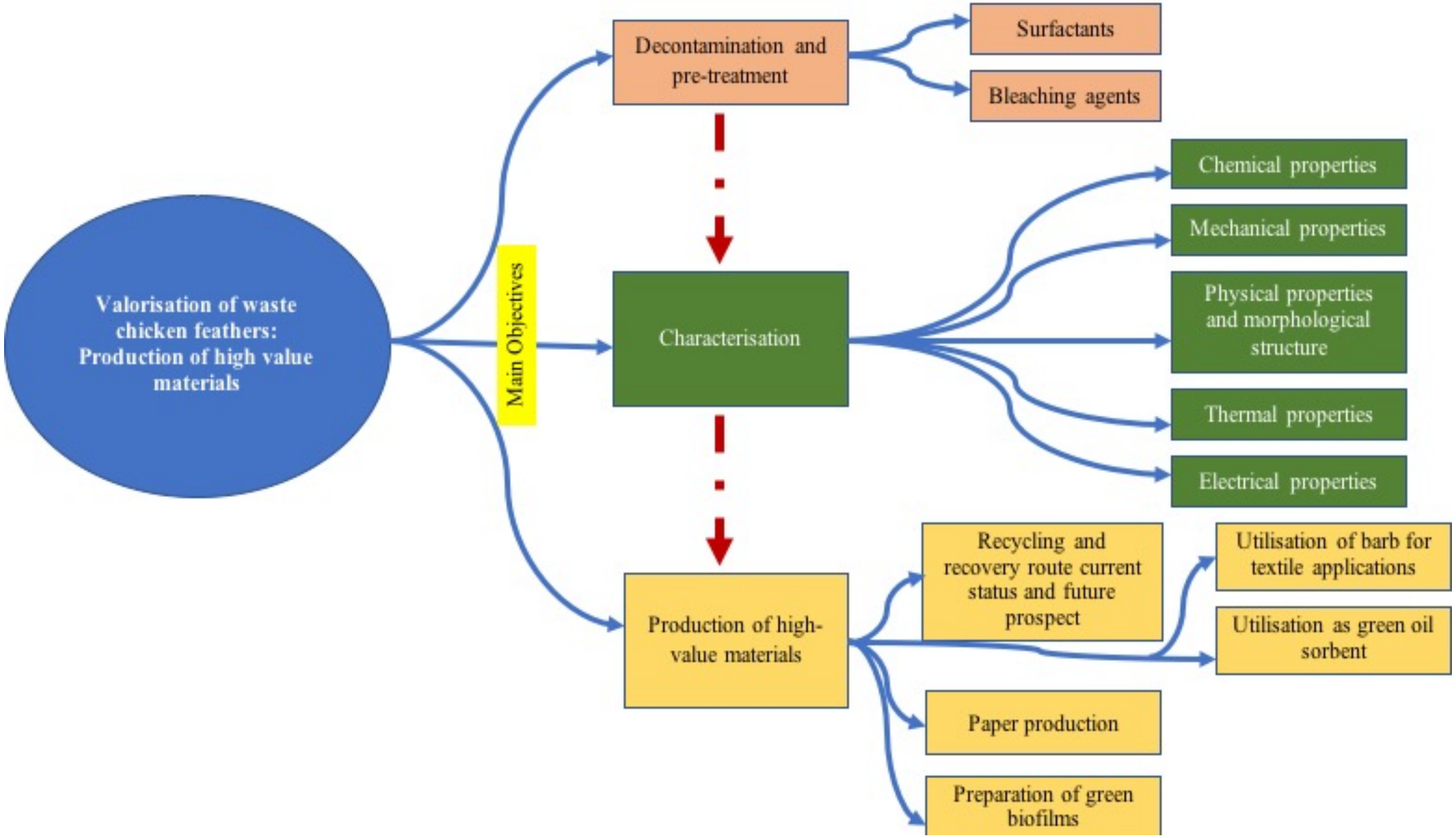

Figure 1.1. Schematic showing the research plan

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CHAPTER 2

LITERATURE REVIEW

Chapter overview

The poultry processing industry is a significant contributor to jobs and the GDP of many countries. However, poultry processing plants generate large amounts of waste in the form of condemned organs, feathers, carcasses, head, feet, dead birds, blood, paunch content, and trimmings. Currently, these wastes are either landfilled, buried, incinerated, or processed into low-grade animal feed and biofertilisers. Improper disposal of these wastes can cause environmental pollution and health risks due to contamination with blood borne pathogens. Also, since the wastes contain biological resources such as enzymes, carbohydrates, lipids and protein, the disposal techniques result in a loss of these potentially valuable resources. Current economic and environmental concerns dictate that society finds or develops sustainable technologies for beneficiating of poultry wastes. This literature review is focused on waste chicken feathers and provides background information on the poultry meat processing industry, a description of the poultry rendering process, information on quantities of waste chicken feathers, characteristics and problems with chicken feathers, current methods for disposal of the waste, and methods for beneficiation of the waste. The review also touches on waste management and legislation of the poultry meat processing industry.

2.1. INTRODUCTION

The use of sustainable and renewable source for the production of high-value bioproducts to decrease the consumption of synthetic materials is a critical need and of increasing interest across the world. These products are environmentally sustainable and are inexpensive resources for use in the development of biobased products (Baiano, 2014).

The poultry processing industry generates a large amount of feathers as a waste product. For example, over 40×10^9 kg of chicken feathers "waste" is generated in the world and 4×10^9 kg by the USA poultry industry alone every year (Compassion in World Farming, 2013). Feathers represent 5-10 % of the total weight of mature chickens and are comprised of mainly protein matter (~ 90% keratin) (Saravanan and Dhurai, 2012). This waste represents a significant disposal problem for the industry as it pollutes the environment. Presently, feathers are considered as "waste" because their current uses are marginally economic and their disposal is difficult. Their utilisation is difficult due to their having a very rigid protein structure (Saravanan and Dhurai, 2012).

Feathers have outstanding characteristics in that they help birds to perform some functions including thermal insulation, flight, waterproofing, protection from cold, communication, and protection from UV rays etc. (Subbiah and Abidha, 2007).

Traditional methods for disposal of waste feathers include controlled landfilling, burial, incineration, rendering, and anaerobic digestion (Blake, 2004; Gurav and Jadhav, 2013; Hairston, 2001; Mijinyawa and Dlamini, 2006; Stingone and Wing, 2001). However, feathers are naturally resistant to deterioration and persist in the environment for decades (Saravanan and Dhurai, 2012). Consequently, they take up large space in landfills and emit unpleasant odours from residual manure, blood and other extraneous materials. In some countries, waste feathers are burned in incineration plants. However, burning of waste feathers is expensive, and the process results in the emission of greenhouse gases and there are problems with disposal of the resultant ash (Mijinyawa and Dlamini, 2006; Stingone and Wing, 2001). Waste chicken feathers could be converted into low-grade animal feed. However, the process is expensive because feathers are hydrolysed at high temperature and pressure requiring large amounts of water and energy in commercial plants (ElBoushy et al., 1990; Mijinyawa and Dlamini, 2006; Molapo, 2009). In general, current disposal methods for waste chicken feathers are environmentally unsound, restricted or result in products that are of low demand. Since waste from the poultry processing industries is not acceptable for use as animal feed or for human consumption due to the risks of bloodborne microorganisms, bovine spongiform encephalopathy, or mad-cow disease, alternative methods of disposal of feathers have been explored (Franke and Insam, 2013; Molapo, 2009).

The significant amount of waste generated from poultry meat processing industry should be properly managed to avoid loss of critical raw materials and environmental damage. In addition to this, legislations on the recycling and recovery of organic solid waste by-product are becoming tighter and more restrictive for traditional waste disposal techniques (Molapo, 2009). The objective of this review paper was to describe and quantify organic solid by-products produced in poultry meat processing industries to evaluate waste treatment options, to assess the impact of wastes generated, discuss the solid waste management legal framework and discuss their recovery and disposal options.

2.2. POULTRY PRODUCTION

2.2.1. Global trends in the poultry industry

Over the last five decades, there has been a rapid change in how animal products are processed, produced, marketed and consumed with rapid increase in meat production. With the increase in world population, the increase in per capita consumption of proteins and the open global marketplace, expectations for growth in the sector are positive. The poultry industry has been the leading industry in livestock production in both developing and developed countries. Production of poultry meat is among the fastest growing livestock sector in the world. The consumption share of developing countries accounted for 36 % of the world production (USDA Foreign Agricultural Service, 2014). Over the last two decades, there has been a rapid growth in the proportion of the world's poultry consumption and production in developing countries from 43 to 54 % (Compassion in world farming, 2013; USDA Foreign Agricultural Service, 2014). The annual projected consumption and production of poultry meat in developing countries in 2030 will increase 3.5 %. In 2015, Brazil, the EU, the USA and China accounted for almost 60 % of global production (Figure 2.1). The data in Figure 2.1. shows that the exports of chicken meat are also more concentrated, with the EU, USA and Brazil accounting for more than 70 % of the world export volumes.

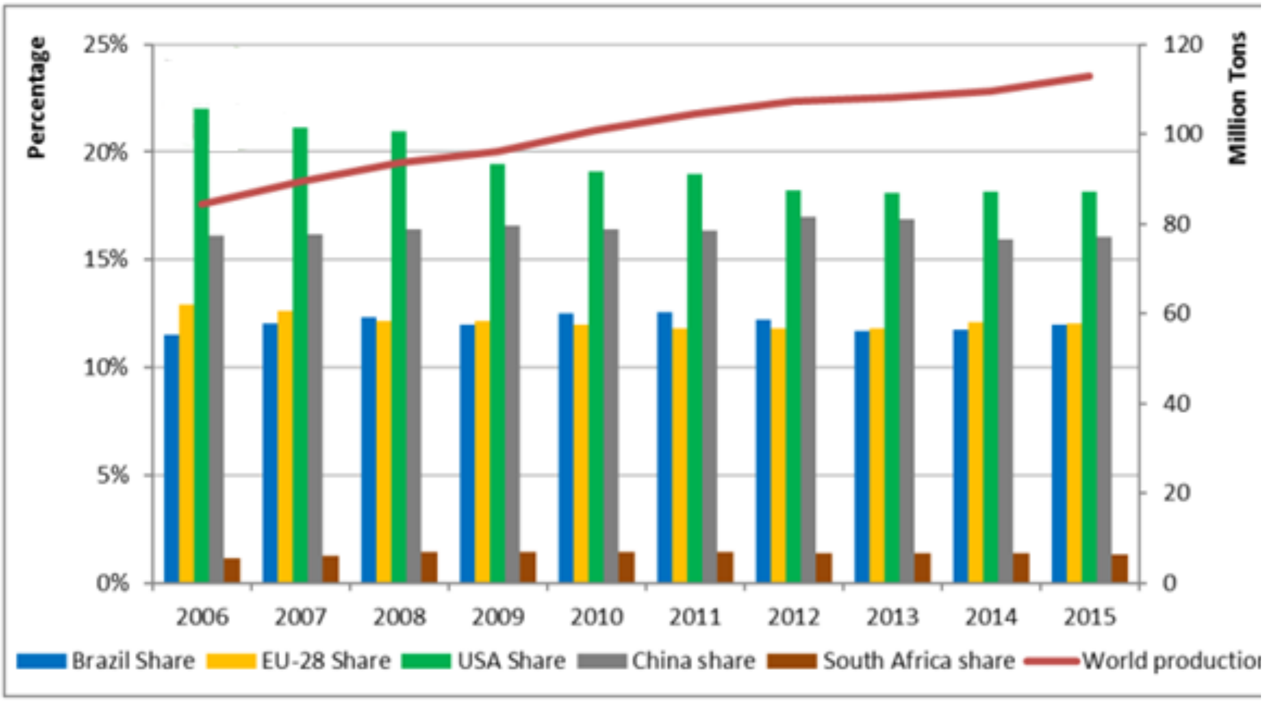

Figure 2.1. Global poultry share (adapted from USDA Foreign Agricultural Service, 2014)

The per capita consumption of chicken meat in selected countries is depicted in Figure 2.2 where it can be seen that the total domestic per capita consumption of chickens in 2014 was 49 kg in the United States; 42.0 kg in Saudi Arabia, 42.3 kg in Australia, 59.7 kg in Israel, and 35.4 kg in Canada (USDA Foreign Agricultural Service, 2014) – in South Africa the consumption rate in 2016 was 36.27 kg (DAFF, 2014).

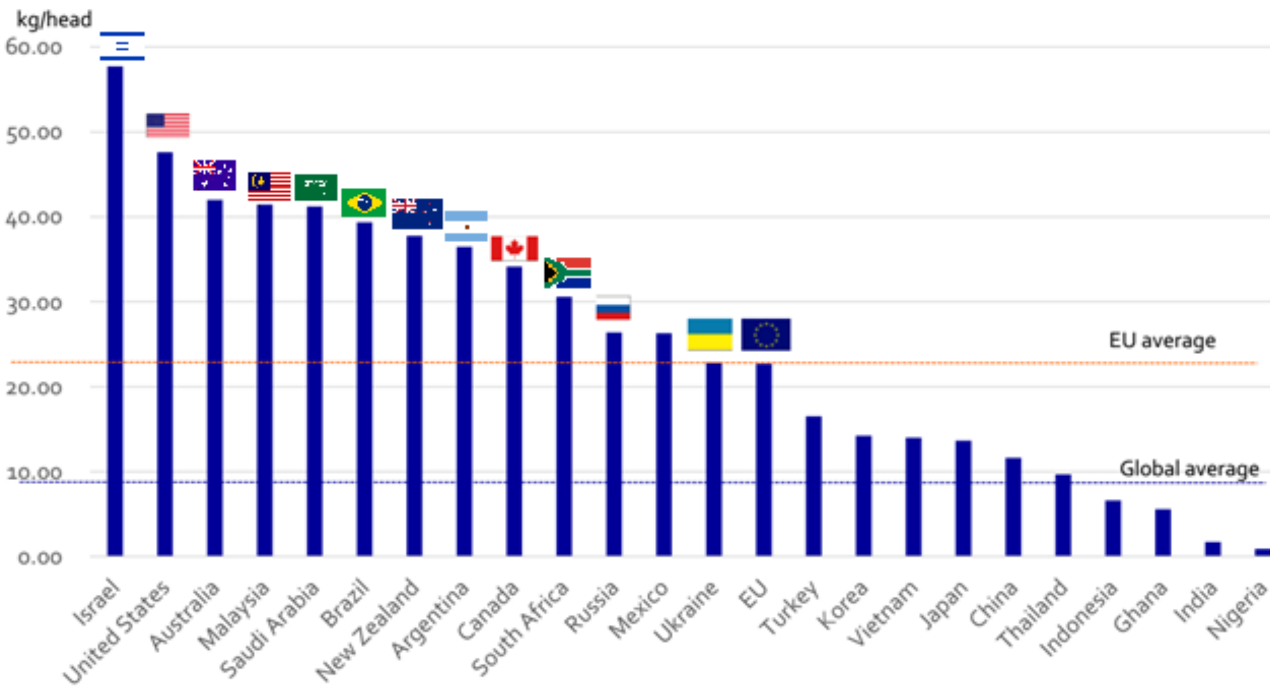

Figure 2.2. Global per capita consumption poultry in 2015 (adapted from USDA Foreign Agricultural Service, 2014)

According to statistics on broiler chickens provided by Compassion in World Farming, around $58x10^9$ chickens are slaughtered for meat in the world every year (Compassion in World Farming, 2013). The United States of Department of Agriculture estimates that $46.6x10^9$ kg of chicken meat was processed in the USA poultry processing industry in 2014 (USDA Foreign Agricultural Service, 2014). World poultry production can generally be divided into broiler chicken, ducks, geese, turkey and others. The major contributors are broiler chickens followed by turkeys (Figure 2.3). Broiler chickens account for 89.46 % of the global poultry production (Figure 2.3).

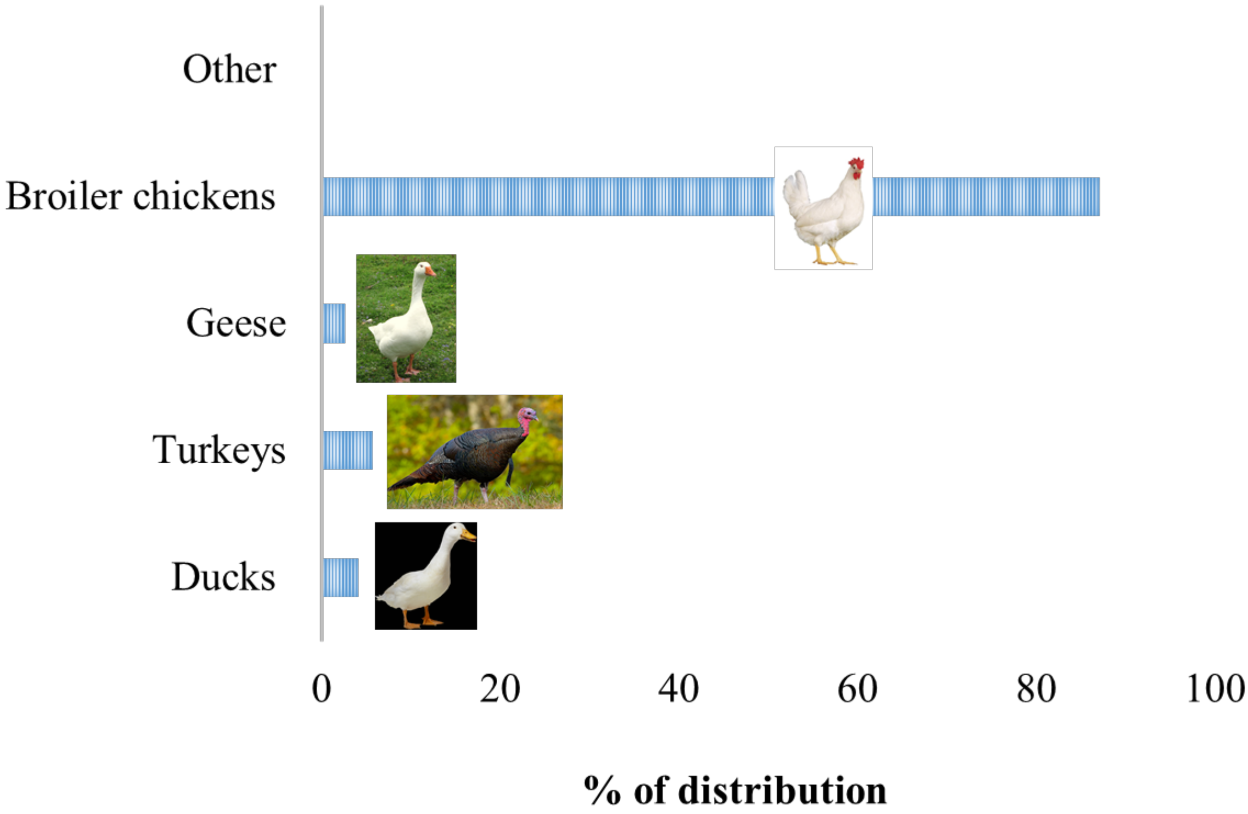

Figure 2.3. Global distribution of poultry production

2.2.2. Poultry industries in South Africa

The South African poultry industry has undergone considerable expansion over the past 50 years and is an important sub-sector within the South African agriculture sector (Molapo, 2009). It provides the most affordable source of animal protein, is the largest contributor to total gross agricultural production, and has a significant effect on the integrated value chain. South Africa had 322 poultry slaughterhouses classified as rural abattoirs (79), low-throughput (67) and high-throughput (176) operations. Locations of slaughterhouses are mainly distributed in the Northwest, Western Cape, KwaZulu-Natal and Mpumalanga provinces as illustrated in Figure 2.4 (Molapo, 2009). About 90 % of the poultry processing industries are privately owned, 5 % are operated as community projects, and the remaining 5 % are government owned (Molapo, 2009).

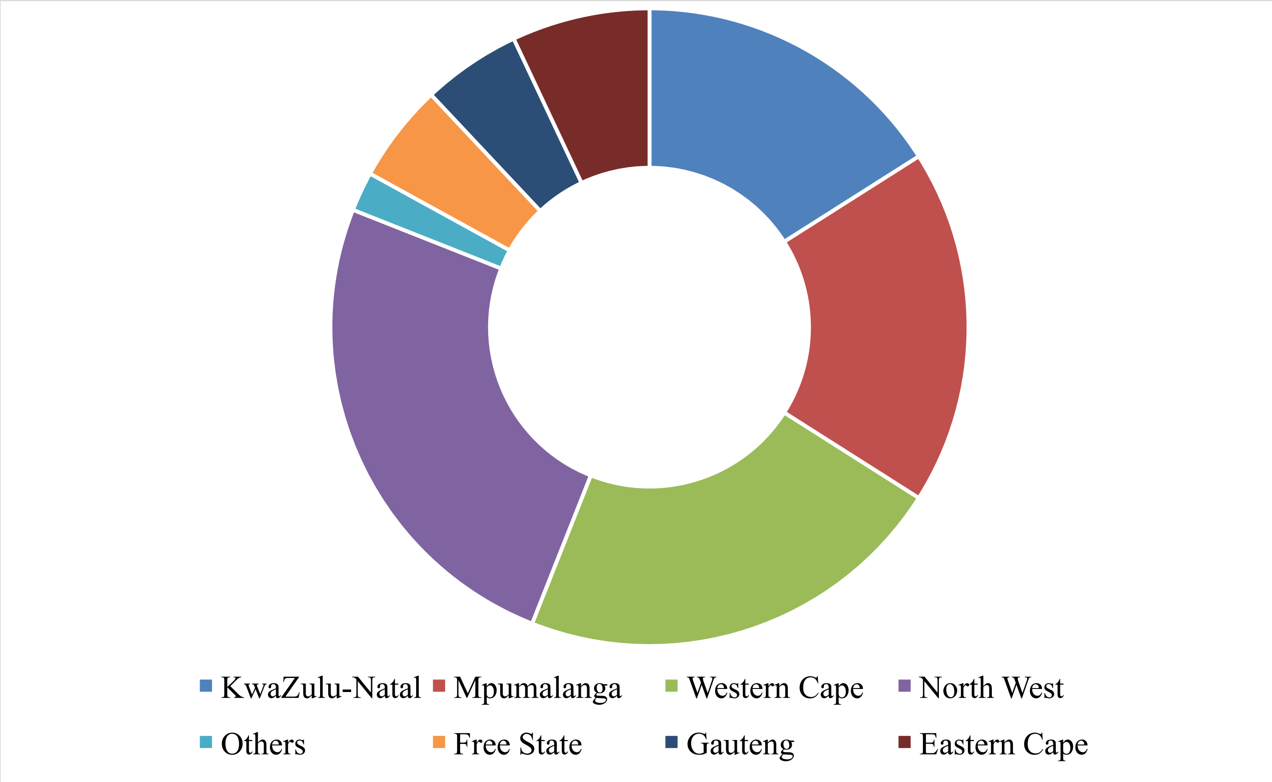

Figure 2.4. Distribution of poultry production by region (adapted from Molapo, 2009)

Poultry meat processing industries in the Republic of South Africa are concentrated in certain areas and the major poultry production region in the Western Cape are concentrated around Cape Town, Worcester and Paarl (Figure 2.5)

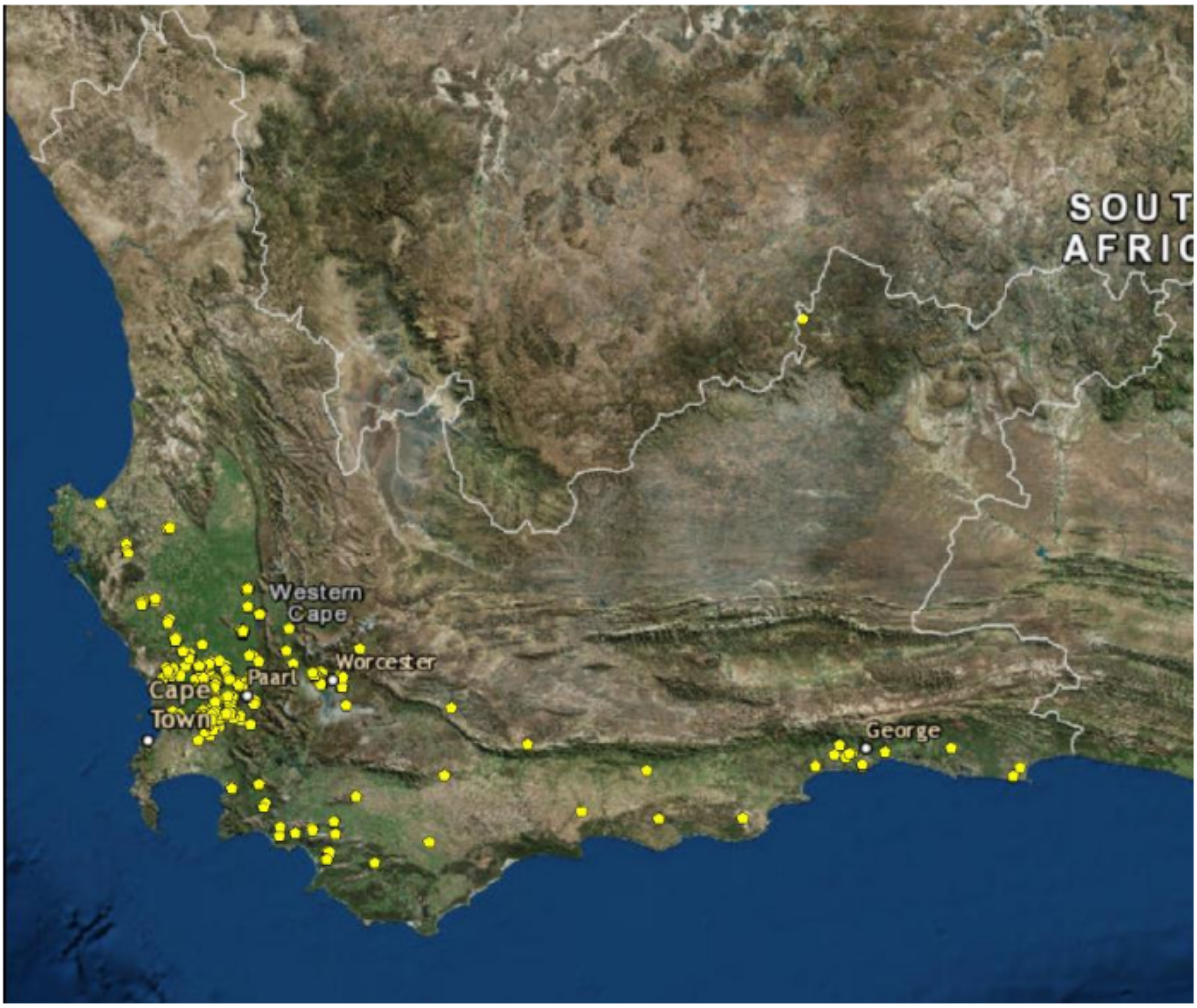

Figure 2.5. Distribution of poultry abattoirs in Western Cape (adapted from Gogela et al., 2017)

Figure 2.6 depicts annual broiler meat production and imported chicken meat in South Africa (DAFF, 2014). South Africa is a small player in the volume of world poultry meat production. Over the past decade, the consumption of poultry meat has increased rapidly in line with global trends. Due to price competitiveness, the local poultry production growth rate has slowed significantly and imports of poultry meat into the country have increased by more than 10 % per annum since 2001 (Figure 2.6). The increase in imported chicken would suggest that there is scope for expansion of domestic production if producers were able to compete more successfully with imported products. In total, $1x10^9$ broilers were slaughtered in 2015; an increase of $44.1x10^6$ compared to 2014 (DAFF, 2014; Molapo, 2009). In the years 2011-2016, the average annual production of poultry slaughter is estimated at 235,900 tons live weight (Molapo, 2009). According to

Figure 2.6, during this period the production of poultry for slaughter indicates a slight increasing trend.

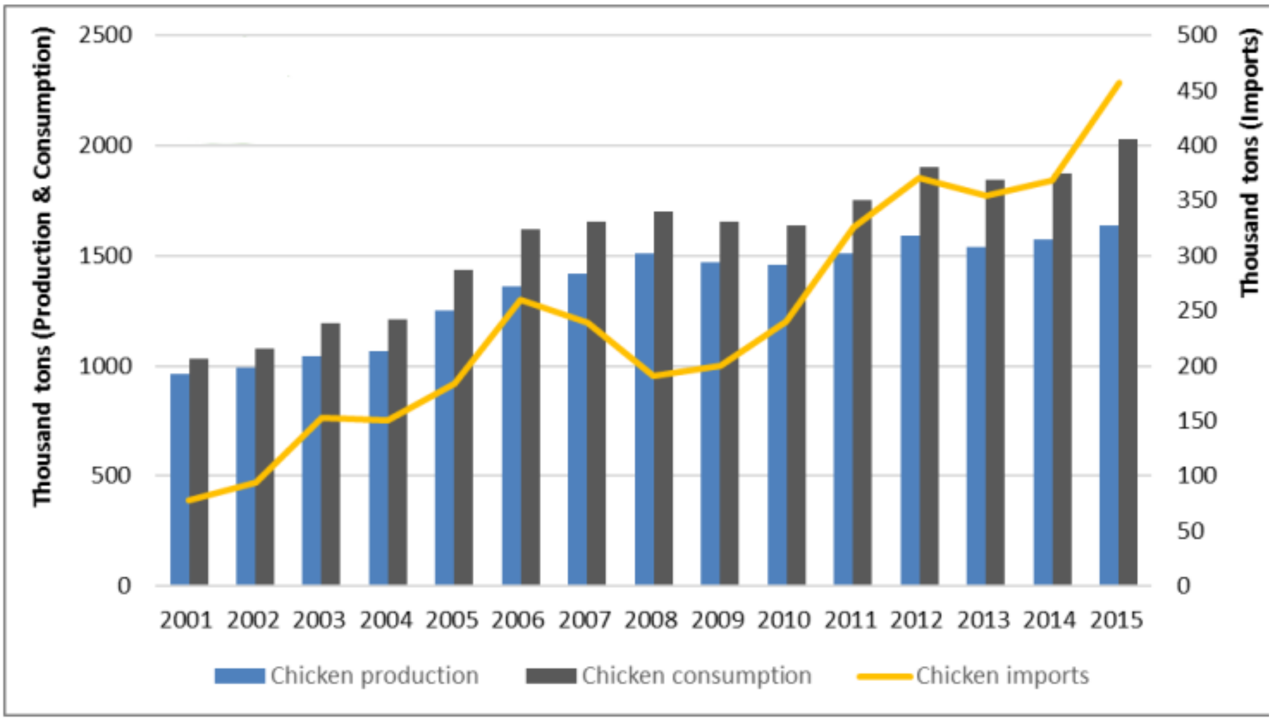

Figure 2.6. Annual slaughter of broilers in South Africa (adapted from DAFF, 2014).

2.3. DESCRIPTION OF THE POULTRY SLAUGHTERING PROCESS

The process flow of the slaughtering process of broiler chicken in poultry processing industries depicted in Figure 2.7. In high-throughput poultry processing industries, the services are mechanised; however, in low-throughput slaughterhouses most of the functions are carried out by hand (Franke and Insam, 2013; Molapo, 2009). Live birds are usually transported from farms and delivered to slaughterhouses. During the transportation, the transportaion containers are usually contaminated with manure wastes (Shari, 2002; Sams, 2001). Consequently, the manure contamination increases the amount of organic effluent produced during the automated container washing equipment after delivery of the chickens (Molapo, 2009; Salminen and Rintala, 2002). On arrival at the slaughterhouse, the poultry are removed from the crates, and the birds are hung upside down, manually by their feet, on a metallic conveyor which moves them towards the stunning machine where a 30-40 vol elctric charge is used to stun the chickens before transfer to the killing line (Molapo, 2009; Sams, 2001). The broilers are stunned by electrical shock as their heads touch a brine solution when they are submerged in a water bath (Shari, 2002). After electrical stunning, the necks of the chickens are partially cut either by a rotating knife-blade and/ or by hand (Franke and Insam, 2013). After killing, the chickens are bled for up to two minutes while moving on the conveyor to reduce the blood content in further processing (Parkhurst and Mountney, 1997; Salminen and Rintala, 2002). 34-50 % of blood is lost during this stage and this decreases the internal body temperature and helps to minimise growth of bloodborne bacteria (Molapo, 2009).

Once bleeding is complete, the birds are then transferred via conveyors to the scald tank to facilitate the de-feathering process for the plucking of feathers (Shari, 2002). Following the scalding operation, chickens enter the de-feathering section comprised of counter-rotating discs with rubber fingers mounted on them, as well as continuous water sprays incorporated within the machines for flushing-out feathers (Franke and Insam, 2013; Salminen and Rintala, 2002). The removed waste chicken feathers are taken to a collection point via a fast-running water channel located below the machine (Shari, 2002). The collected feathers are then transferred to a lorry using a conveyor belt. Other feathers, which escape through water, can be collected in the grit chamber in the preliminary wastewater treatment stage (Parkhurst and Mountney, 1997; Sams, 2001). The waste chicken feathers are collected and pumped over screens before further valorisation or disposal. Some processing lines pass the carcass through a singing stage/sheet of flames to remove fine hair-like feathers and appendages (Franke and Insam, 2013; Molapo, 2009).

The whole birds pass through a washing chamber where water is sprayed for washing. After that, chickens enter the evisceration stage via the conveyors (Scanes et al., 2004). In the evisceration stage, the chickens' heads and feet are cut and removed, and then the chickens are automatically eviscerated whereby the internal organs are removed mechanically using a device which is inserted into the opening, and the viscera are withdrawn (Franke and Insam, 2013). A sucking system is used to remove the lungs and ensure that there are no remaining blood and body liquids in the eviscerated chickens (Shari, 2002). In order to remove any remaining particles, the chickens are washed internally and externally after all evisceration operations (Parkhurst and Mountney, 1997). The chickens are then unloaded, immersed and moved through a counter-flow current in the pre-chiller followed by a chiller at a temperature less than 5 ^{o}C to minimise possible microbiological contamination (Molapo, 2009).

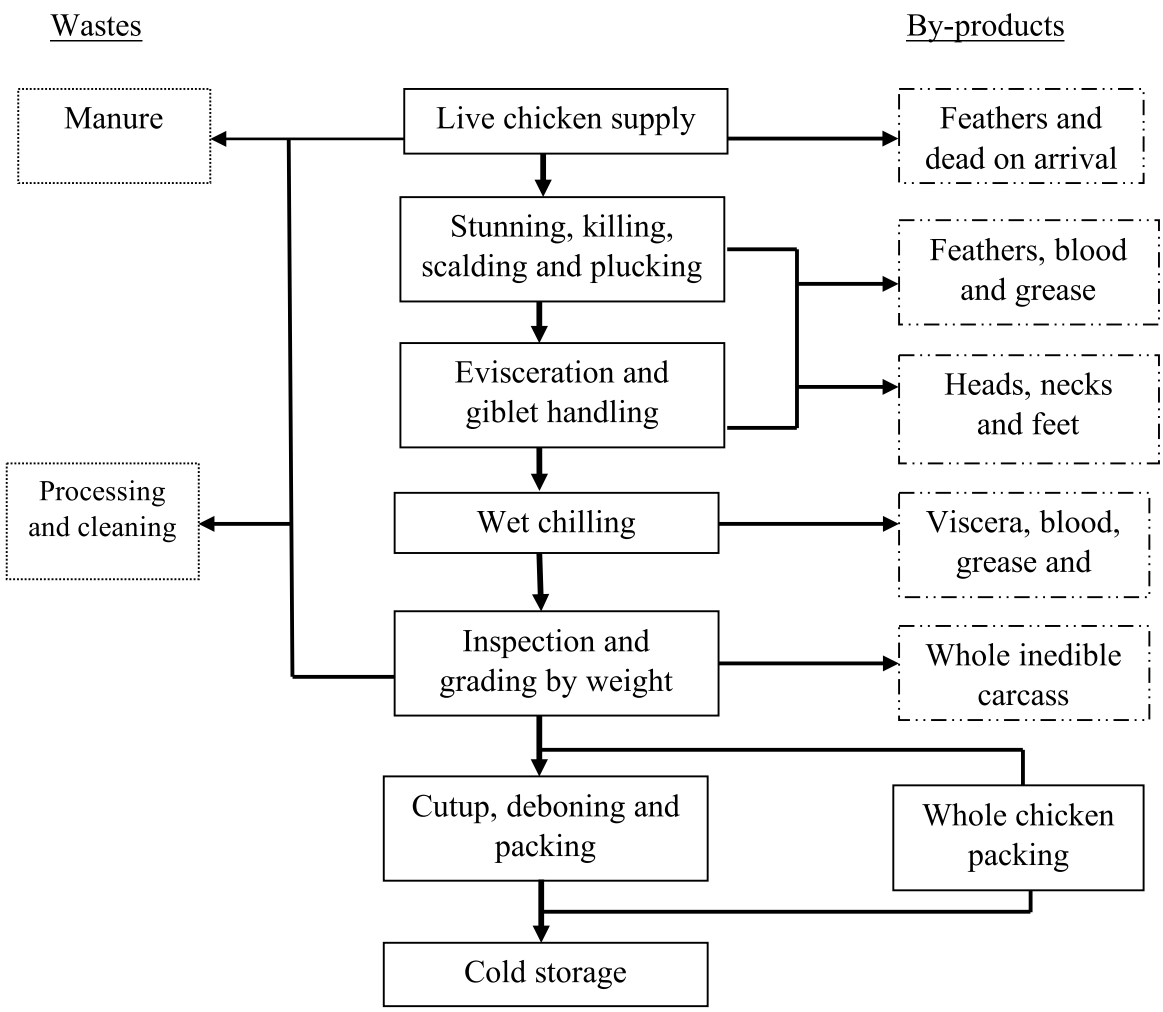

Figure 2.7. A schematic of the poultry slaughtering process (Adapted from Molapo, 2009)

In water immersion, chilled carcasses move through one or more large tanks of water to which chilled water is added (Parkhurst and Mountney, 1997). To improve agitation in order to facilitate the removal of contaminating micro-organisms and cooling, air is sometimes introduced at the bottom of the tanks (Mountney, 1989; Sams, 2001). The birds have to be rehung manually when they leave the chilling tank, and an adequate drip-time afterwards is essential (Franke and Insam, 2013). Air chilling, a dry process, is another chilling technique that uses cold air through an air blast tunnel at -7 to 2˚C for two hours (Sams, 2001). To enhance cooling, the product can be sprayed with water which absorbs heat as it evaporates (Parkhurst and Mountney, 1997; Sams, 2001). Air chilled carcasses have a dried skin appearance that usually returns to normal after packaging (Molapo, 2009).

The carcasses are then hanged on the conveyors to remove excess water (Shari, 2002). In South Africa, heads, feet, livers, rough offal, necks, and hearts are classified as edible products within the poultry meat processing industry and are separated from the main chicken bodies (Molapo, 2009). The chickens are then automatically weighed and graded (fresh or/and frozen chicken, and de-boned) (Franke and Insam, 2013). After weighing and grading, all edible portions are usually packed on polystyrene trays and wrapped with transparent film. The packed meats are then cooled, frozen, and stored for shipping (Sams, 2001; Salminen and Rintala, 2002). The poultry litter enters the cooking stage where it is cooked for 2.5 hours, cooled, and the yield pressed in a pressurised tank to produce fat-oil that is used for the fuel burners (Franke and Insam, 2013; Molapo, 2009).

2.4. QUANTITIES AND CHARACTERISTICS OF POULTRY WASTES

2.4.1. Quantities of wastes

Table 2.1 shows the characteristics and amounts of organic solid by-products of broiler meat processing industries as an example. Though a number of by-products and wastes does depend on the species, the characteristics of broilers do not fundamentally differ from the other poultry species (turkeys, geese, and ducks). The waste generated in poultry meat processing accounts for 16-32 % of the weight of the live birds as illustrated in Figure 2.8 (Berri et al., 2001; Salminen and Rintala, 2002). The amount of waste generated in the poultry industry is also determined by the condition of the birds during transportation, operational catching and pathological conditions (Faria et al., 2010; Salminen and Rintala, 2002). Before slaughtering the birds contain about 2 kg/broiler litter (from excreta and wood chips) (Franke and Insam, 2013; Kelleher et al., 2002).

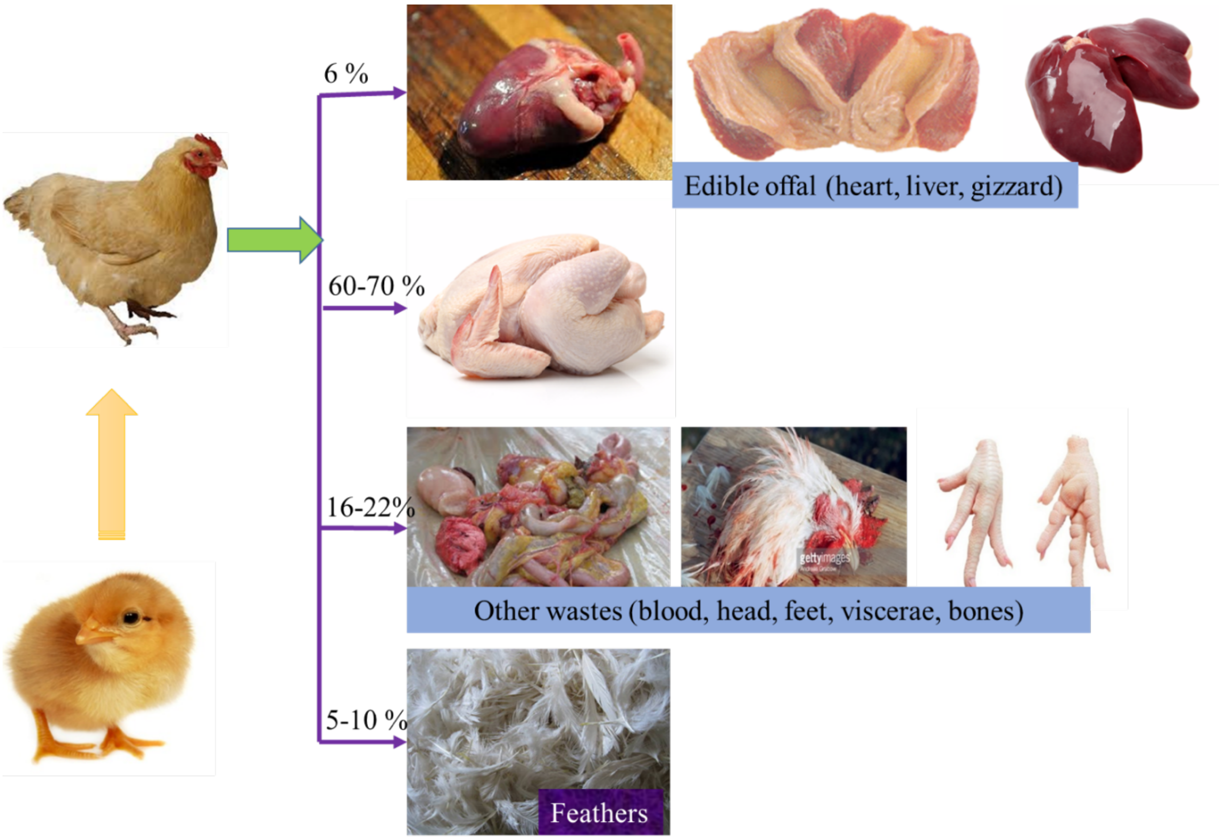

Figure 2.8. Composition of slaughter poultry (adapted from Salminen and Rintala, 2002)

Before they are slaughtered, broilers are grown for 2–6 weeks to a weight of 1.8–3 kg (Molapo, 2009). Dried blood contains about 48 % protein (Table 2.1), and fresh blood represents about 2 % of the weight of live broilers (Salminen and Rintala, 2002). Carcass yield represents about 60-70 % of live weight poultry after slaughter for human consumption (without feathers, necks, heads, giblets, feet, and most of the internal organs) (Berri et al., 2001; Salminen and Rintala, 2002). Subsequent evisceration produces about 16-22 % of live weight of the birds, head (up to 7 %), feet (up to 5 %) and viscera (up to 10 %) (Faria et al., 2010; Salminen and Rintala, 2002) (Figure 2.8).

Feathers represent about 5-10 % the weight of live broilers, and contain 85–99 % keratin proteins (Saravanan and Dhurai, 2012) (Table 2.1). According to statistics on broiler chickens, around 58×10^9 chickens are slaughtered for meat in the world every year (Compassion in World Farming, 2013). The United States of Department of Agriculture estimates that 46.6×10^9 kg of chicken meat was processed in the USA poultry processing industry in 2014 (USDA Foreign Agricultural Service, 2014). Processing of this chicken generates more than 40×10^9 kg of feathers per annum worldwide (Compassion in World

Farming, 2013). Based on this calculation, it is evident that the industry in the Republic of South Africa alone generates a large amount of waste product, e.g., more than 258x10^6 kg of chicken feathers per annum (DAFF, 2014) (Figure 2.1).

2.4.2. Characteristics of wastes

Characterstics of solid wastes in slaughterhouses are shown in Table 2.1. The wastes are highly rich in nitrogen (Table 2.1). The characteristics of broiler litter vary depending on how long the litter remains on the ground (Salminen and Rintala, 2002). With increase in poultry manure deposits, the nitrogen content increases but ammonia volatilises due to uric acid degradation (Salminen and Rintala, 2002). Waste chicken feathers are characterised by high total solid content (24.3 %), high protein content (91 %), low lipid content (1 %) and low methane potential (0.05 M^3/kg weight) (Salminen and Rintala, 2002).

Table 2.1. Characteristics of solid waste in slaughterhouse (adapted from Salminen and Rintala, 2002)

	Total solids %	**Nitrogen content %**	**Protein content %**	**Lipid content %**	**Methane potential (M^3/kg weight)**
Carcass	37	Na	Na	Na	0.2-0.25
Litter	52-81	3.2-5.7	Na	Na	0.1-0.15
Manure	20-47	4.6-6.7	Na	1.5-2.1	0.04-0.06
Feathers	24.3	15	91	1-10	0.05
Blood	22	7.6	48	2	0.10
Offal, feet and head	39	5.3	32	54	0.30
Trimmings and bones	22.4	68.6	51	22	0.15-0.17

Na; not applicable

Table 2.2 compares characteristics of slaugtherhouse and domestic wastewaters. Poultry processing industry by-products are characterised as high strength organic materials in comparison to domestic wastewaters. Slaughterhouse wastes contain significant amounts of blood, which contributes up to 3,500 mg/L of nitrogen as ammonia (Hairston, 2001; Salminen and Rintala, 2002). Overall, slaughterhouse wastewaters contain total nitrogen concentrations of 59 to 330 mg/L (Caixeta et al., 2002; Hairston, 2001). In comparison, typical domestic wastewaters have ammonia concentrations of 4 to 13 mg/L and total nitrogen levels of 26 to 75 mg/L (Caixeta et al., 2002; Salminen and Rintala, 2002). For poultry processing industry wastes, the average biological oxygen demand (BOD) concentration is 1,510 to 3,332 mg/L and total suspended solids (TSS) concentration of 3,673 to 6,404 mg/L concentrations (Mittal, 2004; Mittal, 2007). The toxicity indicators of slaughterhouse wastes are higher than those of household wastewater (TSS and BOD levels of 155 to 330 mg/L and 155 to 286 mg/L, respectively) (Kiepper, 2001).

Table 2.2. Characteristics of slaughterhouse and domestic wastewaters (Caixeta et al., 2002)

	Poultry processing industry wastewater	**Household wastewater**
BOD, mg/L	1,510-3,332	155-330
COD, mg/L	2,400-7,600	500-660
Fecal Coliform, CFU/100 ml	$2.6x10^5$-$2.3x10^{10}$	$1.0x10^6$-$1.0x10^8$
Total Nitrogen, mg/L	59-330	26-75
TSS, mg/L	3,673-6,404	155-286

Bacterial contamination control points in poultry slaughterhouses are depicted in Table 2.3. Due to the warm bloodiness of chicken and the processing of chicken meat, there is a high risk of blood borne pathogens (Jones, 2005). Poultry meat processing industry by-products contain different species of microorganisms in feet, feather, intestinal contents, and processing equipment (bleeding knife, scalding water, plucker's rubber finger, plucking finishing table), including potential pathogens such as *Enterococci, Salmonella sp., Campylobacter, Staphylococcus sp., Coliform bacteria, Clostridium sp. and sulphate-reducing bacteria* (Adesemoye et al., 2006.).

Table 2.3. Bacterial contamination in the poultry industry (adapted from Jones, 2005)

Control point	**Total bacteria viable counts ($Cfu/cm^2/cm^3$)**	**Enterococci ($Cfu/cm^2/cm^3$)**	**Coliform bacteria ($Cfu/cm^2/cm^3$)**	**Sulphate reducing bacteria ($Cfu/cm^2/cm^3$)**
Feathers	69457.0	184.5	0.9	179.1
Bleeding knife	7269.0	227.0	19.6	8.4
Scalding water	6421.0	5.3	0.9	55.2
Pluckers' rubber finger	2362.5	73.1	1.6	21.6
Carcass surface	6984.0	197.1	15.3	4.8
Plucking finishing table	55444.0	793.35	1483.6	225.0

Cfu/g = colony forming units/gram

2.5. DISPOSAL AND BENEFICIATION ROUTES FOR WASTES PRODUCED IN POULTRY SLAUGHTERHOUSES

Poultry slaughterhouse by-products may be defined as parts of animals not intended for direct human consumption and are classified either as high-risk material or low-risk material. High-risk materials present serious health risks to people or animals – they include condemned materials, dead animals, unborn and stillborn animals, and spoiled materials. This section reviews the current disposal, recycling and recovery practices employed for management of organic solid wastes from poultry slaughterhouses.

2.5.1. Disposal as a means of solid waste management

Wastes from poultry abattoirs processes require proper waste management. Since most poultry processing industries in the Republic of South Africa are service-oriented, the disposal of chicken feathers is a great challenge. The most common disposal methods include incineration, burial, and landfilling as discussed below.

2.5.1.1. Incineration: - Incineration refers to thermal destruction of by-products at high temperatures, and is considered as one of the safest way for destroying infectious agents (Mijinyawa and Dlamini, 2006). In this disposal method, waste can be burned as rapidly as it accumulates, creates only a small amount of waste, and the resultant ash does not attract pests and is easily disposed of. The main problems related to this disposal technique are emissions of particulates, greenhouse gas emissions, unpleasant odours, slow throughput, and complaints by the public (Molapo, 2009).

Smouldering poultry wastes may create as much or more toxic air emissions than coal fired plants that present environmental and human health concerns. A study conducted by the North Carolina Department of Environment and Natural Resources found that a 57 MW poultry waste burning plant emitted levels of carbon dioxide (CO_2), nitrogen oxides (NO_2), dioxins, particulate matter (PM), and carbon monoxide (CO) per unit of power generated that were higher than those for new coal plants (Stingone and Wing, 2011). In South Africa some poultry meat processing industries use the open fire method, whereby the sun-dried feathers are allowed to burn in the open. However, this is against the Meat Safety Act (Act 40 of 2000) of Republic of South African legislation (South Africa, 2000) whereby total incineration is prescribed instead of open fire burning.

2.5.1.2. Burial: - Burial of waste by-products which usually takes places on the premises is considered to be the most convenient disposal method due to its low cost and convenience. For this method about 1.5 m of earth covering should be maintained to discourage scavengers and to control odours and flies (Blake, 2004). Open-bottom pits are one example of a burial method. The method is cheap and easy to do though there may be problems such as slow loss of poultry residue, and seepage of phoshorus, nitrogen and pathogens into groundwater (Molapo, 2009). Poultry feathers does not biodegrade easily; they remain jammy and slick for over a year in the soil and can emit a terrible odour. Burial pits cause concerns which include the pollution of groundwater where pits are located (Blake, 2004). Thus burial of dead birds on farms is strictly controlled to avoid groundwater contamination (Hairston, 2001). In South Africa, burial pits are situated either on poultry slaughterhouse premises or less than 500 metres outside abattoir perimeters (Molapo, 2009).

2.5.1.3. Controlled landfilling: - Controlled landfilling can be used for management of waste biomass generated at chicken meat processing industries. However, controlled landfilling of biodegradable by-products leads to leachate production that pollutes groundwaters, emits odours, causes vermin nuisance problems, and leads to carbon dioxide and methane production for long periods after deposition (Blake, 2004). Environmental contamination occurs when controlled landfilling is done under poor waste disposal management (Mittal, 2007). Excessive application of waste chicken feathers in landfilling can result in nitrate (NO_3) groundwater contamination and this can cause cancer, methemoglobinaemia, fatal abortions in livestock, and respiratory illness in humans (Mijinyawa and Dlamini, 2006). With increased tightening of regulations, landfilling must be prevented as much as possible because of its unwanted impacts on the environment, especially the contamination of surface water, groundwater, soil and air (Mittal, 2004; Mittal, 2005). Environmental legislation in South Africa states that landfills must prevent or reduce their effects on the local and global environment (the pollution of groundwater, surface water, air, soil and greenhouse gas emission) (Molapo, 2009). Due to high costs of landfilling and legislation against landfilling of waste chicken feather/or organic wastes, this option is not exercised by most of the abattoirs in South Africa (Molapo, 2009).

2.5.2. Utilising chicken feather waste as a resource

Using waste chicken feathers as a resource for conversion of wastes into high-value materials performs essential sanitary functions also. Currently, low amounts of poultry abbattoir wastes are used for production of fertiliser and low-grade animal feed.

2.5.2.1. Composting: - Composting is the breakdown of biodegradable organic material carried out in either windrows or reactors to promote microbial degradation. Aerobic biological process/composting is a relatively fast biodegradation process and can be shortened by providing adequate process parameters such as moisture content, temperature, feedstock mixture and density (Gurav and Jadhav, 2013). Organic wastes have commonly been added as soil conditioners to utilise their nutrient content, (phosphorus, nitrogen, and potassium) and to improve soil physical characteristics (Veerabadran et al., 2012). Although composting is a biologically and environmentally safe disposal alternative for any type of organic biomass, it has disadvantages such as requirement of large amount of land and loss of nitrogen and other nutrients from soil (Gurav and Jadhav, 2013).

This disposal method has been used for treatment of poultry abattoir by-products, that include grease residues, flotation tailings, screenings, manure, feathers and litter (Slogan et al., 2005). Feathers contain high amounts of nitrogen content, in fact, higher than the best quality blood meal also utilised for such purposes: thus they are ideal for composting purposes (Choi and Nelson, 1996). Consequently, feathers are used for compost in plant growing operations that require abundant nitrogen nutrients (Kelleher et al., 2002). Composting reduces pathogens in waste chicken feathers which is an advantage (Slogan et al., 2005). However, the structure of feathers is such that they are highly cross-linked with cysteine linkages that are difficult to degrade (Park et al., 2000). Therefore, the availability of nitrogen from the feathers when used as fertiliser is considerably low. Feathers can also be used as mulching material.

2.5.2.2. Anaerobic digestion: - Anaerobic digestion is a biological process in which organic matter is degraded to methane under anaerobic conditions (Salminen and Rintala, 2002). Chicken feathers contain high amount of crude protein, carbon, nitrogen and hydrogen (Chandrasekhar et al., 2015; Mijinyawa and Dlamini, 2006). Proteins are composed of amino acids linked by peptide bonds, which are hydrolysed by proteases upon decomposition. The degradation products include short or branched chain organic acids, NH_3, CO_2 and H_2 (Salminen and Rintala, 2002).

Production of biodiesel: Two major challenges facing mankind are waste disposal and the need for an abundant source of clean energy. The perfect solution to both of these challenges is to turn waste into energy which could significantly cut carbon emissions while replacing the need for fossil fuels (Chandrasekhar et al., 2015; Salminen and Rintala, 2002). Soybean, corn, sunflower and cottonseed are the primary sources of renewable energy via biodiesel production (Chandrasekhar et al., 2015). However, the use of these raw materials faces social problems, availability and cost-effectiveness (Chandrasekhar et al., 2015; Demirbas, 2008). Thus, finding alternative non-food, raw materials is a priority. Chicken feathers contain substantial amounts of fat that could be processed for the production of biodiesel from feather meal (Blake, 2004; Chandrasekhar et al., 2015). For biodiesel production, the fats could be extracted from feather meal by solvent extraction and subsequently transesterified into biodiesel using catalysts, nitrogen and methanol (Salminen and Rintala, 2002). Considering the huge amounts of waste chicken feathers that are generated worldwide, it is estimated that hundreds of millions of litres of biodiesel can be produced from the waste (Kelleher et al., 2002). This energy from waste could cut carbon emissions by a significant portion while replacing the need for large amounts of petroleum based fuel (Salminen and Rintala, 2002).

2.5.2.3. Use for animal feed: - Most feathers are not suitable for the aforementioned applications due to their hazardous nature (presence of microbiological pathogens) and their poor digestibility if landfilled (Adesemoye et al., 2006). Therefore, the fundamental strategy for management of waste feathers is conversion of the waste into feather meal to be utilised as feed stock (Franke and Insam, 2013; Mijinyawa and Dlamini, 2006). For the production of feather meal, the rachis must be broken down by hydrolysis to make it digestible. A typical process is as follows:

- Clean feathers
- Dewater
- Steam/wet-cook for 1-2 hours
- Cool, dry, and grind (El Boushy et al., 1990).

Table 2.4. Composition of feather meal (McCasland and Richardson, 1966).

Composition	Percentage
Protein	92.3 % (ranges 70-80 %) as digestible protein.
Moisture	5.9 %
Fat	1.3 %.

Table 2.4 shows the compositions of feather meal. Cooking time and pressure affects hydrolysis of feathers and this directly affects the digestibility of feather meal (McCasland and Richardson, 1966). Feather meal contains about 92 % crude protein and about 70-80 % of it as digestible protein (Table 2.4). However, the protein edibility is extremely weak on account of the vicinity of disulphide bonds which are refractory to digestive enzymes present in chickens. Feather meal is inadequate in four fundamental amino acids, methionine, histidine, lysine, and tryptophan; it is rich in arginine, threonine and cysteine (El Boushy et al., 1990). A reasonable level of utilisation of feather meal in eating routines is 0.5-1.5 % (Park et al., 2000). Unfortunately, concerns of animal health (hog cholera) and disease transmission (*Campylobacter, Salmonella, Trichinella and Toxoplasma*) are of extreme concern when feathers are used for this value addition technique (Adesemoye et al., 2006).

2.6. SOUTH AFRICAN LEGISLATIONS RELATED TO POULTRY SLAUGHTERING PROCESS

2.6.1. General overview of the waste economy in South Africa

According to national waste information the Republic of South Africa waste economy generates more than $108x10^9$ kg of solid waste per year of which about $59x10^9$ kg is general waste, $1x10^9$ kg is a hazardous waste and $48x10^9$ kg unclassified waste (Department of Environmental Affairs and Tourism, 2012) (Figure 2.9). About 65 % of the general waste is classified as recyclable, and therefore could theoretically be diverted from landfill and recovered to be reprocessed/repurposed (Department of Environmental Affairs, 2012). However, the status of waste management in Republic of South Africa shows that about 90 % of the waste generated goes to landfill with a limited amount (10 %) recovered to be reprocessed/repurposed and this is estimated to generate financial venues of R17 billion (~ 0.51 % of the GDP) (Godfrey et al. 2012). The waste management scenario in South Africa is changing from predominately landfilling to more waste diversion as a result of regulatory reforms, limited landfill space, increment in waste disposal costs, and by increased awareness of sustainability (Godfrey et al., 2012). South Africa is aiming to reach the target of 20 % waste diversion by weight by 2019.

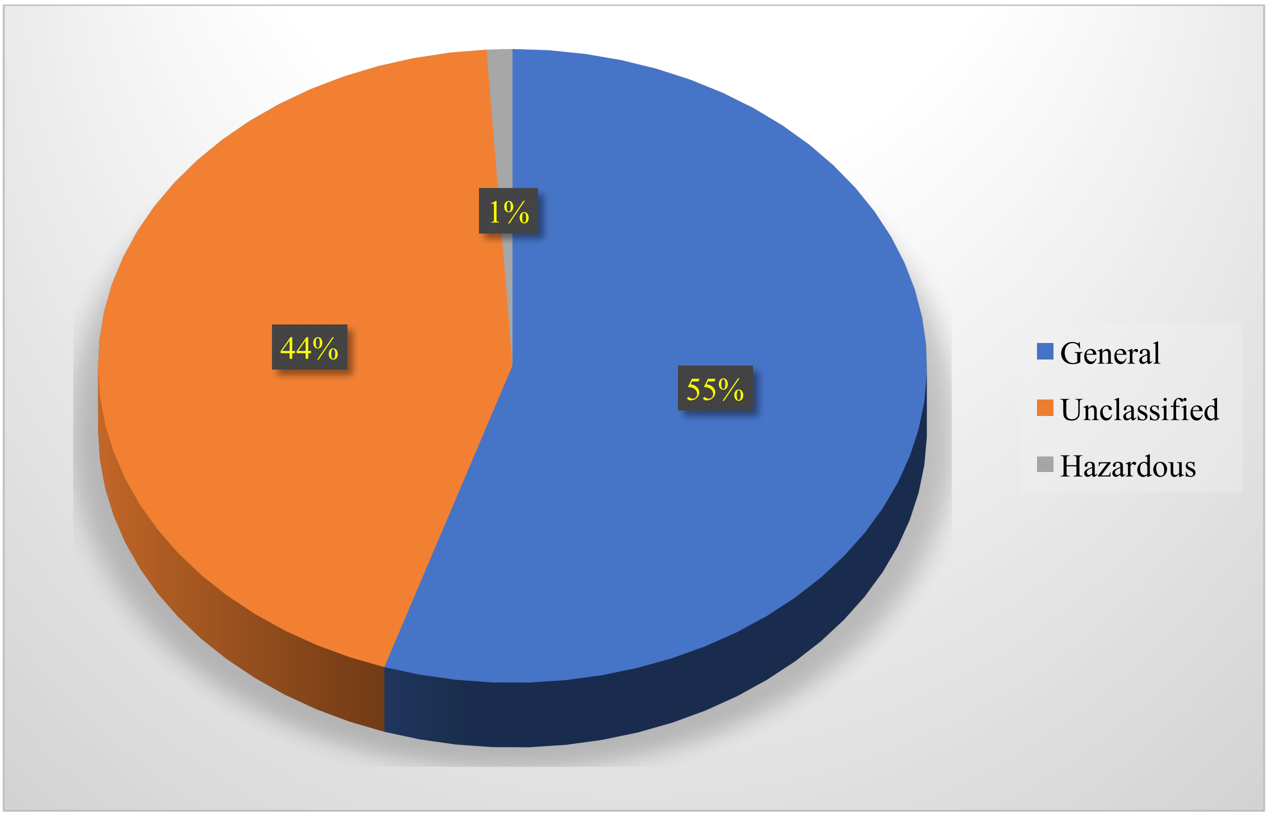

Figure 2.9. Classification of total waste generated in South Africa (adapted from Gogela et al., 2017)

2.6.2. South African framework related to poultry slaughterhouse operations

Due to the implementation of the National Environmental Management: Waste Act (NEM: WA, Act 59 of 2008) the number of companies that operate in the waste sector has increased significantly. The National Environmental Management: Waste Act shifts the focus from the end of the pipe to cradle to cradle solutions, reduce the use of natural resources, avoid/reduce the generation of waste, reuse/recycle/recover valuable material from the waste streams and, as a last resort, treat/safely dispose of waste. The waste sector in South Africa has been guided by the White Paper (Figure 2.10).

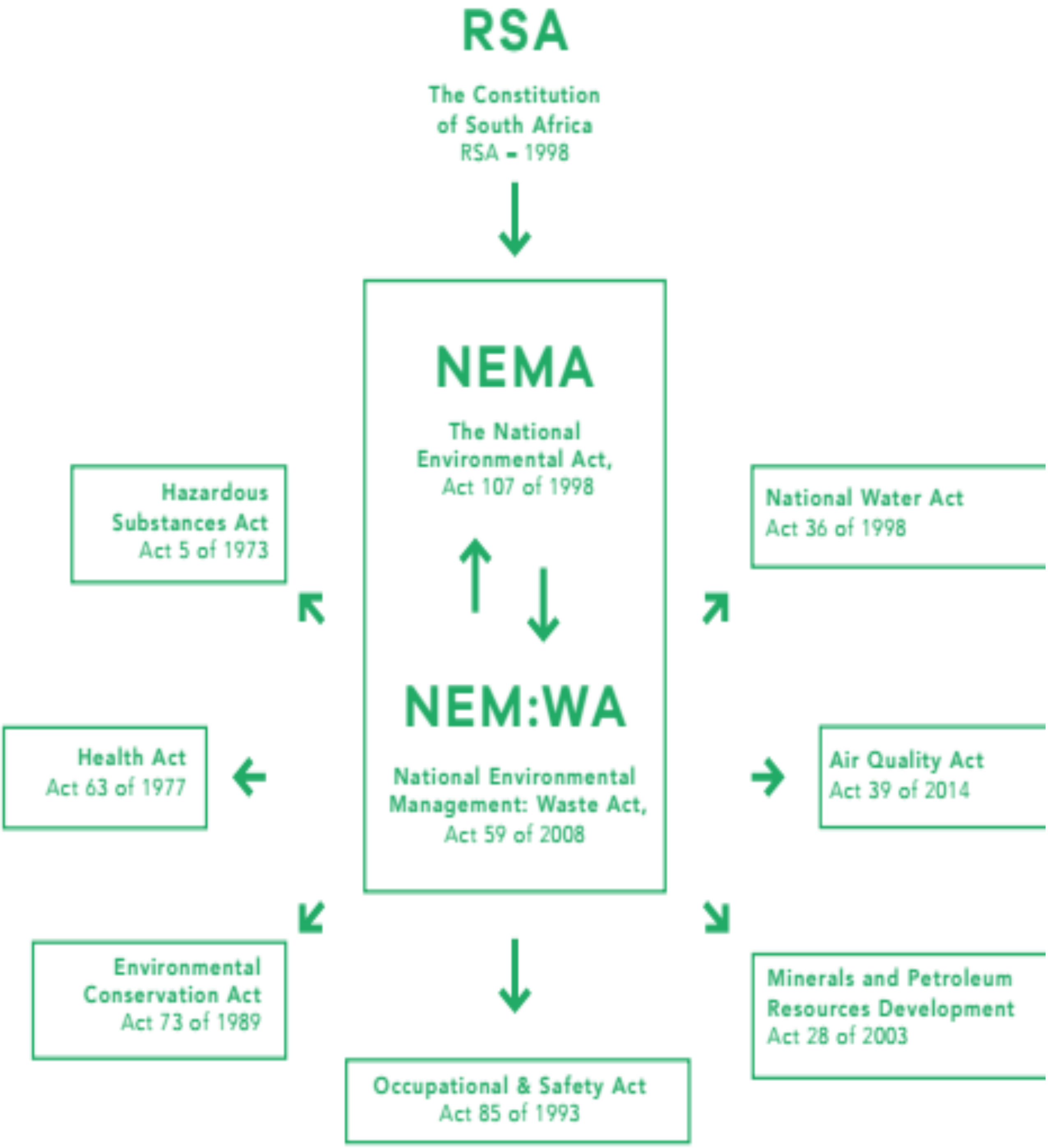

Figure 2.10. South African waste sector regulatory framework (adapted from Godfrey et al., 2012)

The poultry meat processing industries are governed by various legislations related to abattoir operations (Table 2.5). This section provides a brief introduction to the regulatory framework related to poultry meat processing industries in the Republic of South Africa.

Table 2.5. Regulatory frameworks related to poultry processing industry (adapted from Molapo, 2009)

	Article	Description
Constitution of South Africa, 1996	Act 108 of 1996	Section 24(a) highlights the right of all human beings to an environment that is not harmful to their well-being.
National Environmental Management	Waste Bill, 2007	Enforces the proper management of waste according to the hierarchy of waste management (reuse, avoid, minimise, treat, recycle and properly dispose of) in a sustainable way.
Environment conservation Act, 1989 and Abattoir Hygiene Act, 1992	Act no 73 of 1989	Highlights the protection of the environment (air, water, soil, fauna, flora and humans). Section 19 forbids land application, dumping of any condemned waste on any land or water surface. Section 20 regulates the protection of water quality against effects of slaughterhouse waste Section 20 (1) bids option for a continuous disposal, the waste generator should apply for a permit
Meat Safety Act 2000	Act no 40 of 2000	The disposal methods prescribed under Part VIII suggests the methods of disposal of condemned products. These includes: • Total incineration; • Sterilisation/denaturing and • Burial (not less than 100 m from the sloughterhouses at a depth of at least 60 cm) Handling of condemned material which cannot be fit for human and animal consumption, must be • *"Portioned and placed in a theft-proof container which has been marked 'CONDEMNED' in letters not less than 10cm high or conspicuously marked with a stamp bearing the word 'CONDEMNED' using green ink";* • *"Kept in a holding area or a room or dedicated chiller provided for the purpose except if removed on a continuous basis, and removed from the sloughterhouse at the end of the working day or be secured in a dedicated chiller or freezer at a temperature of -2 ^{o}C".* • *"No person may remove condemned material from the sloughterhouse, except with the permission of a registered inspector".*

2.7. INTEGRATED WASTE MANAGEMENT AND BIOREFINERY CONCEPTS IN POULTRY PROCESSING INDUSTRY WASTES

Currently the concept of biorefinery to produce high-value products from the waste materials is gaining attention. By-products from manufacturing industries could be used as a raw material to produce high-value materials for use in bioenergy production, biopolymer production, composites, chemicals, biofibre, pains/dyes, cosmetic additives, enzyme, and gelling agents. Potential high-value materials from organic biomass include gelatin, collagen, chitin, starch, fats, oils, keratin, fibres, enzymes, flavours and aromas, vitamins, pigments, pectin, antioxidant and essential oils (Dunn, 2013).

The waste hierarchy and the value-add hierarchy can be used for identification of value-add opportunities of industrial wastes (Godfrey et al., 2012). In terms of the waste management hierarchy, South Africa is predominantly focusing on recycling, recovery, treatment, and finally, disposal as a last option (Figure 2.11) (Gogela et al., 2017). The value-add hierarchy indicates the relative expected value-add of different products from bio-based feedstocks (Dunn, 2013). It emphasises the importance of reducing waste, rather than alternative uses such as recycling, reprocessing and energy recovery (Godfrey et al., 2012).

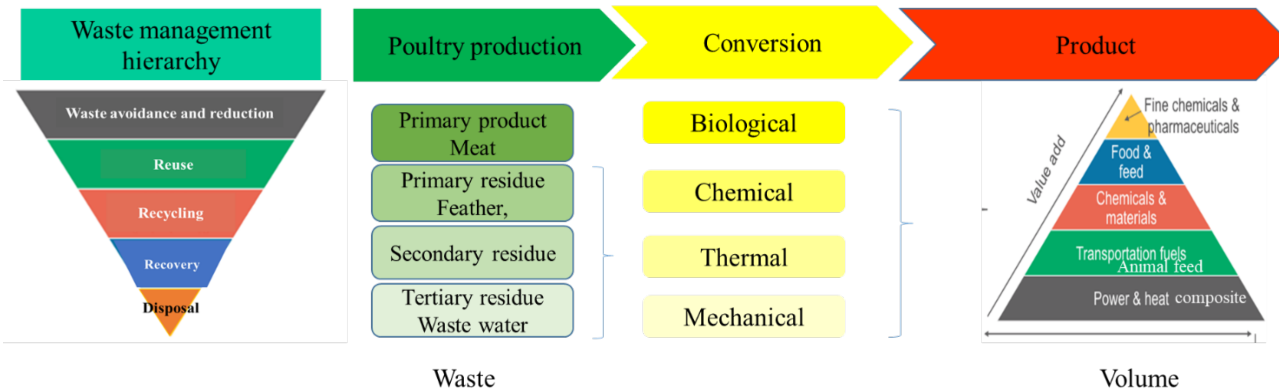

Figure 2.11. The bio-based value-add hierarchy (adapted from Gogela et al., 2017)

Worldwide the poultry industry is struggling with this question: what to do with the more than 40×10^9 kg of poultry feather waste their business generates each year? Although regarded as waste by-products, in some cases poultry meat processing industry waste may be considered a valuable source of financial income if processed correctly. For example, waste chicken feathers can be converted into animal feed stuff. However, only a small portion of waste feathers are used for this purpose since the digestibility of nitrogen in feathers is not good. Therefore, there is need to find or develop valorisation technologies for the waste – this is the main objective of this dissertation. To recover high-value materials from the waste chicken feathers, the first step should be decontamination of feathers as they are contaminated with hazardous microbial organisms. The decontaminated feathers can then be analysed and characterised for their physical, mechanical, chemical, thermal, electrical and morphological properties. The data from the analysis and characterisation of the feathers can be used to ascertain possible beneficiation routes for the waste. Finally, technologies or products can be developed for or from the feathers to prove/demonstrate applicability of the beneficiation routes. This is the approach that was undertaken in carrying this dissertation.

2.8. CHICKEN FEATHERS

A feather is essentially made out of three particular units; rachis, barbs and barbules as shown in Figure 2.12. Rachis is the solid and focal shaft of the feather to which the auxiliary structures, the barbs are joined. In the tertiary structures of the feathers, the barbules are joined to the barbs in such a way that the barbs are attached to the rachis. The rachis runs the whole length of the feather up to 15 cm long. The lengths of barbs range anywhere from 1 to 4.5 cm, contingent upon their location along the length of the rachis. Individual strands at the base of the rachis are longer than those at the tip (Stettenheim, 2000; Tseng, 2013). Chicken feathers have low density – the least of any other natural or engineered filaments commercially available today. Their low density, low thickness, warmth retention, astounding compressibility and strength, capacity to hose sound and particular morphological structure of their barbs make them remarkable fibres (Jeffrey, 2006; Saravanan and Dhurai, 2012; Tseng, 2013). Besides the special structure and properties, feathers are cheap, richly accessible and a renewable resource for protein fibre.

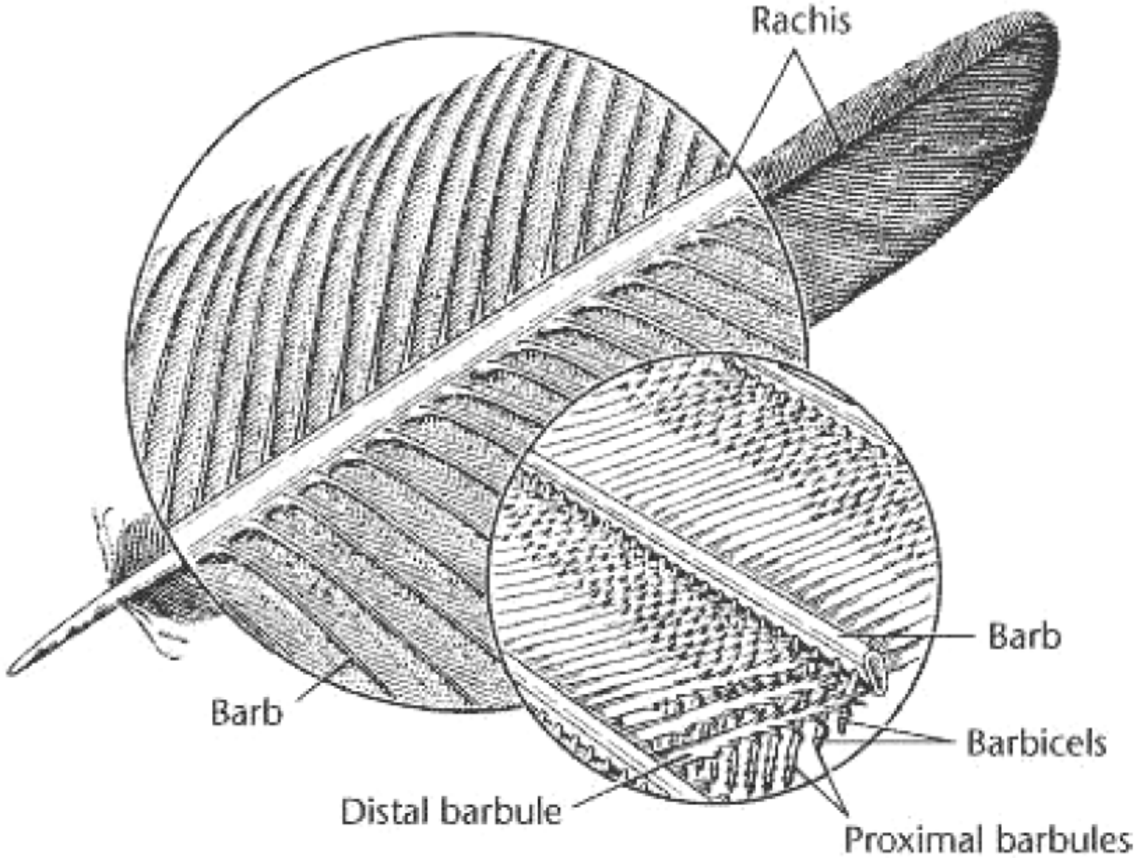

Figure 2.11. Structures of a chicken feather (adapted from Bartels, 2003).

Chicken feathers contain approximately 91 % protein (keratin), 1 % lipids, and 8 % water. The amino acid succession of a chicken feather is precisely the same as that of reptilian keratins from claws (Saravanan and Dhurai, 2012). The amino acid sequence is mainly composed of cysteine, glutamine, proline and serine as shown in Table 2.6. However, histidine, lysine, tryptophan, glutamic acid and glycine are absent. Serine (16 %) is the most abundant amino acid in chicken feathers (Saravanan and Dhurai, 2012). Keratins are insoluble proteins present in rachis, fleece, hooves, scales, hair, nails (hard keratins) and in the stratum corneum (delicate keratins) (Misra and Kar, 2004). These particular proteins, which belong to the scleroprotein groups, are exceedingly impervious to physical, chemical and biological activities. Mechanical stability and high resistance to proteolytic degradation of keratin is because of the presence of disulphide bonds, hydrogen bonds, salt linkages and cross linkages (Misra and Kar, 2004).

Table 2.6. Amino acid content in keratin fibre from chicken feathers (adapted from Saravanan and Dhurai, 2012).

Functional group	**Amino acid**	**Percent content**
Positively charged	Arginine	4.30
Negatively charged	Aspartic acid	6.00
	Glutamine	7.62
Hydrophobic	Tyrosine	1.00
	Leucine	2.62
	Isoleucine	3.32
	Valine	1.61
	Cysteine	8.85
	Alanine	3.44
	Phenylalanine	0.86
	Methionine	1.02
Hygroscopic	Threonine	4.00
	Serine	16.00
Special	Proline	12.00
	Asparagine	4.00

Basically, a chicken feather consists of α- helical and some β- sheet conformations. Its outer rachis is almost entirely made up of β- sheet conformations and few α- helical conformations (Jeffrey, 2006). Hard β- sheet keratins have higher cysteine content than soft α- helix keratins and thus a much greater presence of disulphide (S-S) bonds that link adjacent keratin proteins. The presence of strong covalent bonds stabilises the three-dimensional protein structure and are very difficult to break (Saravanan and Dhurai, 2012). Feathers contain ~91 % keratin protein and thus, potentially, feathers can be beneficiated into high-value compounds or products comprised of keratin proteins or keratin fibres. Thus, valorisation of feathers could be a viable option for sustainable disposal of the waste.

2.9. BRIDGING THE GAP

During slaughtering, feathers are plucked from chickens, the meat is packed, and the feathers often lie as dirt that contains various foreign materials, such as offal, dilute blood, grease, skin, faeces, many biological organisms, fatty and waxy substances, flesh, and water. Raw chicken feathers are wastes that are mixed with offal fat, debris, blood, preen oil and other wastes from the poultry process. Since chickens are warm-blooded, freshly collected feathers could possibly lead to the presence of a variety of microorganisms. Free fatty acids from lipid decomposition can lead to pH changes and lead to microbial growth after slaughter. Microbes that grow on feathers will use feather keratin and decompose it, eventually degrading chicken feathers and making them structurally very weak. Consequently, feathers are biologically hazardous wastes that are contaminated with bacteria, which makes them odoriferous and unfit for valorisation as is. These contaminants must be removed before possible valorisation otherwise the feathers will not be fit for purpose.

There are a few reports on selected types of cleaning processes of waste chicken feathers using two stage treatment employing organic chemicals (pre-treatment using oxidative bleaching agent and cleaning the residual grease content using alcohols) (Sudalaiyandi, 2012; Tseng, 2011; Pourjavaheri et al., 2014). The use of a two stage approach for cleaning chicken feather is energy intensive, costly and time-consuming. Most of the studies focused mainly on removing grease and other impurities (like sand and blood), and not on eliminating the microbial counts. However, none have focused on optimisation of the decontamination processes. Hence, this issue is addressed in this dissertation by optimisation of a one pot decontamination and pre-treatment of waste chicken feather using three different types of surfactant and three different types of bleaching agents, and optimisation by using response surface methodology. Also, the bactericidal effect of surfactants was studied (in contrast to using bleaching agents) to minimise damage to feathers caused by harsh bleaching agents.

In order to determine their suitability for the utilisation of waste chicken feathers as a renewable resource for high-value material production, it is important to understand the physical, chemical, thermal, mechanical, electrical properties and the morphological structure of chicken feathers. Other studies also have been done in this topic, however, the studies were focused on specific applications upfront, e.g., yarn sizing applications

(Reddy and Yang, 2005; Paul et al., 2014; Reddy et al., 2014), composite applications (Jeffrey, 2006), biobased plastic resins containing chicken feather fibres (Roh et al., 2012), removal of heavy metals from wastewater (Al-Asheh and Banat, 2003), and a general description of feathers in domesticated birds (Bartels, 2003) none have focused on comprehensive evaluation of physical, chemical, thermal, mechanical, electrical properties and morphological and fine detail structures of feathers to help ascertain their possible valorisation.

Studies have been conducted on possible beneficiation routes of chicken feathers. For example, it has been reported that chicken feathers can be used in preparation of microbial peptones (Taskin and Kurbanoglu, 2011) and protein hydrolysates for use as a nutritional substrate for microbial production of valuable substances, such as carotenoid (Taskin et al., 2011). Other studies have demonstrated that waste feathers could be used as plant fertiliser (Paul et al., 2013; Jie et al., 2008; Hadas and Kautsky, 1994), low-grade animal feed (Davis et al., 1961; El-Boushy et al., 1990; Grazziotin, 2006), yarn sizing applications (Reddy and Yang, 2005; Paul et al., 2014; Reddy et al., 2014), composite applications (Jeffrey, 2006), biobased plastic resins containing chicken feather fibres (Roh et al., 2012), removal of heavy metals from wastewater (Al-Asheh and Banat, 2003), immobilisation supports for enzymes or chemicals (Chauhan et al., 2016), and for biogas production (Patinvoh et al., 2016) (Table 2.7). More examples are listed in Table 2.7.

Table 2.7. Previous studies on chicken feathers

Studies on chicken feathers	References
Protein hydrolysates for use as a nutritional substrate for microbial production of valuable substances, such as carotenoid	Taskin et al., 2011, Taskin and Kurbanoglu, 2011; Taskin, 2013; Taskin et al., 2012
Plant fertiliser and	Paul et al., 2013; Jie et al., 2008; Hadas and Kautsky, 1994
Low-grade animal feed	Davis et al., 1961; El-Boushy et al., 1990; Grazziotin, 2006
Keratin	Gupta et al., 2012; Martinez et al., 2005; Wang and Cao, 2012; Wrześniewska-Tosik, K. and Adamiec, J., 2007
Reinforcing materials	Acda, 2010; Reddy and Yang, 2010; Jeffrey, 2006;
Sizing agent for textile industries	Reddy and Yang, 2005; Paul et al., 2014; Reddy et al., 2014
Nonwoven mat	Fan, 2008; Hong and Wool, 2005; Huda et al., 2007
Heavy metal separation	Al-Asheh and Banat, 2003; Kar, P. and Misra, M., 2004; Rosa et al., 2008
Microchips	Hong and Wool, 2005
Filtration	Al-Asheh and Banat, 2003; Fan, 2008
Bioenergy	Patinvoh et al., 2016; Kondamudi et al, 2009
Biofibre	Fan, 2008; Jin et al., 2011; Tseng, 2013; Martinez et al., 2005
Bioplastic	Barone and Schmidt, 2005; Roh et al., 2012
Microbial peptone	Taskin and Kurbanoglu, 2011
Immobilisation supports for enzymes or chemicals	Chauhan et al., 2016, Cheng et al., 1995; Gupta, R. and Ramnani, P., 2006

However, no detailed analysis and characterisation of chicken feathers with a view of using the results to ascertain possible beneficiation routes of the waste. This dissertation addresses this gap by providing data and information on the morphology, chemistry, physicochemical properties of chicken feather. The information and data gathered allowed for evaluation and development of possible beneficiation routes for waste chicken feathers. This novel approach is ideal for ascertaining suitable routes for beneficiation of waste chicken feathers.

Besides this the research described in this dissertation is novel in the South African context. No such studies have previously been done in the country. The dissertation provides valuable information to avoid disposal of waste chicken feathers and instead use it to develop high value products and materials from the waste.

2.10. CONCLUSIONS

The continuous growth rate of poultry slaughterhouses results in an increased amount of by-products. Poultry abattoirs result in significant quantities of solid waste as viscera, feathers, dead on arrival and bones. Burying, controlled landfilling and incineration of condemned materials is the most popular disposal method for poultry processing industries. The levy paid by poultry meat processing industries for the waste disposal has a negative economic influence on the abattoirs and affects the price of the meat. The groundwater contamination is also raised. The present waste management systems used by some poultry meat processing abattoirs does not efficiently dispose or enable recovery of the condemned by-products. The poultry processing industries in South Africa should search for effective disposal methods or they have to consider recycling and recovering their waste.

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CHAPTER 3

DECONTAMINATION AND PRE-TREATMENT OF WASTE CHICKEN FEATHERS

Chapter overview

Raw chicken feathers are wastes that are mixed with offal fat, debris, blood, preen oil and other wastes from the poultry process. Consequently, feathers are biologically hazardous wastes that are contaminated with bacteria, which makes them odoriferous and unfit for valorisation as is. These contaminants must be removed before possible valorisation otherwise the feathers will not be fit for purpose. This research focuses on developing and optimising decontamination and pre-treatment technologies for waste chicken feathers generated from poultry meat processing industries in order to make them suitable for valorisation. This chapter contains two peer-reviewed articles: one on using bleaching agents and the other on decontamination with surfactants. Optimisation of the decontamination and pre-treatment technologies was conducted using statistically designed experiments and response surface methodologies. The effects of the decontamination technologies on physicochemical and mechanical properties of the feather were assessed. Under optimised conditions, the microbial counts of the decontaminated and pre-treated chicken feathers were significantly reduced making them safe for handling and use for valorisation applications.

3.1. VALORISATION OF WASTE CHICKEN FEATHERS: OPTIMISATION OF DECONTAMINATION AND PRE-TREATMENT WITH BLEACHING AGENTS USING RESPONSE SURFACE METHODOLOGY

(BASED ON PAPER ONE)

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ABSTRACT

Environmental concerns, rapid oil consumption, the high price of oil, and limited oil reserves are driving research into cheap, biodegradable, sustainable, renewable, and abundantly available green materials. Waste chicken feathers are abundant and cheap by-products from poultry processing plants and their beneficiation offers possible solutions to these issues. Raw chicken feathers are wastes that are mixed with offal fat, debris, blood, preen oil and other wastes from the poultry process. Consequently, feathers are hazardous wastes that are contaminated with bacteria, which makes them odoriferous and unfit for valorisation as is. These contaminants must be removed before possible valorisation otherwise the feathers will not fit for purpose. The effects of oxidative (H_2O_2 and NaOCl) and reductive ($Na_2S_2O_4$) compounds as decontamination agents were studied on chicken feathers to assess their decontamination and pre-treatment efficiency and their effects on physicochemical and mechanical properties of the feathers. Statistically designed experiments were used to optimise the decontamination process using response surface methodology with a Box-Behnken experimental design. Regression equations were obtained to analyse microbial count and the optimum process parameters were identified. Under optimised conditions, the treated samples were characterised and their properties compared with those of unwashed sample. From the results, it was deduced that the inorganic bleaching treatments were effective in removing the microbial impurities from the feathers and their use resulted in enhanced physicochemical properties of the chicken feathers.

Keywords: *- chicken feathers, bleaching agents, physicochemical properties, microbial counts, decontamination*

3.1.1. Introduction

With the development of large-scale poultry farming, the disposal of large amounts of waste chicken feathers is a long-standing problem. On a world scale, it is estimated that approximately 40x10^9 kg of chicken feathers are produced from the slaughter of more than 58x10^9 chickens (Compassion in World Farming, 2013). In 2013, the South African poultry industry generated more than 258x10^6 kg of feathers (DAFF, 2014). Chicken feathers constitute 5-10 % of the weight of the chicken and comprise a significant portion of the poultry wastes (Tseng, 2011; Pourjavaheri et al., 2014). Poultry waste is divided into solid waste (feathers, viscera, heads, feet, carcases, skin and bones), and liquid waste (blood and liquid effluents) (EL Boushy et al., 2000). The disposal of this waste gives rise to environmental and health concerns, guided by legal requirements and contemporary best practice, such as the Zero Waste Initiative in South Africa (Karani and Jewasikiewitz, 2007).

In poultry processing plants, chicken feathers are contaminated with impurities exudates from preen glands, grease, dirt, suints/dried perspiration, burrs/dried vegetable, woody fragments, and mineral materials (Cunningham, 2012; Tseng, 2011; Pourjavaheri et al., 2014). The preen gland secretes lipids essential to maintain the feather's physical properties such as waterproofing and are responsible for the dull yellow colour on feathers (Cunningham, 2012). Suints are soluble in water whereas feather grease is a complex mixture of ester, diester and hydroxyester fatty alcohols like lanoline and fatty acids that are soluble in organic solvents and can be hydrolysed in mild alkali environments (Jones, 2005). Dirt originates from material held by the adhesive action of suits and fats whereas burrs are from vegetable and woody fragments collected during scratching of the chicken bodies against the ground.

During slaughtering, feathers are plucked from chickens, the meat is packed, and the feathers often lie as dirt that contain various foreign materials, such as offal, dilute blood, grease, skin, faeces, many biological organisms, fatty and waxy substances, flesh, and water (Figure 3.1.1). Since chickens are warm-blooded, freshly collected feathers could possibly lead to the presence of a variety of microorganisms (Richard, 2010). Free fatty acids from lipid decomposition can lead to pH changes and lead to microbial growth after slaughter. Microbes that grow on feathers will use feather keratin and decompose it, eventually degrading chicken feathers and making them structurally very weak. Thus, chicken feathers from the poultry industry are a waste disposal/environmental pollution hazard that is incinerated or dumped in landfills. However, feathers can be beneficiated into high value materials and products

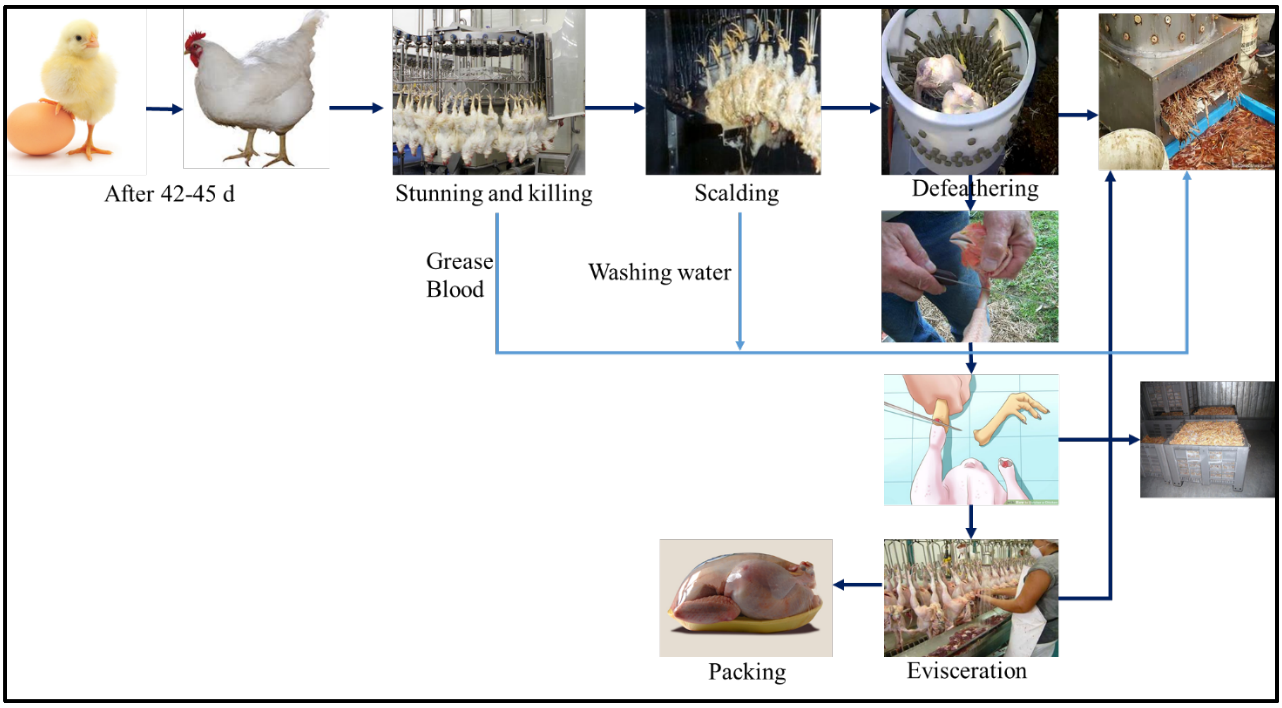

Figure 3.1. 1. Slaughtering house process flow

Chicken feathers can be used in many applications, such as bedding materials, cosmetics, textiles, yarn production, pharmaceuticals, composites for biomedical engineering, geotextiles, composite manufacturing, carbon nanotube production, biofuel and energy storage (Tesfaye et al., 2017). Pre-treatment and decontamination of chicken feathers should be the first step prior to their valorisation in order to eliminate the microbacterial content and enable beneficiation of the feathers. A variety of processes are available to remove the impurities and the microorganisms from feathers, and to improve the physical, chemical and mechanical properties of the chicken feathers. Cleaning (pre-treatment) of the chicken feathers removes the accumulation of surface contaminants that have resulted from nature, slaughtering, transportation and storage. Decontamination is the removal or reduction of microbial count whereas pre-treatment refers to cleaning activities mainly for the removal of grease, fat, sand etc. Decontamination and pre-treatment can be achieved by dissolution in solvents, mechanical detachments, evaporation, or chemical degradation (Bateup, 1986; Hurren et al., 2006) as illustrated in (Figure 3.1.2).

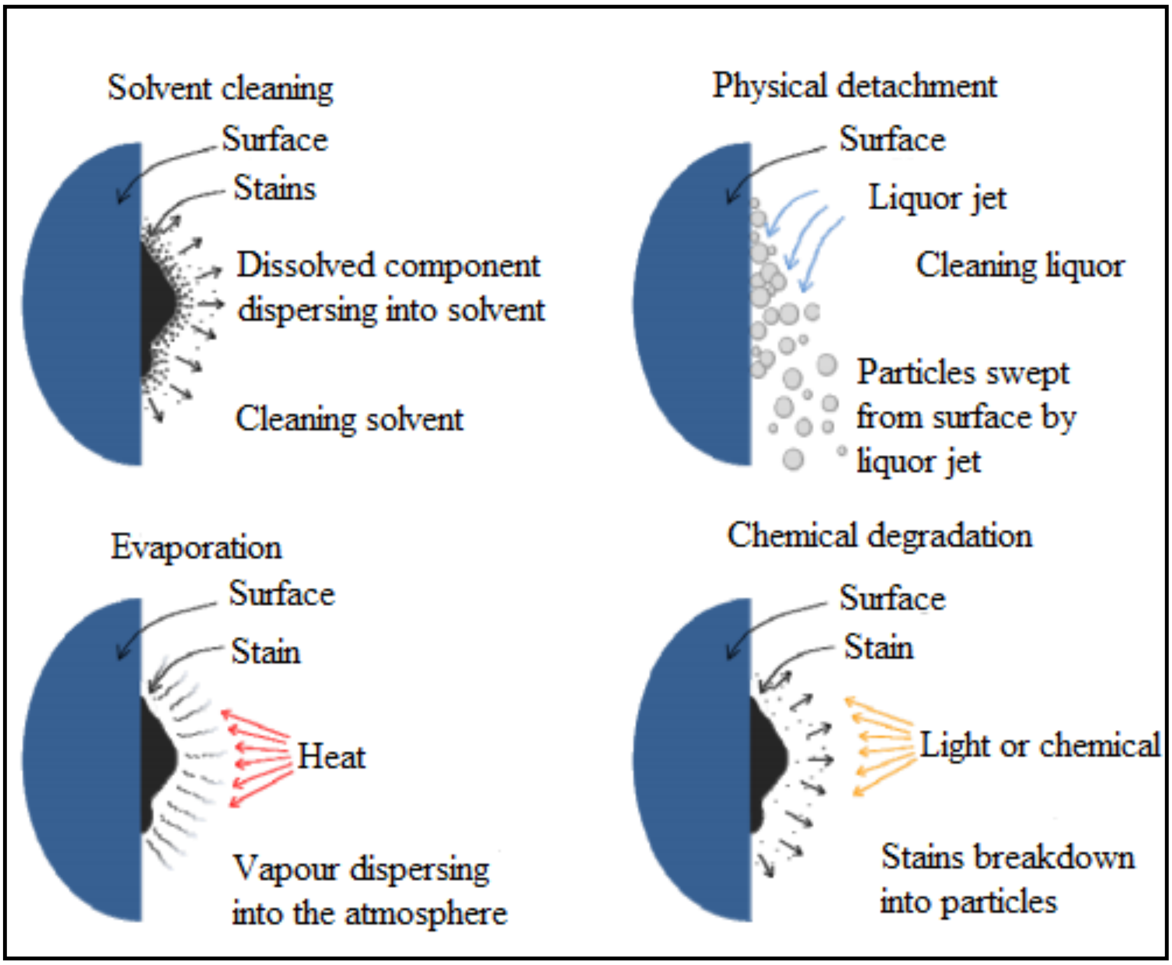

Figure 3.1. 2. Mechanisms involved in cleaning of surface contaminants.

Chemical cleaning can occur due to the chemical nature of the surface that is contaminated or by a chemical agent exposed to the contaminant on the surface (Bateup, 1986; Hurren et al., 2006). Common chemical cleaning agents that are used are oxidative in nature and include hydrogen peroxide (H_2O_2), sodium hypochlorite ($NaOCl$), sodium chlorite ($NaClO_2$), sodium perborate ($NaBO_3$), or sodium percarbonate ($Na_2CO_3.5H_2O_2$); reducing agents like sodium dithionite ($Na_2S_2O_4$) and sodium thiosulphate ($Na_2S_2O_3$) can also be used (Bateup, 1986; Hurren et al., 2006) as well as metal oxides such as titanium dioxide (TiO_2), tungsten oxide (WO_3), and zinc oxide (ZnO) (Hurren et al., 2006). Three bleaching agents we evaluated in this study: hydrogen peroxide, sodium hypochlorite, and sodium dithionite.

Hydrogen peroxide is a favourable bleaching agent for peroxidation of melanin pigment, chromatophores, and lipids, and, because it does not react with proteins, it is widely used for decontamination of animal fibres (Jones, 1999). This aids in retaining the mechanical properties of the fibres. During the oxidation reaction, H_2O_2 is converted into the perhydroxy species (HO_2^-), which is responsible for bleaching (Christoe, 1984; Jones, 1999; Noyori et al., 2003). Additionally, the rate of decomposition of H_2O_2 rises with increase in temperature and pH, as does the rate of bleaching (Christoe, 1984; Sudalaiyandi, 2012; Tseng, 2011; Pourjavaheri et al., 2014).

Sodium hypochlorite, the sodium salt of hypochlorous acid, caused lysis of the lipid bilayer of bacterial cell membranes. It oxidises and aids in the removal of dirt, acts as a disinfectant, and whitens the material under treatment (Sudalaiyandi, 2012; Tseng, 2011; Pourjavaheri et al., 2014). Unsaturated fatty acids are hydrolysed via addition of chlorine and hydroxyl groups to carbonyls. At higher concentrations, the hypochlorous acid oxidises sulphhydryl groups on cysteine to denature keratin and form hydrochloric acid (Sudalaiyandi, 2012; Tseng, 2011; The Chlorine Institute, 2011). NaOCl reacts with HCl to form chlorine gas. This is prevented by maintaining the pH of the solution to 10 by addition of NaOH. However, the effluent must be thoroughly rinsed with water because NaOH degrades animal fibres and NaOCl releases oxygen violently upon contact with hydrogen peroxide; at pH 5-8.5 the bleaching solution contains predominantly hypochlorous acid; at pH less than 5 there is liberation of chlorine (Tseng, 2011; The Chlorine Institute, 2011).

Sodium dithionite is a powerful, inexpensive, safe and readily available reducing agent. It is primarily used as a reducing agent for the reduction of sulphur containing dyes and vat dyes, and in the removal of pigments on textiles that may have been improperly dyed (Anonymous, 2017). Besides its use as a reducing agent, sodium dithionite is also used as a bleaching agent in reductive bleaching processes. It especially reduces carbonyl and alcohol functional groups, which are responsible for the colour of textile materials (Anonymous, 2017).

Decontamination and cleaning of chicken feathers will ensure that the feather surfaces are freed from lipids and fatty acid coatings and prevent decay of the feathers. Therefore, technologies should be developed and customised for commercial pre-treatment and decontamination of feathers. The present investigation was undertaken to determine the effect of inorganic chemical pretreatment and decontamination strategies using bleaching agents. It was also important to assess the effect of the decontamination and pre-treatment on physicochemical and mechanical properties of the treated chicken feathers.

3.1.2. Materials and methods

3.1.2.1. Materials

Feathers: Chicken feathers were supplied by a slaughterhouse in the province of KwaZulu-Natal, South Africa.

Chemicals: Oxidising agents (hydrogen peroxide (H_2O_2) and sodium hypochlorite (NaOCl)) and a reducing agent (sodium dithionite ($Na_2S_2O_4$)), were supplied by Sigma–Aldrich to be used as feather pre-treatment and decontaminating agents. Hexane (Sigma–Aldrich) was used for grease content analysis. Peptone (Merck) and yeast extract agar (Merck) were used for the bacteriological analyses.

3.1.2.2. Decontamination and pre-treatment

Samples containing 5 g raw chicken feathers were treated in dilute inorganic bleaching agents in different concentrations, as listed in Table 3.1.1. Decontamination and pre-treatment were carried using a Soxhlet apparatus according to Table 3.1.1. After decontamination and pretreatment, the liquid was removed by filtration using a 0.5 mm mesh filter. In all methods, the treated chicken feathers were rinsed with tap water until constant pH. The treated chicken feathers were laid on aluminium foils and dried to constant mass at 70 ^{o}C in an air-forced dryer after which they were stored in sealed plastic bags, in a controlled laboratory environment (20 °C, 65% relative humidity) for further characterisation (Figure 3.1.3). In addition to these methods, the chicken feathers were decontaminated by autoclave in a sterilisation process (vertical type steam steriliser, HL-340, Already Enterprise Inc. Taipei, Taiwan) with saturated steam at 132 ^{o}C for 20 minutes at 4 kg/cm^2. This decontamination process was used as a control.

Table 3.1.1. Coded values of variables used in Box-Behnken design

Coded value	Independent variables	H_2O_2			NaOCl			$Na_2S_2O_4$		
		Level								
		-1	**0**	**1**	**-1**	**0**	**1**	**-1**	**0**	**1**
X_1	Concentration (% v/v)	0.25	0.50	0.75	0.50	1.50	2.5	0.25	0.63	1.00
X_2	Temperature (^oC)	25.00	52.50	80.00	25.00	62.50	100.00	40.00	60.00	80.00
X_3	Time (min)	5.00	32.50	60.00	5.00	32.50	60.00	5.00	32.50	60.00
X_4	Number of stage	1.00	2.00	3.00	1.00	2.00	3.00	1.00	2.00	3.00

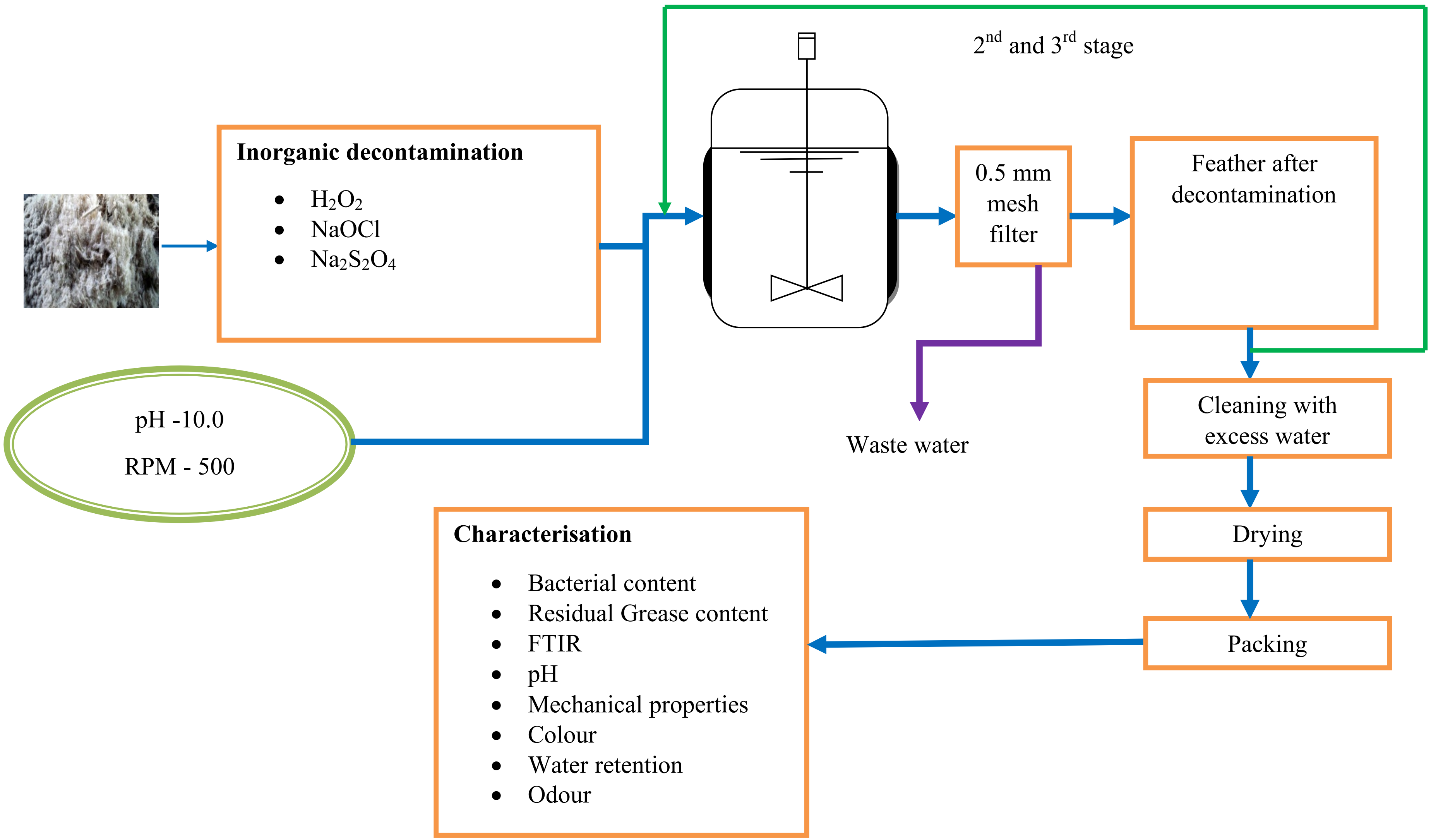

Figure 3.1. 3. Block diagram for decontamination and pre-treatment of waste chicken feathers.

3.1.2.3. Determination of microbial content

Treated, untreated, and autoclaved chicken feather samples were conditioned at ambient temperature for 1 hour prior to testing for microbial content using standard methods (Pourjavaheri et al., 2015). A 0.1 g sample was mixed with 9.9 ml of sterile peptone water (8.5 g NaCl and l g peptone (Merck) per litre) to restore microbial cells to enable a good estimate of microbial counts. The sample was then shaken at 120 rpm for 30 minutes to ensure proper mixing and homogenisation. 1.0 ml of the homogenised mixture was pour plated onto yeast agar (Merck) and incubated at 30 ^{o}C for 24-48 hours, after which the microbial colonies were counted on a digital plate reader. A schematic of the process is summarised in Figure 3.1.4.

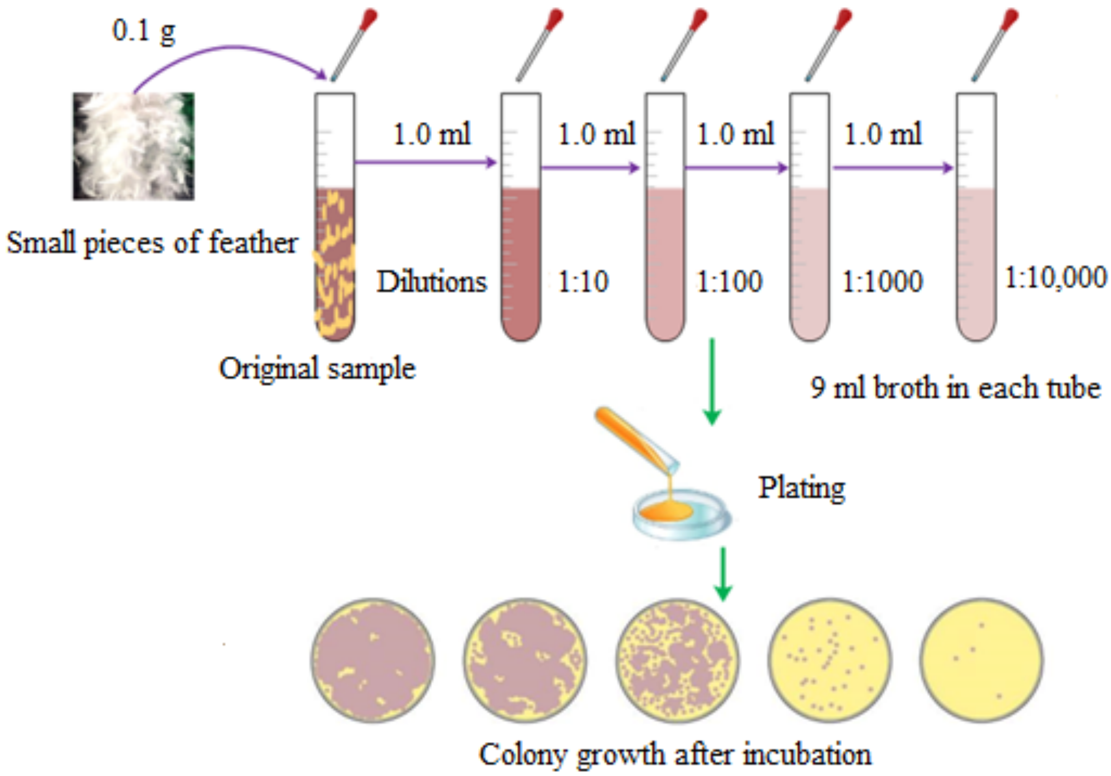

Figure 3.1. 4. Pour plate technique for microbial test on treated and untreated chicken feathers

3.1.2.4. The effect of decontamination and pre-treatment on physicochemical and mechanical properties of chicken feathers

Impurity removal: - Impurity removal is the measure of mass lost from the raw chicken feather during pre-treatment and decontamination, represented as a percentage of the weight loss and calculated using Equation 1:

$$Impurity\ removal\ (\%) = \frac{M_1 - M_2}{M1} * 100 \qquad [1]$$

where M_1 is a raw chicken feather and M_2 is a decontaminated and pretreated feather in grams.

Residual grease content: - Residual grease is the grease content of chicken feathers after pre-treatment and decontamination. The residual grease content of treated chicken feather was determined by extracting the washed samples with hexane using a Soxhlet apparatus according to ASTM D1574. Three replicate samples were measured for each of the decontaminating and pre-treatment techniques.

Fourier transform infrared (FTIR) spectroscopy: - FTIR spectroscopy (Frontier Universal ATR-FTIR, from PerkinElmer) was used to ascertain if the decontamination and pre-treatment procedures affected the functional groups of the feathers. A universal attenuated total reflectance (ATR) module was used for all spectra in a wave number range between 400 cm^{-1} and 4000 cm^{-1}.

Whiteness and yellowness indices: - The pre-treated and decontaminated feathers were monitored for their colour using a spectrocolorimeter, which was standardised with Hunter lab colour standards. The colour of the chicken feathers in terms of $L*$, $a*$, and $b*$ values were measured with a Hunter lab Colorimeter (Greta Macbeth Colour Eye 3100). The whiteness value was obtained according to equation 2:

$$\text{Whiten}ess\ \% = 100 - [(100 - L)^2 + a^2\ + b^2]^{\frac{1}{2}} \qquad [2]$$

Fibre density: - The density of the chicken feather fractions was measured using a liquid pycnometer (Rude et al., 2000). Five replicates were performed for each sample type.

Water retention and moisture regain: - Decontaminated and untreated chicken feather samples were dried at 105 °C for over 4 hours and weighed (W_1) before soaking in distilled water at different temperatures for 5 min. The wet chicken feathers were removed and centrifuged for 5 min at 9000 rpm and weighed again (W_2). Water retention (%) was calculated according to equation 3 and the average of three tests was taken:

$$Water\ retention\ (\%) = \frac{W_2 - W_1}{W_1} * 100 \qquad [3]$$

Morphological and elemental profile analysis: - The impact of the decontamination and pre-treatment techniques on the morphology and elemental composition of the feathers was investigated using low-resolution scanning electron microscopy and energy dispersive spectroscopy (EDS). Chicken feathers from experiments that showed superior bactericidal efficacy were further analysed using high-resolution scanning electron microscope (SEM) analysis as well as elemental profile analysis using energy dispersive spectroscopy (EDX) using a Field Emission Gun Scanning Electron Microscope with EDX capability (Carl Zeiss, Oberkochen, Germany).

Mechanical properties: - Chicken feathers barbs were dried and conditioned at a relative humidity 65 ± 2 % and a temperature 22 ± 2 ºC. The conditioned samples were used for testing the bundle strength tenacity & liner density according to the bundle tensile strength (Flat bundle method) – ASTM D1445. The bundle tensile test was carried out on the Instron Tensile Tester (Model 3345) at 0 mm gauge length using Pressley clamps with leather facing. The dynamic mechanical analysis (DMA) of the chicken feather barbs was done using a Perkin Elmer DMA 8000 DMA dynamic mechanical analyser. Feather barbs were tested in the tensile mode, while heating from 20 °C to 200 °C at a heating rate of 2 °C min^{-1}, and at a frequency of 1 Hz.

Thermogravimetric analysis: - The thermal properties of untreated and treated samples were measured using a Perkin-Elmer TGA thermogravimetric analyser, under temperatures that ranged between 25 °C and 550 °C, at a heating rate of 5 °C min^{-1} under nitrogen gas purge.

3.1.2.5. Optimisation of decontamination using response surface methodology (RSM)

Response surface methodology, an empirical statistical technique, was employed to study interactions between relevant factors and possible optimisation of operating parameters (Montgomery, 2008). For this study, a Box-Behnken design (BBD) was used. The design consisted of four independent variables (concentration, the number of treatment stages, treatment time, and temperature) with a total of 27 experimental runs employed for each bleaching agent. The coded values of the variables at various levels are given in Table 3.1.3. Microbial count/dependent variables were determined by the coefficient of determination, analysis of variance, and contour plots with the help of Statistica 13 software (TIBCO Software Inc., California, USA). The partial least square fitting method was used to validate experimental data and to generate a mathematical equation which could be used for optimisation or for the forecast of microbial count result. Using multiple regression analysis of dependent variables, the data obtained was fitted to a second-order polynomial equation 4.

$$Y = \beta_0 + \beta_i X_i + \beta_{ij} X_i X_j + \beta_{ii} {X^2}_i \quad [4]$$

where *Y* is the predicted response variable; β_0, βi, βii, βij are constant regression coefficients of the model; and *Xi, Xj* (*i=1, 3; j=1, 3; i≠ j*) represent the independent variables in the form of coded values.

3.1.3. Results and discussions

3.1.3.1 Effect of pretreatment on appearance and odour of chicken feathers

Unprocessed raw feathers appeared straw-like, with a greasy texture, bloody appearance, brown colour, and had an obnoxious odour and the barbs were stuck to the rachis. (Tseng, 2011; Pourjavaheri et al., 2014). As can be seen in Figure 3.1.5, the barbs of raw chicken feathers were tangled and stuck to the rachis. When left at room temperature, the raw wet feathers turned dark brown after two days and had a distinct putrid smell - the raw chicken feathers turned dark brown from bacterial decomposition. After washing with water, their barbs opened and appeared white, however, the odour remained. The untreated feathers contained blood, which looked pink upon collection but turned brown as it dried. This is in agreement with what has been reported in the literature (Tseng, 2011; Pourjavaheri et al., 2014). The freshly collected feathers could possibly be potential biological hazards for a variety of disease causing anaerobic, aerobic, and enteric bacteria, due to the presence of blood borne pathogens. The common genera of microbes known to cause gastroenteritis, which are found on raw chicken feathers are *Campylobacter, Enterobacter, Salmonella and Escherichia* (Tseng, 2011; Pourjavaheri et al., 2014). The growth of the bacteria on feathers will consume feather keratin, decompose it, and eventually degrade the feathers making them mechanically very weak and dark in colour. The feathers treated with all the chemicals used in this study showed weight losses compared to the raw and autoclaved samples. This indicates that there was a large amount of impurities in the initial sample. The pre-treatment and decontamination processes imparted a sickly-sweet bleach odour to the feathers and changed them from brown to white. During the final washing stages, the residual cleaning chemicals had to be properly removed by rinsing with tap water to constant pH to retard further chemical degradation that resulted in development of objectionable odours in the feathers (Tseng, 2011; Pourjavaheri et al., 2014).

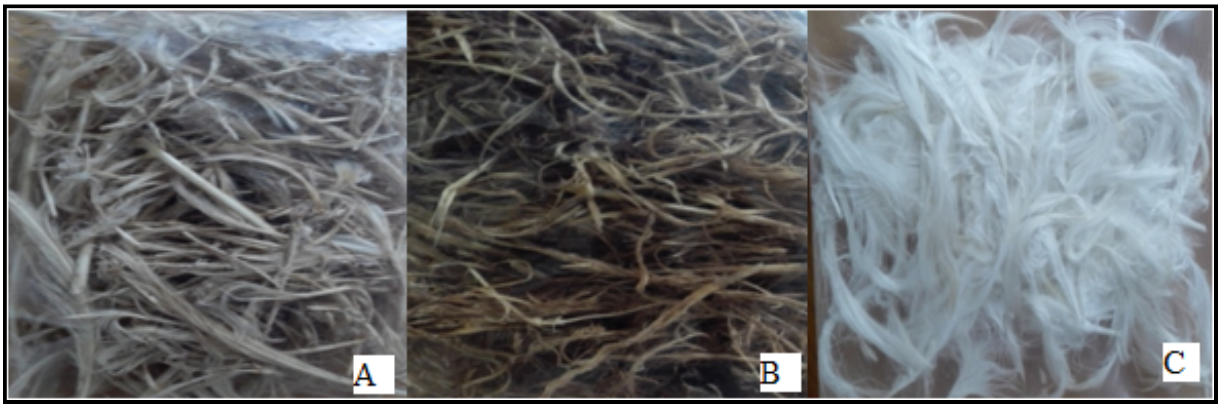

Figure 3.1.5. Chicken feathers after sampling (A); after 3-day storage at room temperature (B); and after washing with bleaching agents (C)

3.1.3.2. The effect of decontamination on microbial counts

Figures 3.1.6-3.1.8 show viable counts of general/standard microbial counts that resulted from decontamination with inorganic decontamination agent. The results show that the bleaching agents were effective in removing microorganisms from the feathers. The lower general microbial counts in the treated samples could be due to death and/or washing away of microorganisms during the decontamination and pre-treatment processes. As shown in Figures 3.1.6-3.1.8, the order for microbial reduction followed the order H_2O_2

> NaOCl > $Na_2S_2O_4$. The lower microbial counts indicate higher bactericidal removal. The untreated chicken feathers had the highest microbial counts (1.48E+07±6.72E05 Cfu/g) whereas autoclave decontamination showed the most reduction in the microbial count (2.81E+06±5.62E04 Cfu/g). All the bleaching agents studied showed significant decreases in microbial counts (Figure 3.1.6-3.1.8). This is in agreement with literature data that indicate that inorganic decontamination agents are capable of eliminating a broad range of microorganisms (Bateup, 1986; Cui, 1999; Gill, 1998; Noyori et al., 2003; Augurt et al., 2008).

3.1.3.3. Optimisation of decontamination by a Box-Behnken design

The microbial count decreased more than a thousand-fold after decontamination and pretreatment (Table 3.1.2). Twenty-seven experimental runs were conducted for each bleaching agent. In this model, the effects/ of individual, or a combination/interaction of independent variables on microbial count were assessed. The processed data from the experimental design enabled the calculation of the coefficients of the regression equation - which characterises the dependency of microbial count on the independent variables. Based on the experimental data on the microbial count and various interaction terms of the variables a multiple mathematical model equation was regressed (Equation (5, 6 and 7)) after the exclusion of insignificant coefficients of the regression.

Table 3.1.2. The characteristics of chicken feather before and after treatment

Pre-treatment	Microbial count
Control	1.48E+07±6.72E05 Cfu/g
Autoclave	2.81E+06±5.62E04 Cfu/g

$$(\mathbf{MC\ (H2O2)})^{\mathbf{0.49}} = 56.81 - 55.08 * X_1 - 0.21 * X_2 + 1.27 * X_3 - 33.70 * X_4 - 1.18 * X_1 * X_2 - 0.82 * X_1 * X_3 + 55.69 * X_1 * X_4 - 4.48\text{e} - 004 * X_2 * X_3 + 0.16 * X_2 * X_4 - 0.35 * X_3 * X_4 \quad [5]$$

$$(\mathbf{MC(NaOCl)})^{\mathbf{0.23}} = +9.79 + 5.60 * X_1 - 0.09 * X_2 - 0.12 * X_3 - 3.41 * X_4 + 8.83 * X_1 * X_2 - 0.02 * X_1 * X_3 - 0.13 * X_1 * X_4 + 6.89 * X_2 * X_3 - 1.07 * X_2 * X_4 + 0.02 * X_3 * X_4 - 1.60 * X_1^2 + 4.60\text{e} - 004 X_2^2 + 3.77\text{e} - 004 X_3^2 + 0.51 X_4^2 \quad [6]$$

$$(\mathbf{MC(Na2S2O4)})^{\mathbf{0.01}} = +1.12 - 7.01e - 003 * X_1 - 1.35\text{e} - 004 * X_2 - 2.49\text{e} - 005 * X_3 - 0.02 * X_4 \quad [7]$$

Where MC is microbial count and X_1, X_2, X_3, X_4 represent concentration, temperature, time and number of stages, respectively.

Analysis of the equation of regression allows us to draw a conclusion that the criterion of microbial count optimisation in the selected factor is influenced by concentration of the bleaching agents, time, temperature and number of stage. The negative values of coefficients of the regression equation confirm that an increase in the value of any of the factors will lead to a decrease in the value of microbial count. The mathematical model (Eq. 5-7) of the decontamination and pre-treatment of chicken feather attests that the desired value of microbial count is within the limits of the tested factor space. The statistical significance of the model equations 5-7 and the model terms were evaluated by the F-test for analysis of variance (ANOVA), which indicated that the regressions were statistically significant.

3.1.3.4. Optimisation of the pre-treatment and decontamination of waste chicken feather

Table 3.1.3 shows the Analysis of Variance (ANOVA) results of the regression equation for microbial count optimisation of the decontamination process of waste chicken feathers. In all decontamination treatments, the F-values were high indicating that the model was significant, and there was 0.01 % chance that the model F-value this large could occur due to noise (Table 3.1.3). The insignificant lack of fit F-value is good agreement with a model reported in the literature (Kuila et al., 2011b). The fit of the model was checked by the R-squared/R^2 value, the higher R^2 coefficient (Table 3.1.3), as a measure of a number of reductions in the variability of the response, obtained using the independent factors within the model confirms a satisfactory adjustment of the proposed model to the experimental data. No significant difference was observed between the R^2 and adjusted R^2 values; i.e., the difference is less than 0.2, indicating that the regression model is reliable, competent, and designates the fit relation between the experimental work and mathematical model for all decontamination treatments of waste chicken feathers.

Table 3.1.3. Analysis of variance (ANOVA) for the fitted linear model for optimisation of microbial count

Bleaching agent	Source	Sum of Squares	Degree of freedom	Mean Square	F Value	p-value Prob >F	
H_2O_2	Model					< 0.0001	*Significant*
	Concentration (%v/v)	*4607613.01*	*2*	*2303806.50*	*6.11*	*0.0094*	
	Number of stage	*38685819*	*2*	*19342909.5*	*51.32*	< 0.0001	
	Time (min)	*550177.45*	*2*	*275088.73*	*0.73*	*0.4956*	
	Temperature (^{o}C)	*118461.89*	*2*	*59230.95*	*0.16*	*0.8557*	
	Total sum of square	*52043793.9*	*26*				
	Pure Error	*6784074.58*	*18*	*376893.03*			
	R^2=0.87, Adjusted R^2=0.83						
NaOCl	Model					*< 0.0001*	*Significant*
	Concentration (%v/v)	*2612420.98*	*2*	*1306210.49*	*8.86*	*0.0020*	
	Number of stage	*13269366.50*	*2*	*6634683.27*	*45.02*	*< 0.0001*	
	Time (min)	*97321.37*	*2*	*48660.68*	*0.3*	*0.7230*	
	Temperature (^{o}C)	*8811.92*	*2*	*4405.96*	*0.03*	*0.9705*	
	Total sum of square	*19030138.10*	*26*				
	Pure Error	*2652386.58*	*18*	*147354.81*			
	R^2=0.86, Adjusted R^2=0.80						
$Na_2S_2O_4$	*Model*					*< 0.0001*	*Significant*
	Concentration (%v/v)	*3401568*	*2*	*1700784,19*	*7.96*	*0.0033*	
	Number of stage	*16837202*	*2*	*8418600,96*	*39.39*	*< 0.0001*	
	Time (min)	*93696*	*2*	*46848,07*	*0.22*	*0.805*	
	Temperature (^{o}C)	*19930*	*2*	*9965,07*	*0.05*	*0.954*	
	Total sum of square	*24692608*	*26*				
	Pure Error	*3847206*	*18*				
	R^2=0.844, Adjusted R^2=0.78						

The coefficient of variation (Cv) indicates the ratio of the standard error of the estimate to the mean value of the observed response (Table 3.1.4). Generally, a model can be considered reasonably reproducible if the Cv is not greater than 15% (Montgomery, 2008). Here, the Cv values were 9.35% (H_2O_2), 11.30% (NaOCl), and 13.47% ($Na_2S_2O_4$) indicating high degrees of precisions in the experiments. From Table 3.1.4 the negative sign for the coefficients of factors in the fitted models for microbial count indicated that the level of microbial count decreased with increasing levels of factors. Also, the greatest coefficients of factor and number of stage, revealed high sensitivities of responses to this factor. Adequate precision is a measure of the range in predicted response relative to its associated error, which provides a measure of the "signal-to-noise ratio". In the present study, the ratios of 9.35% (H_2O_2), 11.30% (NaOCl), and 13.47% ($Na_2S_2O_4$) indicated adequate signals, thus this model can be used to navigate the design space. Simultaneously, low values of the coefficient of variation (Cv) (9.35%) indicated good precision, reproducibility and reliability of the experiments.

Table 3.1.4. Coefficient of variation for fitted model for optimisation of microbial count

Type of Chemicals	Factor	Coefficient Estimate	T-value	Standard Error	95% CI Low	95% CI High
H_2O_2	Intercept	1328.28	204.64	6.49	898.35	1758.21
	Concentration (%v/v)	-1217.00	354.44	-3.43	-1961.66	-472.34
	Number of stage	-3191.00	354.44	-9.00	-3935.66	-2446.34
	Time (min)	-427.00	354.44	-1.20	-1171.66	317.66
	Temperature (^oC)	-166.33	354.44	-0.47	-910.99	578.33
NaOCl	Intercept	811.56	127.96	6,34	542.73	1080.38
	Concentration (%v/v)	-902.50	221.63	-4.07	-1368.12	-436.88
	Number of stage	-1903.83	221.63	-8.60	-2369.45	-1438.21
	Time (min)	-166.00	221.63	-0.75	-631.62	299.62
	Temperature (^oC)	-41.00	221.36	-0.19	-506.62	424.62
$Na_2S_2O_4$	Intercept	950.11	6.16	154.10	626.35	1273.87
	Concentration (%v/v)	-1029.00	-3.86	266.92	-1589.77	-468.23
	Number of stage	-2160.67	-8.09	266.92	-2721.44	-1599.90
	Time (min)	-156.67	-0.58	266.92	-717.44	-404.10
	Temperature (^oC)	-79.67	-0.30	266.92	-626.10	215.16

Further steps were taken to examine the effect of time, concentration, number of stage and temperature on the microbial count of the chicken feathers. Three-dimensional (3D) surface plots were generated by Statistica 13 software. In general, the 3D surface plot shows the overall contribution of concentration, number of stage, temperature and time, (independent variables) to the microbial count (dependent variable). The green region signifies that independent factors had high impacts on the microbial count reduction. The significance of independent variables increases with the intensification of colourisation from the dark red region to dark green region progressively. The stationary point, which is denoted by dark green region on the lower part of the wedge-like 3D plot is the optimised point. Hence, it can be justified that concentration and number of stage (Figure 3.1.6, 3.1.7 and 3.1.8 a); concentration and time (Figure 3.1.6, 3.1.7 and 3.1.8 b); concentration and temperature (Figure 3.1.6, 3.1.7 and 3.1.8 c); number of stage and time (Figure 3.1.6, 3.1.7 and 3.1.8 d); number of stage and temperature (Figure 3.1.6, 3.1.7 and 3.1.8 e); and time and number of stage (Figure 3.1.6, 3.1.7 and 3.1.8 f) are critical parameters in altering microbial count of the decontaminated chicken feather. At higher concentration, higher temperature, higher number of stage and higher time of treatment, the microbial count of the decontaminated chicken feather is lowest throughout the surface plot. This result is valid as for all bleach treatments. The data in Figures 3.1.6-3.1.8 also signifies that the microbial counts of the treated chicken feathers were significantly dependent on the number of stages and concentration of chemical used followed by time, and temperature. The results demonstrated that the first number of stage does not reduce the standard microbial loads as effectively as the 2^{nd} and 3^{rd} decontamination cycles. However, a single decontamination cycle will provide sufficient disinfection if the treated feathers were used for the production of composites.

The nature of the response shape was further explored as depicted in the 3D response surface plots (Figure 3.1.6-3.1.8). The three-dimensional response surfaces depict that the interactions between two variables was perfect because the contour plots are elliptical (Haji et el., 2014). Figures 3.1.6-3.1.8 demonstrated that the surface plots of the response microbial count at optimal values of the independent variables; concentration, temperature, time and number of stage. As shown in Figure 3.1.6, the shapes of the contour plots are all elliptical except for Figures 3.1.6C and 3.1.6F, indicating that the mutual interactions between every two variables were significant. The three-dimensional surface plots (Figures 3.1.7a-c) indicated that only the number of stage and concentration have the highest significant influence on the microbial count of the waste chicken feathers. The interactions between every two variables (Figure 3.1.8) were significant; this is confirmed by the elliptical contour plot of the design.

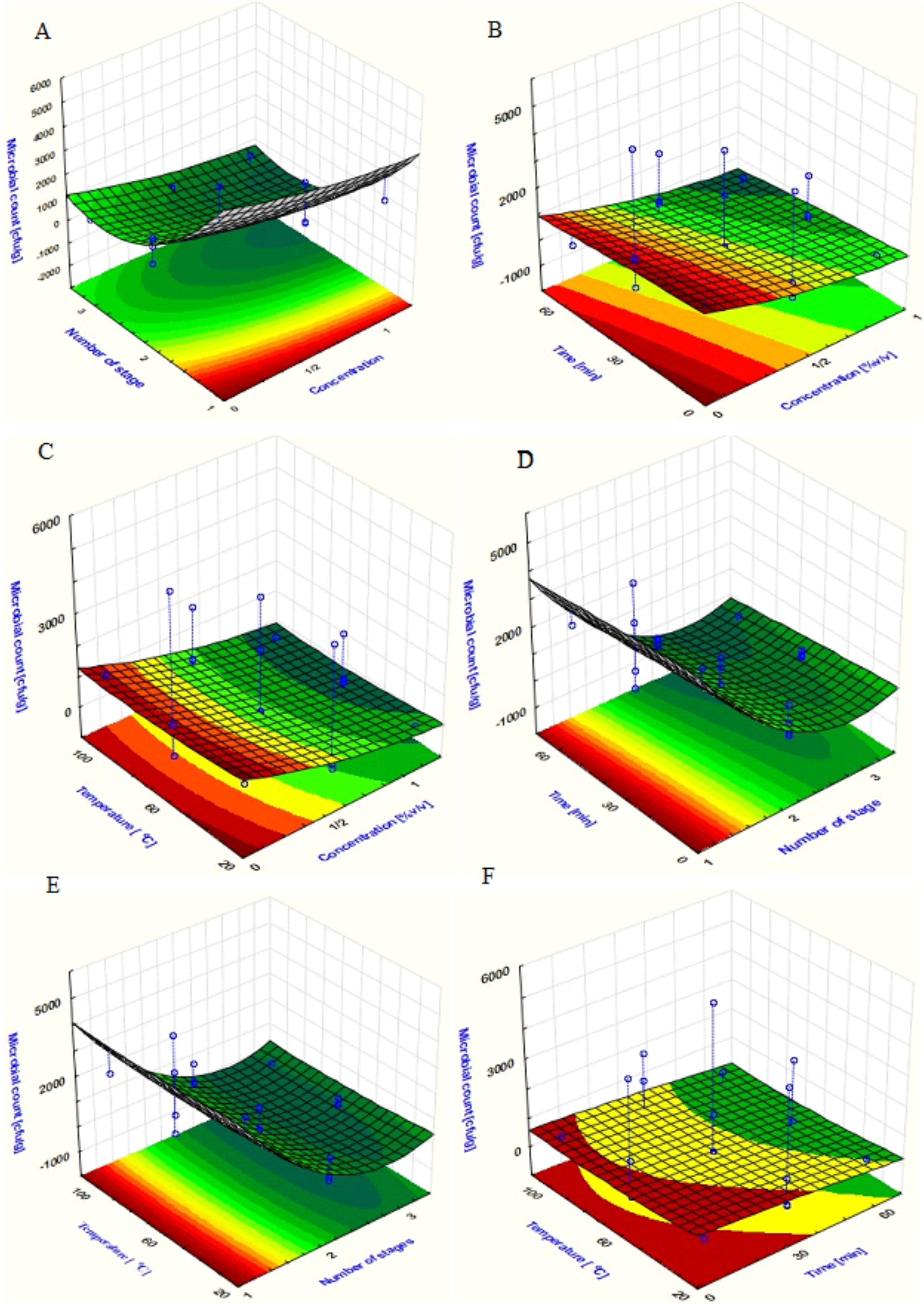

Figure 3.1.6. Three-dimensional plots of the effect of four variables on the microbial counts. The interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

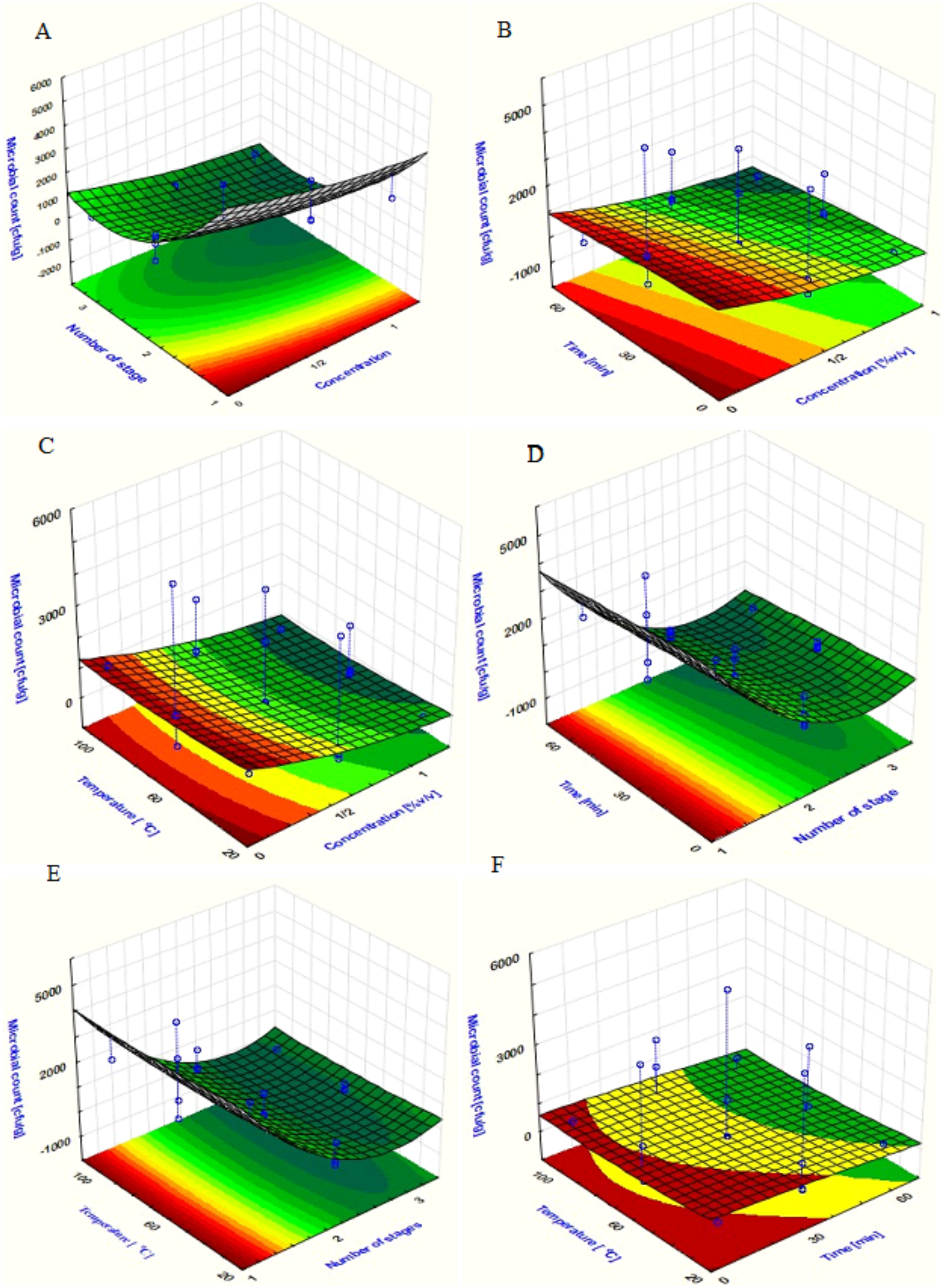

Figure 3.1.7. Three-dimensional plots of the effect of four variables on the microbial count. The interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

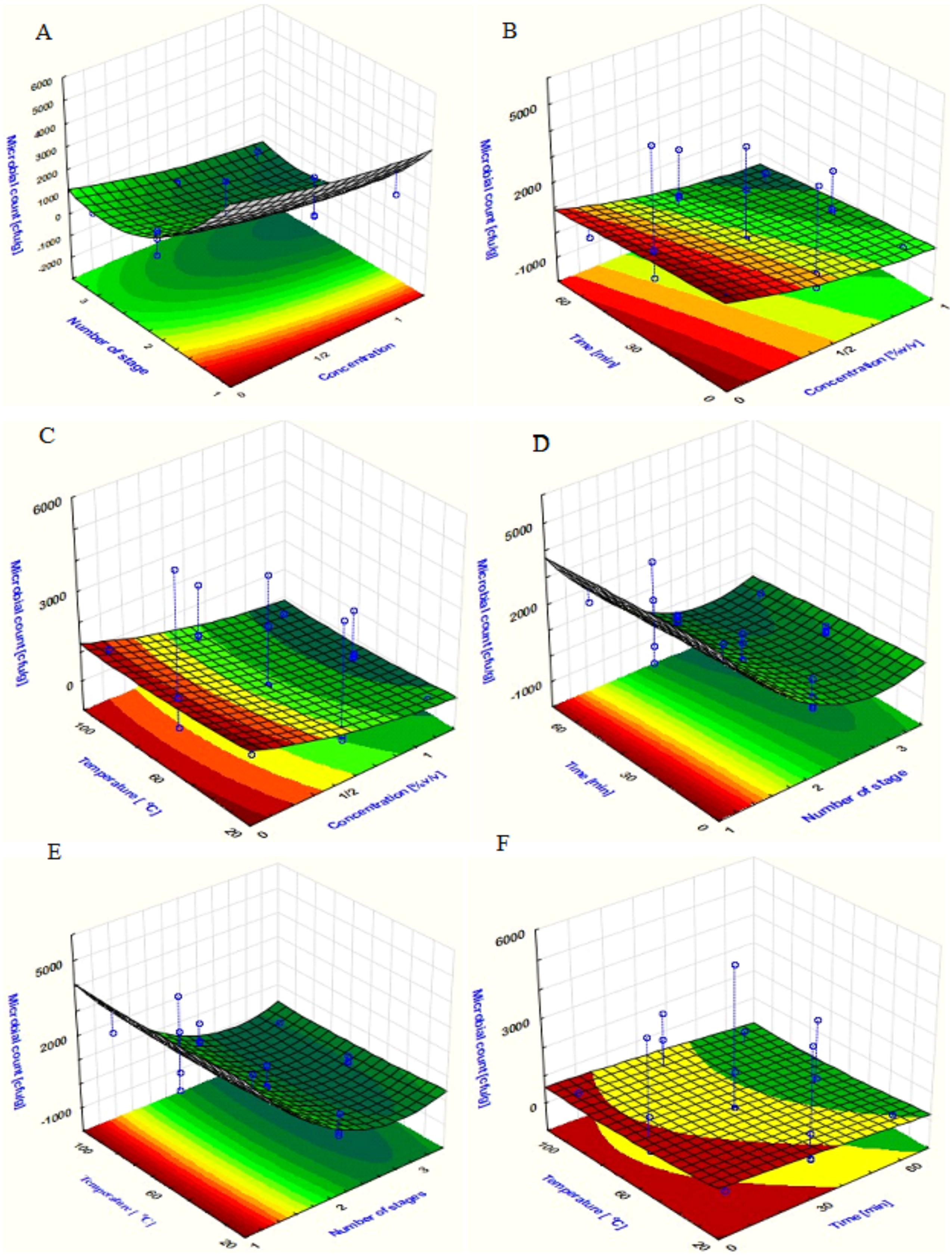

Figure 3.1.8. Three-dimensional plots of the effect of four variables on the microbial count. The interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

The actual Vs predicted plot displays demonstrated the closeness of the actual data to the predicted data. For validation of the results, the experimental values of the responses were compared with the anticipated values and the percentage predictions. The less deviation from the straight line indicates less deviation from the predicted value and is a satisfactory correlation between experimental data and predictive data. For the microbial count of the decontaminated chicken feather checkpoint, the result was well within limits. The closeness of the anticipated and experimental data (significant R^2 value and low magnitude errors) proves the high prognostic ability of the Box-Behnken Design. To further clarify the data and judge the adequacy of the model in the experimental data, diagnostic plots were drawn and the linear patterns observed in the plot suggest that there was high accuracy in the experimental data.

3.1.3.5. The effect of decontamination and pre-treatment on physicochemical and mechanical properties of chicken feathers

The effect on removal of impurities: - The removal of impurities in decontaminated and pre-treated chicken feathers was plotted against concentration, number of stage, time and temperature as shown in Figure 3.1.9. The impurity removal after washing was about 8-18 %. This impurity removal is due to the washing out of short fibres and foreign materials such as vegetation, suints, blood, dust and some other contaminants from the poultry industry and proves that the impurity removal has direct dependency on the cleaning agents used. From Figure 3.1.9 it can be seen that there was a significant reduction in impurity content compared to the untreated chicken feather. The results in Figure 3.1.9 suggest that a single stage would be insufficient in reducing impurities to an acceptable level - thus more than one stage of cleaning is required. The results also revealed that the number of stages and concentration have significant effects on impurity removal compared to treatment time and temperature.

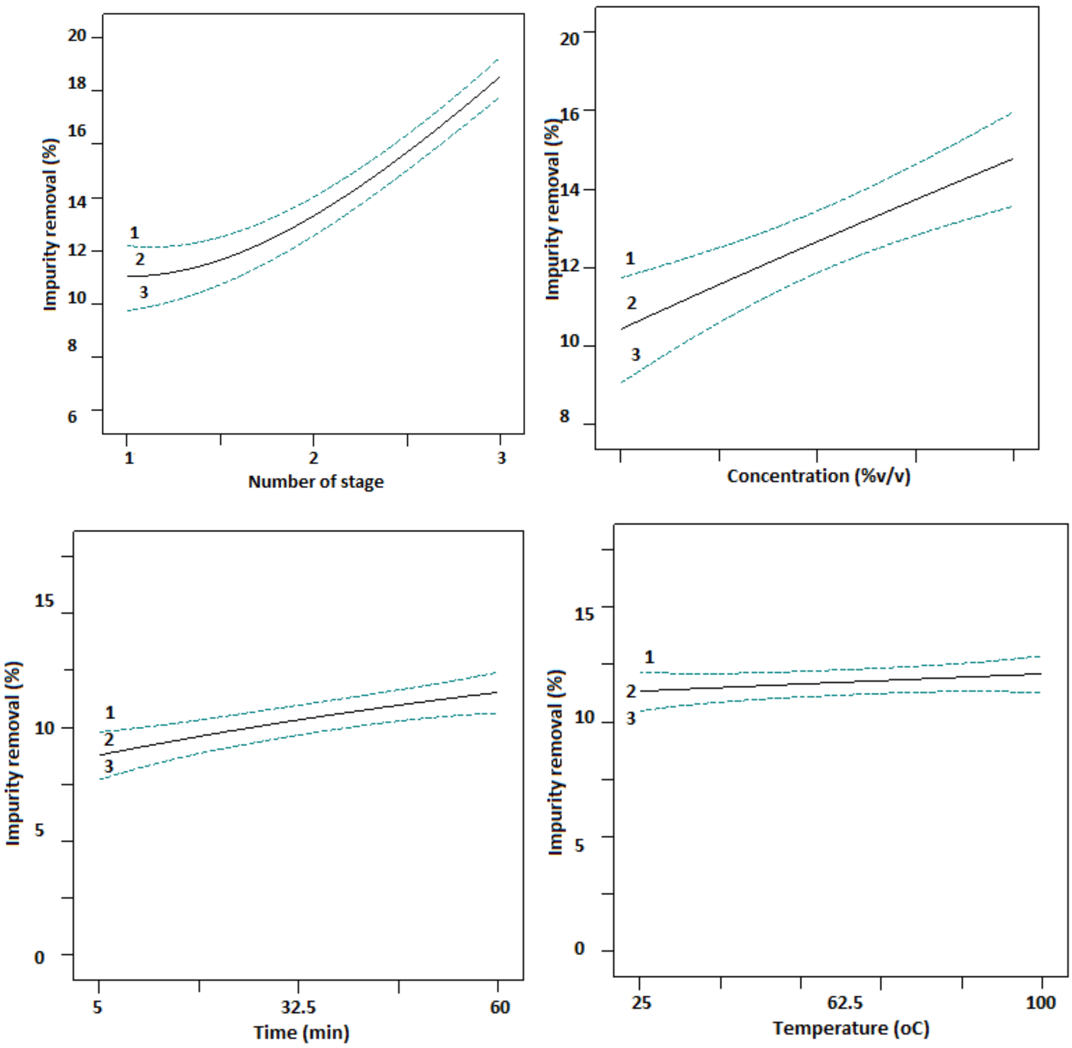

Figure 3.1.9. The effect of independent variables on impurity removal [%] (1= H_2O_2, 2=NaOCl, 3=$Na_2S_2O_4$)

The effect of pre-treatment on residual grease content: - Figure 3.1.10 shows the residual grease content after hexane extraction of the decontaminated and pre-treated chicken feathers at 60 ^{o}C. It is noticeable that increasing the number of stage and concentrations significantly reduces the residual grease content of samples treated with all chemicals. The highest mean residual grease content was obtained for $Na_2S_2O_4$ whereas the lowest mean residual grease content was obtained for chicken feather treated with H_2O_2. The higher number of stages improves emulsification and removes grease more effectively. This is evident even at the lower concentrations of bleach agents. The greatest scouring ability of the oxidising and reducing agents used in this study significantly depended on the number of stages and concentration. The residual grease content of a chicken feather needs to be below 2 % to make processing easier during further valorisation activities (Bateup, 1986). The second and third stage decontamination and pretreatment cycles, especially at higher concentrations, produced feathers with low residual grease content. As can be seen from Figure 3.1.10, the reduction of decontamination and pretreatment time and temperature affect the level of residual grease on the feathers. However, the effect of time and temperature is not as significant as the number of stage and concentration. All second and third stage decontamination and pretreatments, especially at higher concentrations, produced feathers with low residual grease content.

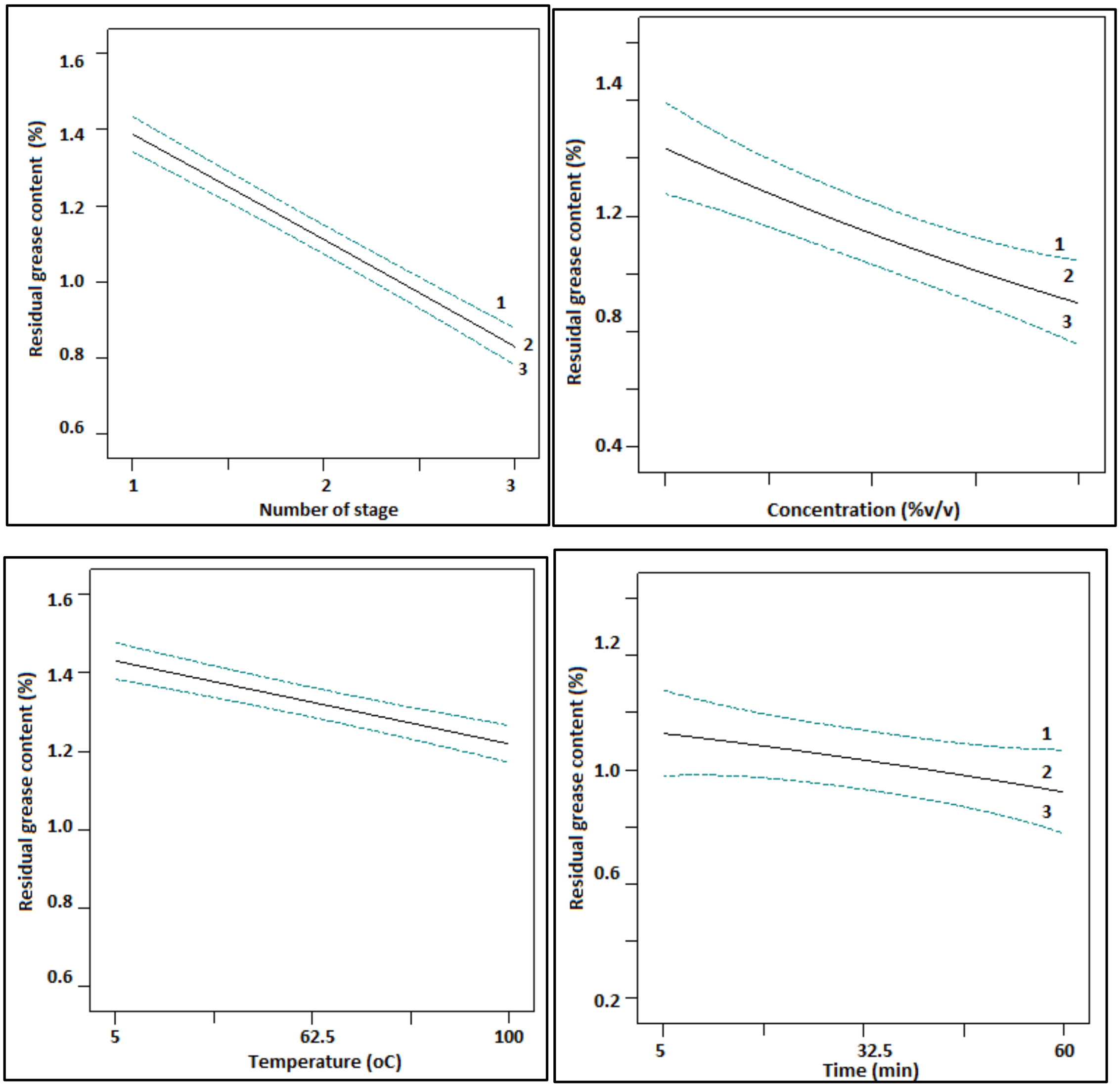

Figure 3.1.10. The effect of independent variables on residual grease content [%](1= H_2O_2, 2=NaOCl, 3=$Na_2S_2O_4$)

The effect of bleaching on FTIR spectra: - FTIR spectra of untreated, autoclaved and decontaminated and pre-treated chicken feathers are shown in Figure 3.1.11. There were no significant differences in the chemical composition and structure of all samples except for the autoclaved sample. However, in autoclaved and untreated chicken feathers the stretching vibration, with carbonyl groups of a fatty acid ester C=O stretching and long alkyl chain hydrocarbons (C-H, stretching, CH_2 and CH_3), 2800-3000, 1700 and 1260 cm^{-1} were observed (Figure 3.1.11). These signals can be attributed to alkyl chains in both radical groups of amino acids and more probably to natural fats like adipic acid ester usually found on animal skins. Elimination of the stretching signals associated with these ester groups in decontaminated and pre-treated chicken feather confirms the capability of the washing method in removing fatty materials from untreated chicken feathers. However, the autoclaved technique did not significantly remove adhered waste materials and fats as the peak for autoclaved sample coincides with those of untreated feathers.

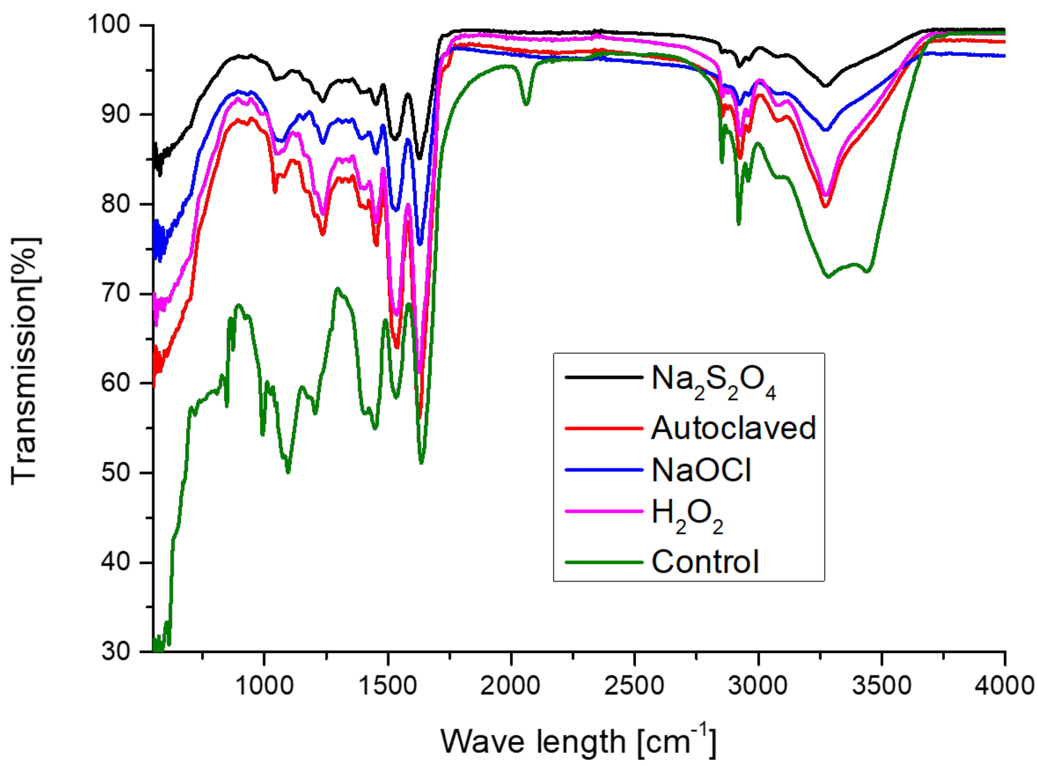

Figure 3.1.11. FTIR spectra of treated and untreated chicken feathers

During bleaching, cysteic acid is produced along with cysteine monoxide and cysteine dioxide due to oxidation of cysteine bonds (S–S–) present in the chicken feather (Pourjavaheri et al., 2014). The agents either damage or remove the surface protein by reacting with the cysteic acid group generated during bleaching. All the treated samples, show S–O contractions in the wavelength region of 1033–1100 cm^{-1} compared to the untreated chicken feathers. This result indicates that all the treated chicken feathers contain the cysteic acid group.

The effect of pre-treatment on water retention and moisture regain of feathers: - The water retention properties of the barb of the chicken feather are presented in Table 3.1.5. There were no significant differences in the data among all bleaching agents studied; however, the values from all the treatments were significantly higher than those of the untreated and control samples. The amount of water retained by chicken feather barbs increases with an increase in the hydrophilic tendency of the feathers due to the removal of lipids from chicken feather surfaces.

Table 3.1.5. Water retention of treated and untreated chicken feathers

	Untreated	Autoclaved	H_2O_2	NaOCl	$Na_2S_2O_4$
Water retention	46.63	51.24	61.28	56.81	58.75

Removal of grease, dirt, suints, burrs and woody fragments and mineral matter from chicken feathers can also result in moisture regain change due to surface modification of treated chicken feathers (Tseng, 2011). Pre-treated and decontaminated chicken feathers absorbed water from the atmosphere quickly whereas the water saturation values after 24 hours were not as large as that for the untreated feathers (Figure 3.1.12). The reduction of the polar groups after pre-treatment and decontamination reduced the water regain saturation values. As can be seen in Figure 3.1.12, the moisture is attracted to the polar groups present in the treated chicken feathers. A practical implication of this observation is that increase in moisture regain will cause reduction in the electrical resistance of chicken feathers resulting – this, in turn, will induce static electricity on the feathers (Hearle and Morton, 2008).

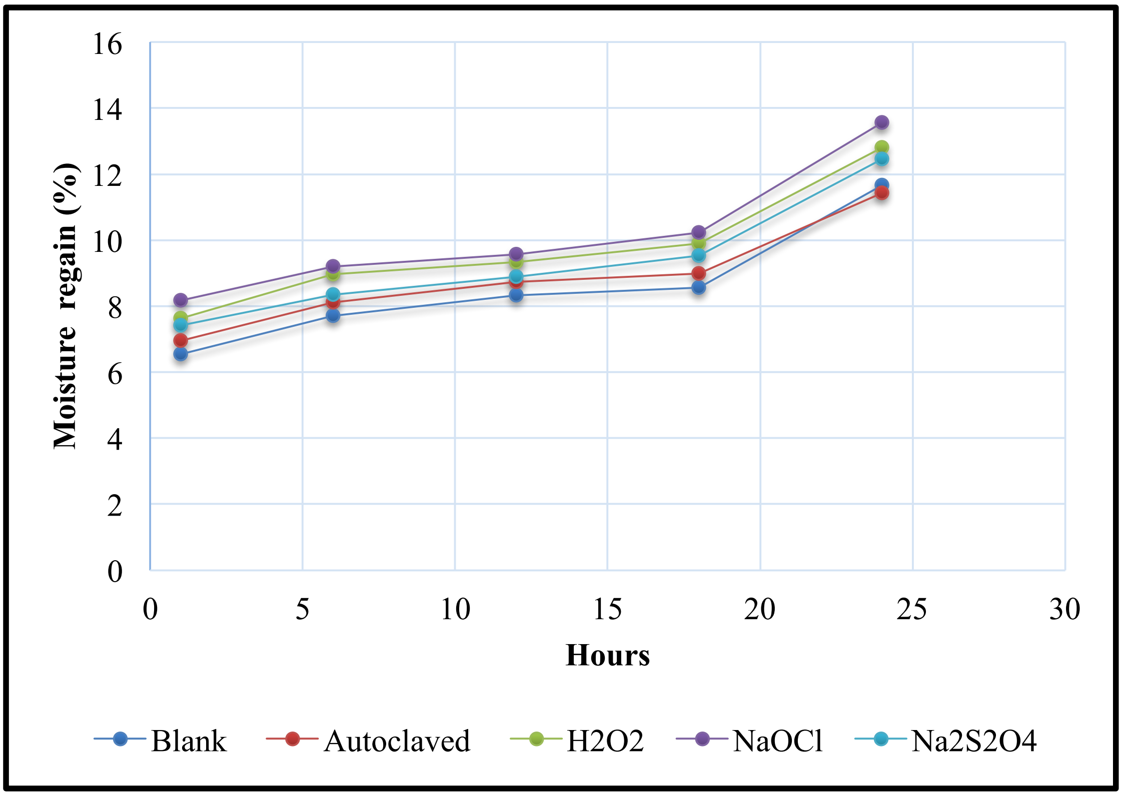

Figure 3.1.12. Moisture regain of treated and untreated chicken feathers

The effect of pre-treatment on whiteness and yellowness index: - The average whiteness index (WI), yellowness index (YI) and colour changes (ΔE) of chicken feather after decontamination and pre-treatment results are summarised in Table 3.1.6. Feather colour varies not only in terms of the type of pretreatment but also in terms of the age variation and the slaughtering processes. A varying amount of preen, particulates from dust bathing, faecal matter and type of feed contributes to the variation in colour of the chicken feathers. Since the raw chicken feather contains blood and may have been collected several hours before decontamination, the colour becomes dark brown due to bacterial development. According to the results in Table 3.1.6, a considerable increase in whiteness index and accordingly a decrease in yellowness index has occurred in all decontamination and pre-treatment methods. Samples treated with H_2O_2 showed the highest brightness rating compared to samples treated with the other decontamination and pre-treatment methods (NaOCl, and $Na_2S_2O_4$). Samples treated with H_2O_2 gave higher whiteness value and the highest colour changes. The results indicate that NaOCl has a better oxidising property than the other chemicals in removing the discolouration of waste chicken feathers. Samples treated with $Na_2S_2O_4$ produced the poorest colour properties in terms of whiteness. However, the whiteness of NaOCl treated chicken feathers was not significantly different from $Na_2S_2O_4$ treatment. The lower whiteness index and the higher colour changes in chicken feathers treated with $Na_2S_2O_4$, and NaOCl may imply that these decontamination and pre-treatment agents had somehow reduced the brightness of the samples. This whiteness result, however, shows that a slightly yellowish-white can be obtained using a first stage decontamination and pre-treatment. Normally, for further whiteness degrees, a second and third stage bleaching is preferably required. The results indicate an inverse relationship between the whiteness values and yellowness index of all treated chicken feather samples. The improvement of the whiteness and yellowness indices in treated and untreated samples depends on the concentration of bleaching agents, number of stage and time of treatment. It was noticed that the increase in each factor led to an increase of chicken feather whiteness and decrease in yellowness index.

Table 3.1.6. CIE tristimulus values, whiteness index and colour differences (ΔE) for treated and untreated chicken feathers

Type of feather	L^*	a^*	b^*	ΔE	WI CIE	YI E313
Control	75.36	2.81	19.59	77.91	-57.75	43.18
Autoclaved	81.49	1.89	18.29	6.13	-34.36	37.70
Hydrogen peroxide	94.59	0.35	5.87	23.75	59.94	11.30
$Na_2S_2O_4$	89.35	0.13	11.85	16.21	18.28	22.70
NaOCl	92.25	0.07	4.01	22.83	59.64	9.98

WI CIE: CIE whiteness index

YI E313: Yellowness index

The effect of bleaching on density of feathers: - Density measurements of whole chicken feathers and fractions (rachis and barb) showed clear differences, almost two-fold, between barb and rachis fractions for treated and untreated chicken feathers. The difference between the densities of barb and rachis is due to the morphological structure of both fractions (a cross-section of a rachis fraction shows an open porous structure, which could be responsible for lower density, whereas the presence of barbules and hooklets in a barb of the chicken feather could make the density higher) (Tesfaye et al., 2017). The density of whole feathers was closer to that of the barb fraction in almost all cases whereas values for untreated chicken feathers showed noticeably higher dispersions due to inhomogeneity of the sample. On the contrary, there were no significant differences in densities of the treatment samples, irrespective of the treatment method used (Figure 3.1.13). The density of chicken feathers was lower than 1 g/cm^3 with the exception of the untreated and autoclaved sample. This value is a lower value than the density of cellulosic and other protein fibres such as wool. Generally, the density values for chicken feathers were in agreement with those reported in the literature (0.8-0.89 g/cm^3) (Pourjavaheri et al., 2014).

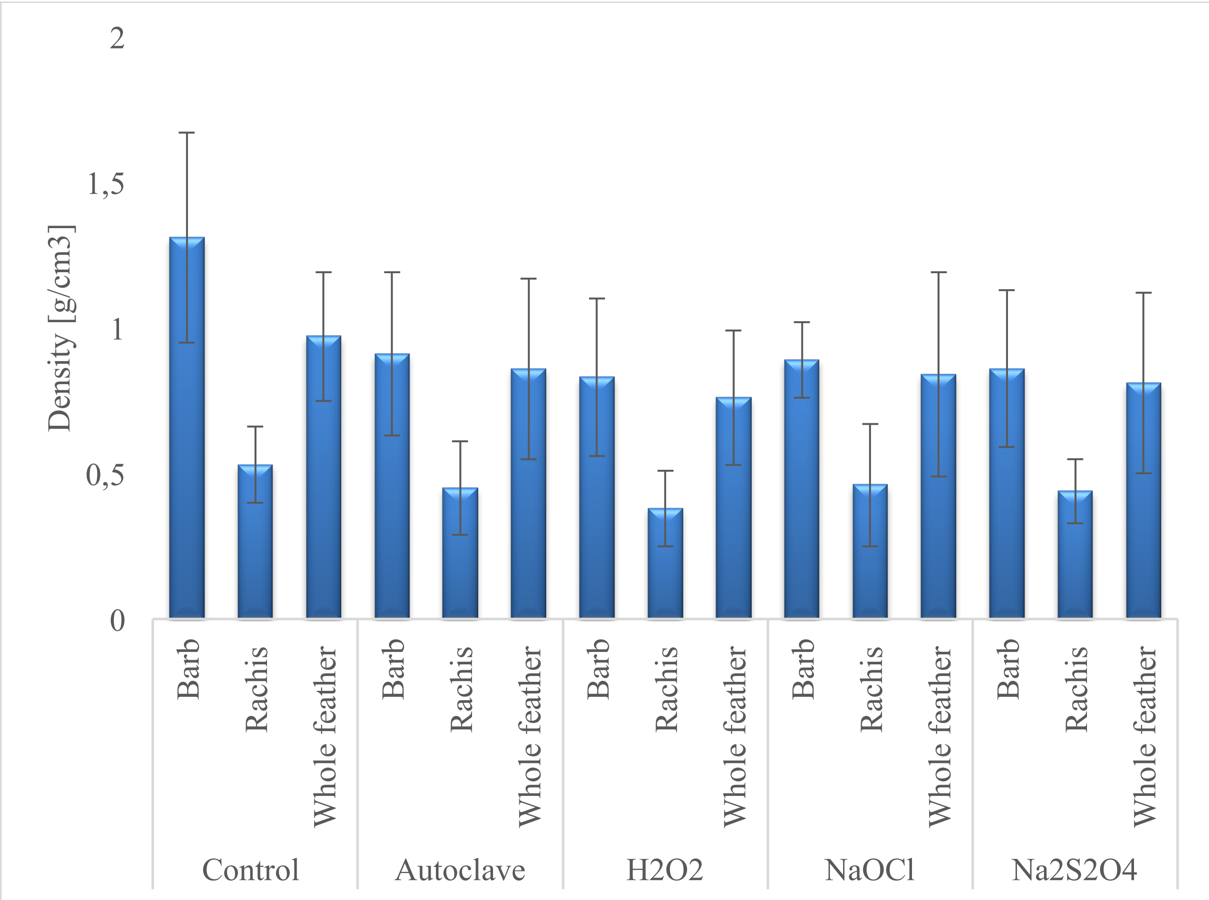

Figure 3.1.13. Density measurement for untreated and treated chicken feathers

The effect of bleaching on mechanical properties of feathers: - Since chemical treatments and bacteria, such as aerobic, anaerobic and enteric bacteria, could adversely affect the mechanical properties of untreated chicken feathers, their mechanical properties were evaluated after implementing bleaching. The mechanical properties of feather barbs for all samples studied are presented in Figure 3.1.14. The data indicate that the modulus of rupture exhibits the same pattern as the modulus of elasticity (except control samples) but does not show any significant variation when the level of treatment increased. This may be due to the chemical reaction of the chicken feather structure. Chicken feathers suffer reversible tensile strength loss when wet (Wang et al., 2003). This could be due to hydrogen bonds that are dissociated in aqueous conditions resulting in reduction of disulphide bonds in the feathers. In aqueous media, protein chains can be ionised and attract charged molecules – hence chicken feathers are susceptible to chemical damage (strong alkali and strong acids) in aqueous media (Tesfaye et al., 2017). The results revealed that, in all chemical treatments, decontamination of feathers with bleaching agents results in minimal fibre damage. This suggests that treated feathers can withstand more mechanical strain than untreated ones thus delaying mechanical failure of materials made from them. Consequently, chicken feather barbs could potentially be used as materials for reinforcement in natural fibre composites.

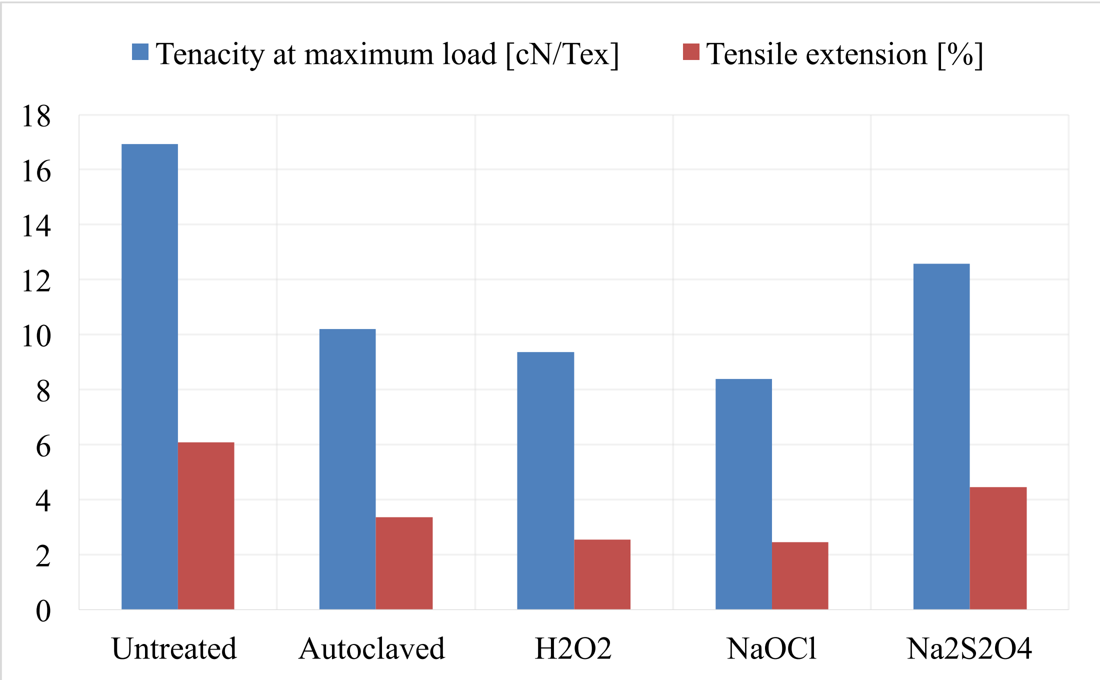

Figure 3.1.14. Tensile properties of treated and untreated chicken feathers

Figure 3.1.15 shows the DMA results of untreated chicken feather barbs (CF1), H_2O_2 treated feather barbs (CF2) and $Na_2S_2O_4$ treated feather barbs (CF3) heated from 20 to 150 °C at a heating rate of 2 °C min^{-1}, and at a frequency of 1 Hz. Chicken feather barbs are composed of β-keratin which is extremely insoluble in water and organic solvents. The β-keratin is made up of protein strands hydrogen-bonded into β-sheets, that are twisted and crosslinked by disulphide bridges giving strength and stiffness to the protein structure (Ullah et al., 2011; Zhan and Wool, 2011). From Figure 3.1.15a, the storage modulus for all chicken feather samples gradually decreases with increasing temperatures, but the modulus did not drastically decrease within the measured temperatures. This implies that the stiffness of the fibre was not significantly reduced along the measured temperatures owing to the crosslinked network of disulphide bridges within the fibre structure.

The decrease in stiffness observed at high temperatures may be attributed to the degradation of the fibres as a result of increased temperatures. It is known that at elevated temperatures, molecular segments become readily mobile and have no difficulty resonating with the load (Zhan and Wool, 2011). Therefore, the entanglements more or less remain firmly in place, but may occasionally slip and become disentangled. This can be observed from high tan delta peaks of CF2 and CF3 that signify disentanglement of molecular chains in the barbs (Figure 3.1.15c). The untreated feathers CF1 show higher storage and loss modulus than CF2 and CF3 feather barbs (Figure 3.1.15a and b). This suggests that the chemical treatments applied on the CF2 and CF3 might have dissolved some of the crosslinked network of the protein structure, especially for bleached (H_2O_2) CF2 feather barbs.

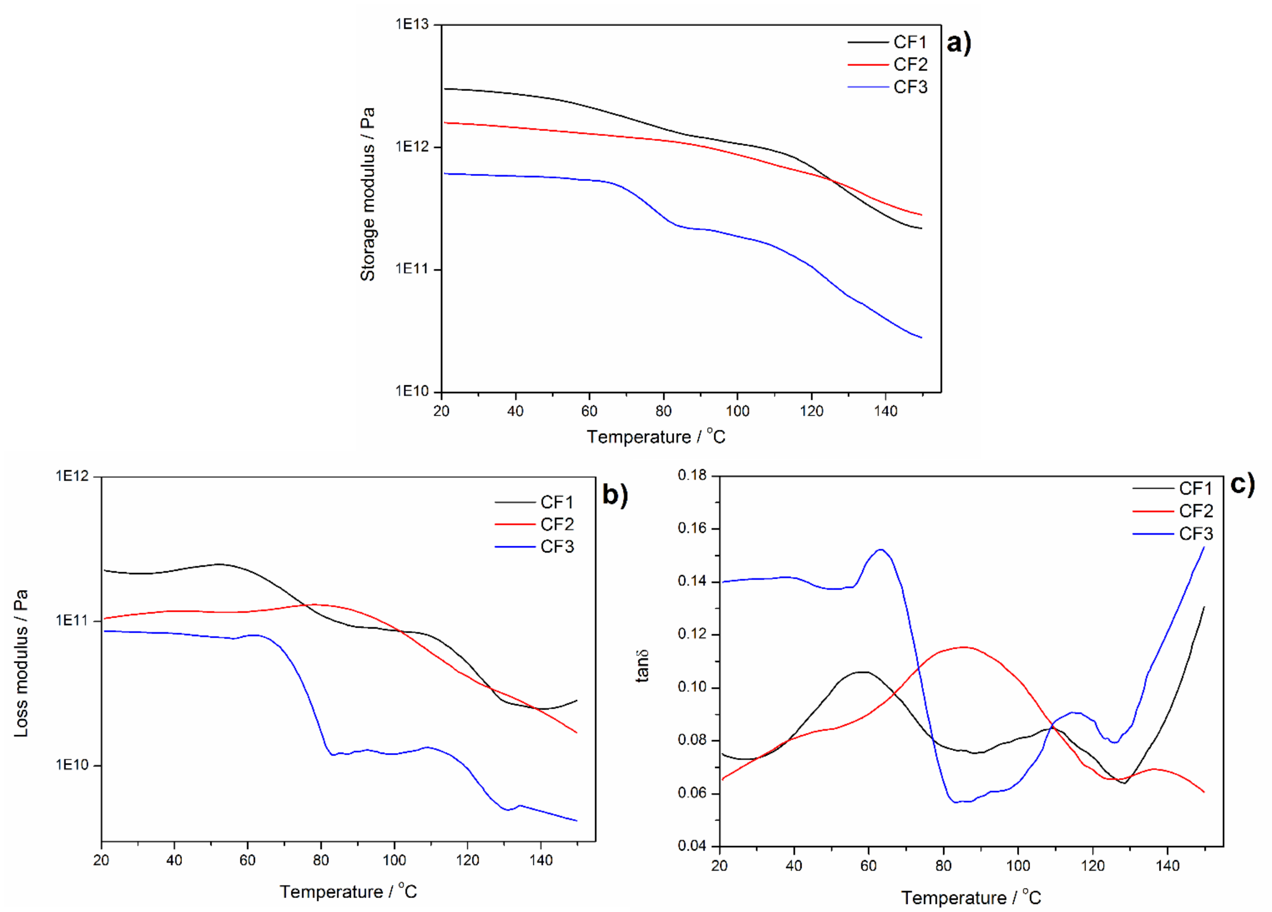

Figure 3.1.15. DMA analysis (a) storage modulus, (b) loss modulus and (c) tan delta of chicken feather barbs

The effect of bleaching on SEM/EDX data: - The morphology and elemental profile composition of the feathers were studied by SEM/EDX in order to ascertain if the decontamination and pre-treatment procedures had induced any effects on the feathers. The SEM images of untreated chicken feathers in Figure 3.1.16 show that a lot of natural dust particles and waxy substances were bound to the feather surfaces. Most of the surface contaminants on the chicken feathers could be easily removed after bleaching. The images on Figures 3.1.16 reveal that the bleaching agents used washed the chicken feathers cleanly, leaving them free from dust with their naturally smooth surfaces. This is probably due to the removal of dirt and lipid layer that coated the chicken feather as a result of the bleaching action. The bulk of the decontaminated and pre-treated chicken feather became white and fluffy. The tangled and curled chicken feathers started to unfurl after decontamination and pre-treatment. Feather whiteness and unfolding of the barb from the rachis increased as the number of pre-treatment stages increased. The autoclave treated samples remain folded due to lipid residues whereas the untreated chicken feathers had an abundant amount of contaminants, lipids, and closely linked barbules on the surface. These observations are similar to those reported for pre-treatment of alpaca fibres (Wang et al., 2003).

All bleaching treatments show a good level of contaminant removal. However, Figure 3.1.16 shows that there was cracking on the surface of the feathers. The feather microstructure was not damaged after bleaching and barbules remained intact. Figure 3.1.16 shows that hydrogen peroxide was very effective at removing oil, dirt, and stains. The $Na_2S_2O_4$ was the next most effective inorganic treatment. The treated chicken feathers exhibited a hard texture whereas the autoclave treated feathers had the same appearance and texture as the untreated feathers. However, the rachis of the chicken feathers became softer in the bleaching solutions and made them more brittle. The level of feather entanglement and fibre length are important factors if the feather fractions are to be used for textile applications.

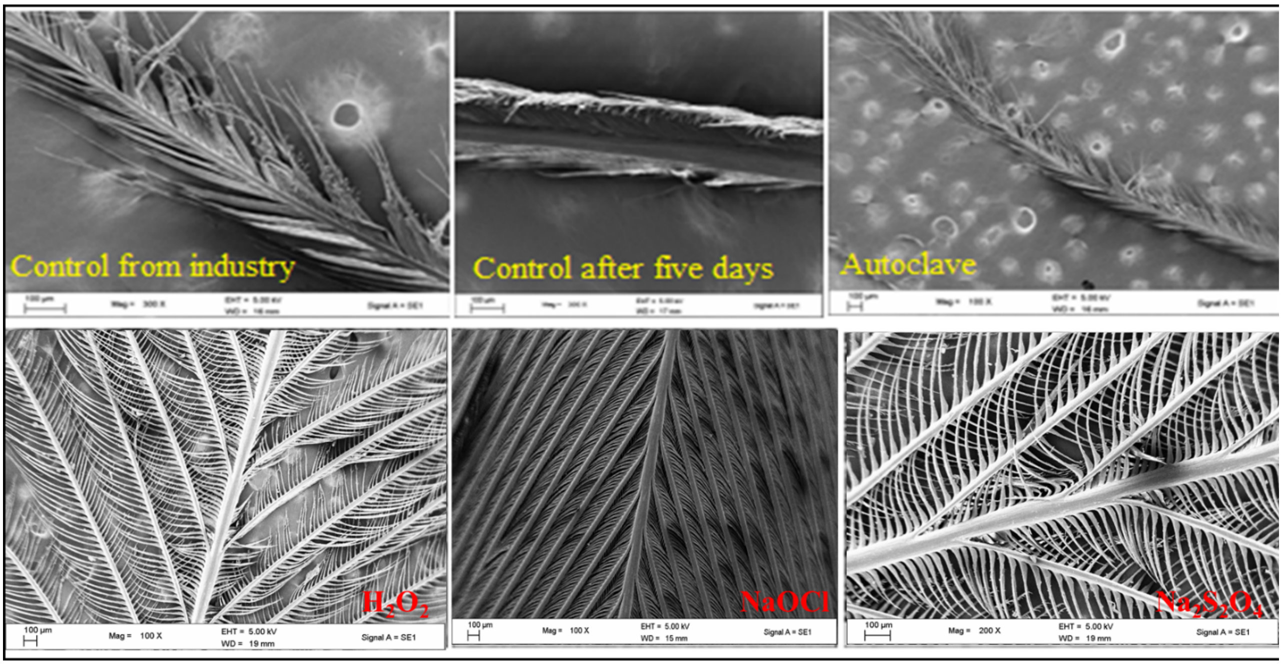

Figure 3.1.16. The SEM structure of treated and untreated chicken feathers

Figure 3.1.17 shows SEM-EDX images and elemental profiles of the samples. The relative proportions of the sulphur element decreased whereas the carbon content increased in all the treated samples. This may be due to the removal of dirt and contamination (blood, skin and other dirt) from the surface of the chicken feathers.

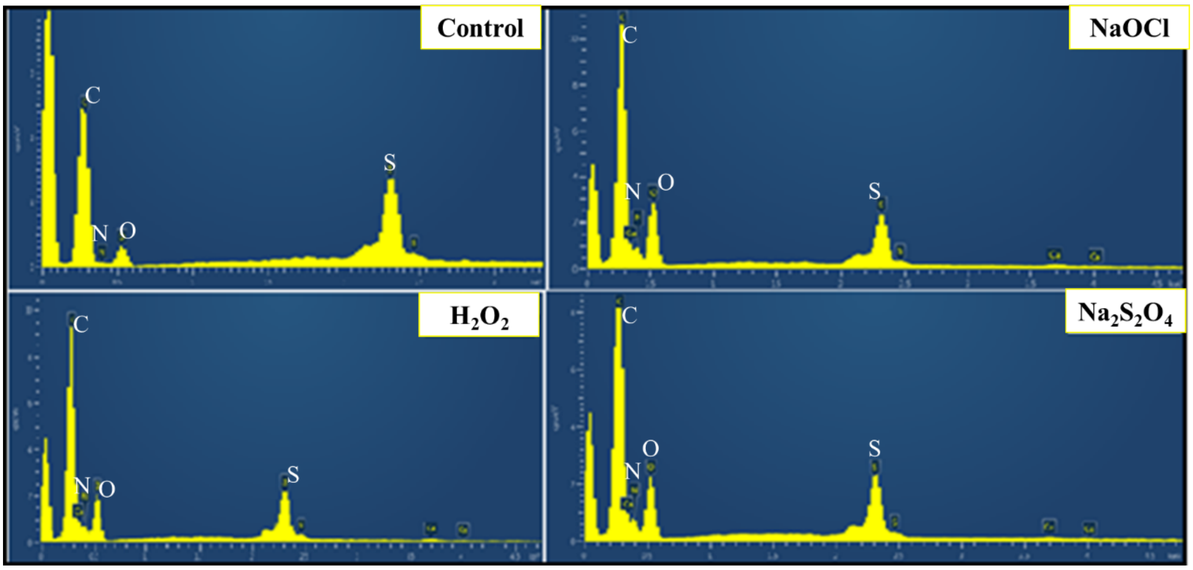

Figure 3.1.17. SEM-EDX images and elemental profiles from treated and untreated chicken feathers

Carbon, hydrogen, nitrogen, and sulphur data of the untreated, as well as treated chicken feather, were measured and the data are summarised in Figure 3.1.18. There were significant differences in the data among the samples. This is in agreement with the elemental analysis shown in Figure 3.1.17.

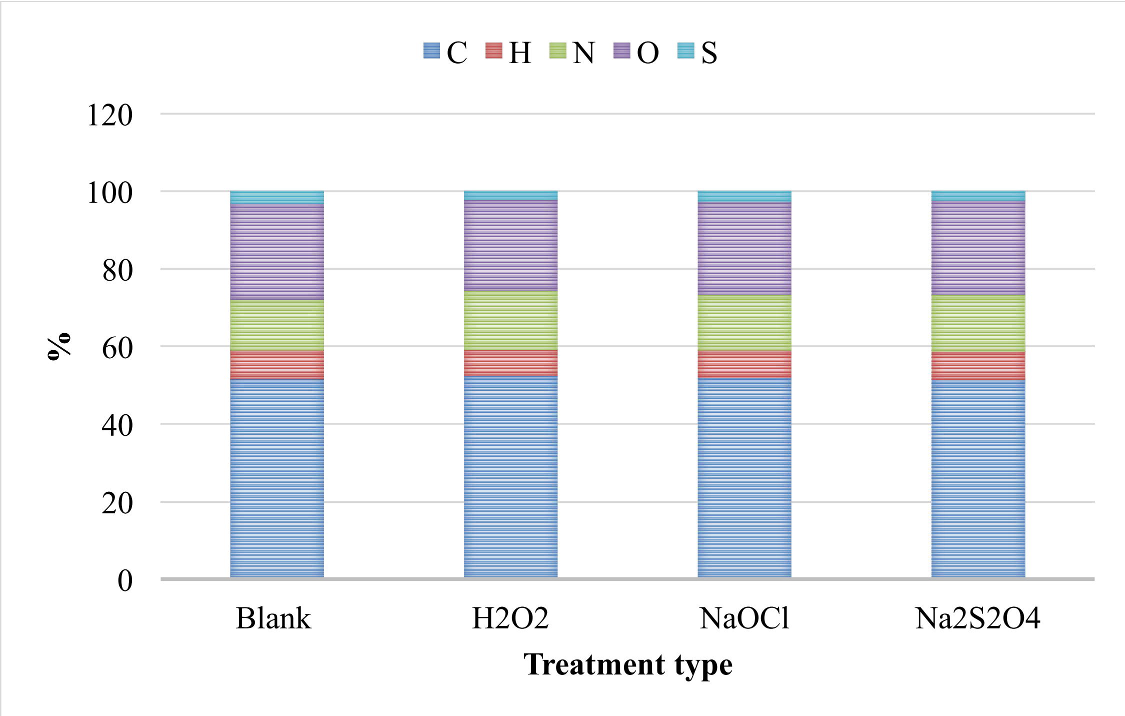

Figure 3.1.18. Elemental analysis of untreated and treated chicken feathers

The effect of bleaching on thermogravimetric analysis: - The effect bleaching on the thermal behaviour of waste chicken feathers was studied by TGA/DSC under nitrogen flow in the temperature range of 25-550 ^{o}C (Figure 3.1.19). Although the mass loss profiles for treated and untreated chicken feathers were very similar a closer examination of the derivative diagram shows significant differences in the profiles (Figure 3.1.19). The first mass loss observed in the temperature range of 25–235 °C can be attributed to water vaporisation heat in the chicken feather. The second and third stage weight losses (around 235–350 °C and 350–550 °C respectively) are related to denaturation of chicken feathers. The complete degradation of the chicken feather carbonic chain takes places in the temperature range of 350–550 °C (Figure 3.1.19A). Figure 3.1.19 A shows rapid decomposition in the temperature range between 235–550 °C.

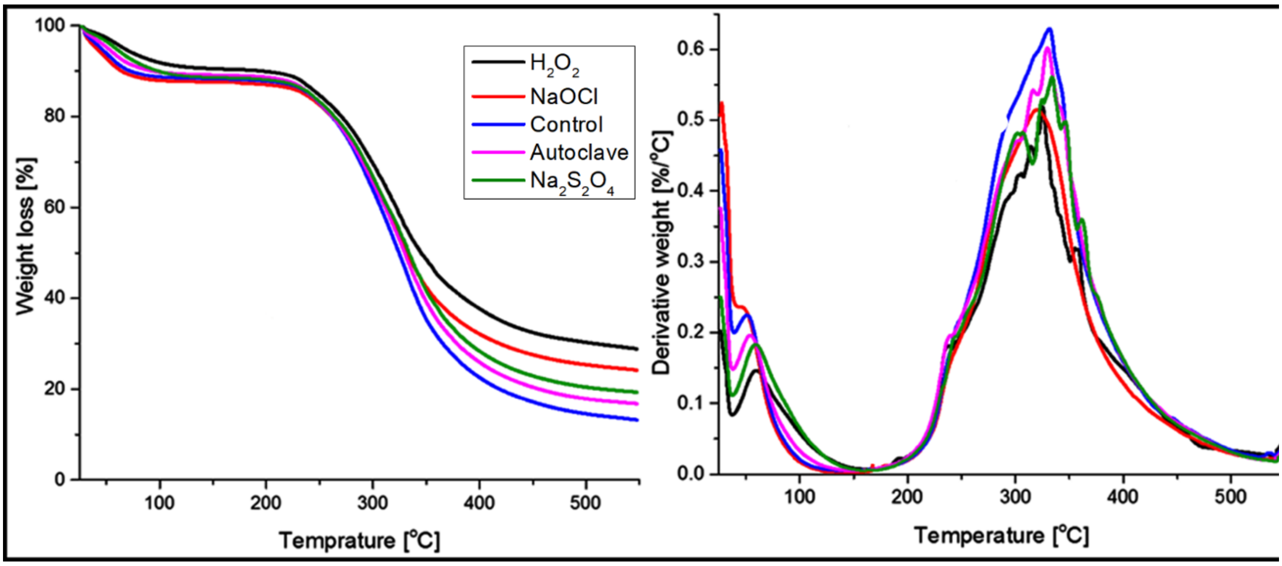

Figure 3.1.19. Thermogravimetric (A) and derivative curves (B) for treated and untreated chicken feathers

The DSC curves in Figure 3.1.19B indicate an endothermic peak near 70 °C, which is attributed to the removal of moisture when the chicken feather was heated, whereas the exothermic peak between 290-350 °C was attributed to protein denaturation. In Figure 3.1.19B the denaturation temperature increases after bleaching. Chemical treatments of chicken feathers promote stability of the feather structure and shift the denaturation temperatures higher by increasing the ionic interactions (Monteiro et al., 2005). Disinfecting and pre-treatment of chicken feathers show a large degradation of the cystine disulphide bonds inside and between the chains (Pourjavaheri et al., 2014; Wortmann et al., 2006), and therefore the treated feathers exhibit higher denaturation temperatures than the control chicken feather samples. It is apparent that more energy is spent to disorganise the structure of untreated chicken feathers than in the treated chicken feathers. This is supported by the observed increase of the denaturation temperature and the decrease in the denaturation enthalpy of chicken feathers (Monteiro et al., 2005) (Figure 3.1.19B).

3.1.4. Conclusions

Chicken feathers are hazardous wastes due to contamination with microbiological organisms. The feathers can be beneficiated into high value products to avoid their disposal by landfilling or by incineration. The beneficiation requires decontamination of the feathers to eliminate the microbial contamination. This study is a comparative analysis of using bleaching agents for decontamination of waste chicken feathers. The results showed that bleaching agents were effective in decontamination of chicken feathers and the order of efficacy followed the order H_2O_2 > NaOCl > $Na_2S_2O_4$. The bleaching agents were also effective in removing grease and impurity content and favourably influenced the physicochemical and mechanical properties of the chicken feathers.

ACKNOWLEDGMENTS

The authors are highly grateful for the financial and technical support received from: the Institute of Technology for Textile and Fashion Design/EiTEX at Bahir Dar University, Ethiopia; the Thermodynamics Research Unit at the Discipline of Chemical Engineering, University of KwaZulu-Natal; the Biorefinery Industry Development Facility, Council for Scientific and Industrial Research (CSIR), and the Department of Science and Technology, Waste Research Development and Innovation Roadmap.

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3.2. OPTIMISATION OF SURFACTANT DECONTAMINATION AND PRE-TREATMENT OF WASTE CHICKEN FEATHERS BY USING RESPONSE SURFACE METHODOLOGY

(BASED ON PAPER TWO)

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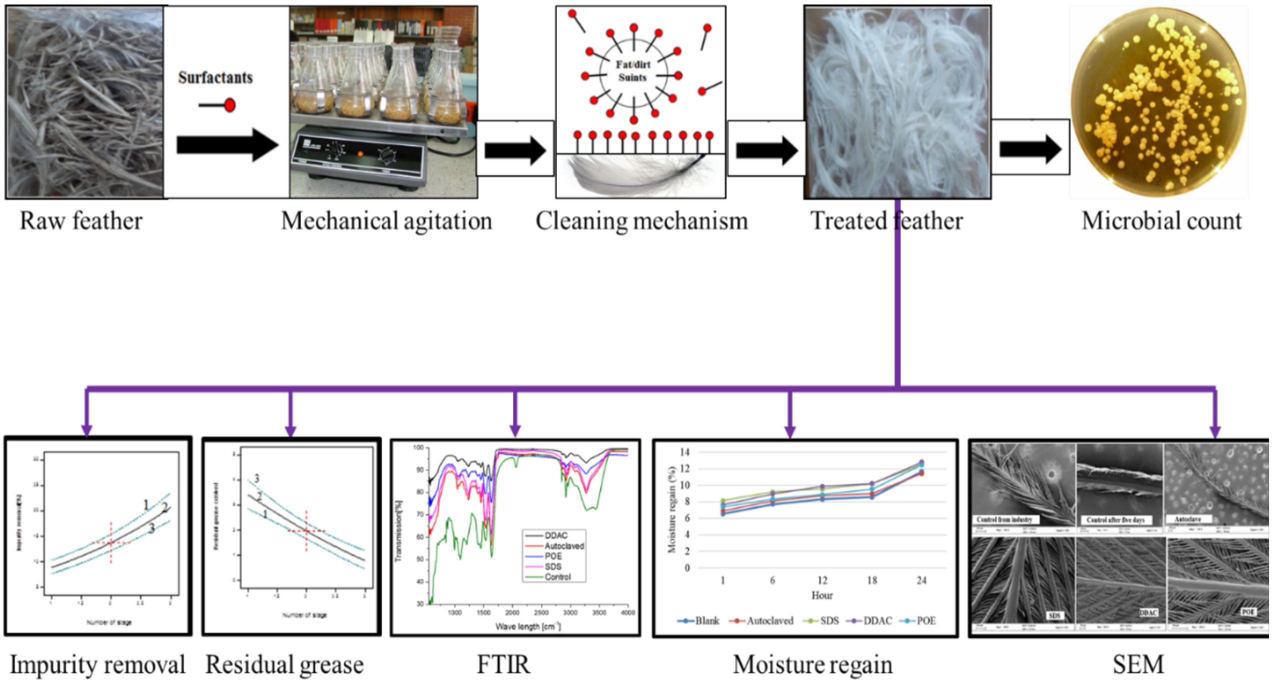
ABSTRACT

Commercially processed, untreated chicken feathers are biologically hazardous due to the presence of blood-borne pathogens. Prior to valorisation, it is crucial that they are decontaminated to remove the microbial contamination. The present study focuses on evaluating the best technologies to decontaminate and pre-treat chicken feathers in order to make them suitable for valorisation. Waste chicken feathers were washed with three surfactants (sodium dodecyl sulphate) dimethyl dioctadecyl ammonium chloride, and polyoxyethylene (40) stearate) using statistically designed experiments. Process conditions were optimised using response surface methodology with a Box-Behnken experimental design. The data were compared with decontamination using an autoclave. Under optimised conditions, the microbial counts of the decontaminated and pre-treated chicken feathers were significantly reduced making them safe for handling and use for valorisation applications.

Keywords: - *microbial count, chicken feather, grease content, whiteness, surfactant*

Graphical abstract



3.2.1. Introduction

With the development of large-scale poultry farming, the disposal of large amounts of waste chicken feathers is a long-standing problem. On a world scale, it is estimated that approximately $40x10^9$ kg of chicken feathers are produced from the slaughter of more than $58x10^9$ chickens (Compassion in world farming, 2013). In 2013, the South African poultry farming activity generated more than $528x10^6$ kg of feathers (DAFF, 2014). Chicken feathers constitute 5-10 % of the weight of the chicken and comprise a significant portion of the poultry wastes (Tseng, 2011; Pourjavaheri et al., 2014). Poultry waste is divided into solid waste (feathers, viscera, heads, feet, carcases, skin and bones), and liquid waste (blood and liquid effluents) (EL Boushy et al., 2000). The disposal of this waste gives rise to environmental and health concerns, and are guided by legal requirements and contemporary best practices, such as the Zero Waste Initiative in South Africa (Karani and Jewasikiewitz, 2007). Common disposal techniques such as incineration, landfilling and composting are not environmentally sustainable in that they are energy intensive, and/or take up valuable landfill space, as well as contribute to the emission of greenhouse gases (Sudalaiyandi, 2012; Coward et al., 2006; Tseng, 2011; Pourjavaheri et al., 2014). Hence valorisation of chicken feathers by conversion into valuable materials is a desirable route for dealing with the waste. For example, it has been reported that waste chicken feathers can potentially be converted into high value materials and products such as automotive products (side trims, door inner panels and body panels), medical products (drug delivery carriers, scaffolding and tissue engineering), cosmetics (for skin and hair), bioplastics, paper additives, nonwoven textiles, superabsorbent materials, biodiesel, energy storage, electrical insulators, and composites for use as reinforcements in construction and furniture industries (Tesfaye et al., 2017).

It has also been reported that chicken feathers can be used in preparation of microbial peptones (Taskin and Kurbanoglu, 2011), protein hydrolysates for use as a nutritional substrate for microbial production of valuable substances, such as carotenoid (Taskin et al., 2011), polysaccharide (Taskin et al., 2012), glutathion (Taskin 2013), and lactic acid (Taskin et al., 2013). Other studies have demonstrated that waste feathers could be used as plant fertilizer (Paul et al., 2013; Jie et al., 2008; Hadas and Kautsky, 1994) and low-grade animal feed (Davis et al., 1961; El-Boushy et al., 1990; Grazziotin, 2006) immobilization supports for enzymes or chemicals (Chauhan et al., 2016), in paper production (Tesfaye et al., 2017 (a, c)), for biogas production (Patinvoh et al., 2016), and for preparation of carbon nanotubes (Gao et al., 2014).

As mentioned in the preceding paragraphs, waste chicken feathers are biological waste that is loaded with microbial contamination from bacteria in the intestinal tracts of the harvested chickens. Consequently, disinfection of waste feathers is an important prerequisite for valorisation of this waste biomass. Mesophilic or psychotropic organisms can grow on all parts of chicken feathers considering that chickens are warm-blooded mammals (Richard, 2010). In poultry processing plants, feathers are plucked from the chickens and they generally lie in heaps, containing smaller amounts of various foreign materials such as offal, dilute blood, biological organisms, grease, skin, faeces, flesh, and water. Due to the contamination with blood, intestinal contents, offal fat, fatty acids, debris and preen oil fresh chicken feathers can be a suitable habitat for many microorganisms (Cunningham, 2012; Gill, 1998). In general, as a by-product of poultry processing, unprocessed raw feathers appear straw-like (the barbs get stuck to the rachis); they have a greasy texture, a brown colour, and are spattered with blood, emitting an obnoxious odour (Tesfaye et al., 2017 (a, b).

There are a variety of reasons for the appearance and texture of plucked feathers. A preen gland secretes lipids to uphold the feather's properties (e.g., waterproofing), giving rise to the greasy texture (Jones, 2005). Free fatty acids from lipid decomposition and pigment cells, called melanocytes, are responsible for microbial growth and the dull yellow colour of feathers after slaughter. The growth of microorganisms on chicken feathers will cause them to decompose and could impart potentially fatal biological hazards for humans. Table 3.2.1 shows bacterial control points in a typical waste chicken feather biomass. It is evident that chicken feathers contain different types of hazardous microorganisms and the major ones are enterococci, coliforms, and sulphate reducing bacteria. Indeed, chicken feathers contain the highest total microbial counts (69,457 Cfu/cm^2/cm^3) (Table 3.2.1) compared to other control points in poultry slaughtering industries. Consequently, waste chicken feathers need to be adequately disinfected before handling and processing for valorisation purposes. Since the objective is to valorise feathers, it is important to develop technologies for decontamination and pre-treatment of chicken feathers that will render the feathers safe for handling but without negatively impacting the composition and structure of the feathers.

Table 3.2.1. Bacterial contamination control points in the poultry industry (adapted from Jones, 2005)

Control points	**Total viable counts (Cfu/cm^2/cm^3)**	**Enterococci (cfu/cm^2/cm^3)**	**Coliforms bacteria (Cfu/cm^2/cm^3)**	**Sulphate reducing bacteria (Cfu/cm^2/cm^3)**
Feathers	69457.0	184.5	0.9	179.1
Bleeding knife	7269.0	227.0	19.6	8.4
Scalding water	6421.0	5.3	0.9	55.2
Pluckers' rubber finger	2362.5	73.1	1.6	21.6
Carcass surface	6984.0	197.1	15.3	4.8
Plucking finishing table	55444.0	793.35	1483.6	225.0

Cfu= colony forming units

Chicken feathers could be a fatal hazard for humans if they are not processed or disposed of properly. Technologies need to be developed and customised for commercial pre-treatment and decontamination of feathers to a standard that is appropriate for their further use. Most importantly, raw chicken feathers require decontamination and pre-treatment to remove pathogens and impurities that cause objectionable odours, discoloration and to ensure process hygiene. Technologies for cleaning feathers can be adapted from those used for decontamination and pre-treatment of natural fibres used in the textile industry, e.g., washing with organic or inorganic solvents, or washing with surfactants (Augurt and Van Asten, 2000; Falbe, 2012; Sudalaiyandi, 2012; Tseng, 2011; Pourjavaheri et al., 2014). Decontamination is the removal or reduction of microbial count whereas pre-treatment refers to cleaning activities mainly for the removal of grease, fat, sand etc. Cleaning of contaminants from the feather material can be done by dissolution of the contaminants in suitable solvents, mechanical detachment, evaporation, and chemical treatment.

In this study, decontamination by washing with surfactants was selected and the efficacies of the procedures were compared with decontamination by high heat using an autoclave unit. The efficacy of the decontamination was evaluated by monitoring the microbial content of the treated and untreated samples as well as by monitoring grease content of the samples. The use of surfactants for decontamination was selected as this would be more cost effective than using high energy intensive autoclaving technology. Surfactants are commonly used in decontamination and pre-treatment of materials; they are surface-active detergents that provide remarkable benefits in dispersing, chemical or dye absorption, heat transfer, wetting, softening, emulsification, dye fixation, melting, vaporisation, sublimation, foaming and defoaming in the textile industry (EL Boushy et al., 2000; Pletnev and Michael, 2001). The surface activity and disinfecting/bactericidal performance of a surfactant is dependent on various factors such as concentration, pH, solid to liquid ratio, the number of treatment cycles, temperature, and contact time (Mandavi et al., 2008). Their bactericidal activity has not been extensively investigated, but it is claimed that they do have strong bactericidal activity (Pletnev and Michael, 2001; Tadros, 2006).

3.2.2. Materials and methods

3.2.2.1. Materials

Waste chicken feathers were supplied by a slaughterhouse in the province of KwaZulu-Natal, South Africa. The surfactants evaluated for use as combined pre-treatment and decontamination agents were: sodium dodecyl sulphate (SDS) – (anionic surfactant); dimethyl dioctadecyl ammonium chloride (DDAC) – (cationic surfactant); and polyoxyethylene (40) stearate (POE) – (non-ionic surfactant), and all were obtained from Sigma–Aldrich. Hexane (Sigma–Aldrich) was used for grease content analysis. Peptone (Merck) and yeast extract agar (Merck) were used for the bacteriological analyses.

3.2.2.2. Decontamination and pre-treatment

Pre-treatment was done by removal of materials that were not feathers: these included offal, dilute blood, grease, sand, faeces, and waste water. Decontamination was done to remove blood borne pathogens during slaughtering and microorganisms present in chickens. In this study the materials and contaminants were removed by one pot treatment using various surfactants.

Sampling: - The act of obtaining samples from a bulk system is subject to errors that can neither be detected not compensated due to the bulk system being non- homogeneous and the sample therefore possibly not being exactly representative. Since waste chicken feathers fall under this category, maximum representative samples were prepared by placing raw feathers in a mixing vessel and thoroughly mixed to form an aggregate sample from which the final sample was obtained using the sample division system.

Decontamination and pre-treatment procedures: - Statistically designed experiments on decontamination and pre-treatment of waste feathers were used to ascertain optimum conditions for decontamination and pre-treatment of waste feathers. For factor screening analysis, 5 g raw chicken feathers were processed by Soxhlet extraction under different conditions that were: surfactant concentrations, contact time, temperature, number of stages, feather to liquid ratio, pH, and stirring speed as listed in Table 3.2.2. After screening the most significant factors using a Plackett-Burman design, the optimisation process was carried out using a Box-Behnken design (Table 3.2.3). For the optimisation process the following combinations were used; surfactant concentrations (0.15-1.00 % w/v), number of stages, (1-3), time (5-60 min), and temperature (25-100 ^{o}C). After decontamination and pre-treatment, the liquid was filtered using a 0.5 mm mesh filter and the treated chicken feathers were rinsed with tap water until the washing solution was free of surfactants (no foaming). The treated chicken feathers were laid on aluminium foils and dried to constant mass at 70 ^{o}C in an air-forced dryer after which they were stored in sealed plastic bags, in a controlled laboratory environment (20 °C, 65% relative humidity) for further characterisation (Figure 3.2.1). In addition to these methods, the chicken feathers were decontaminated by autoclaved in a sterilisation process (vertical type steam steriliser, HL-340, Already Enterprise Inc. Taipei, Taiwan) with saturated steam at 132 ^{o}C for 20 minutes at 4 kg/cm^2. This was used as a comparison with the raw and treated chicken feathers.

3.2.2.3. Determination of microbial content

Treated, untreated, and autoclaved chicken feather samples were conditioned to ambient temperature for 1 hour prior to testing for microbial content using standard methods (Pourjavaheri et al., 2015). A 0.1 g sample was mixed with 9.9 ml of sterile peptone water (8.5 g NaCl and l g peptone (Merck) per litre) to restore microbial cells to enable a good estimate of microbial counts. The sample was then shaken at 120 rpm for 30 minutes to ensure proper mixing and homogenisation. 1.0 ml of the homogenised mixture was pour plated onto yeast agar (Merck) and incubated at 30 ^{o}C for 24-48 hours, after which the microbial colonies were counted on a digital plate reader. A schematic of the process is summarised in Figure 3.2.2.

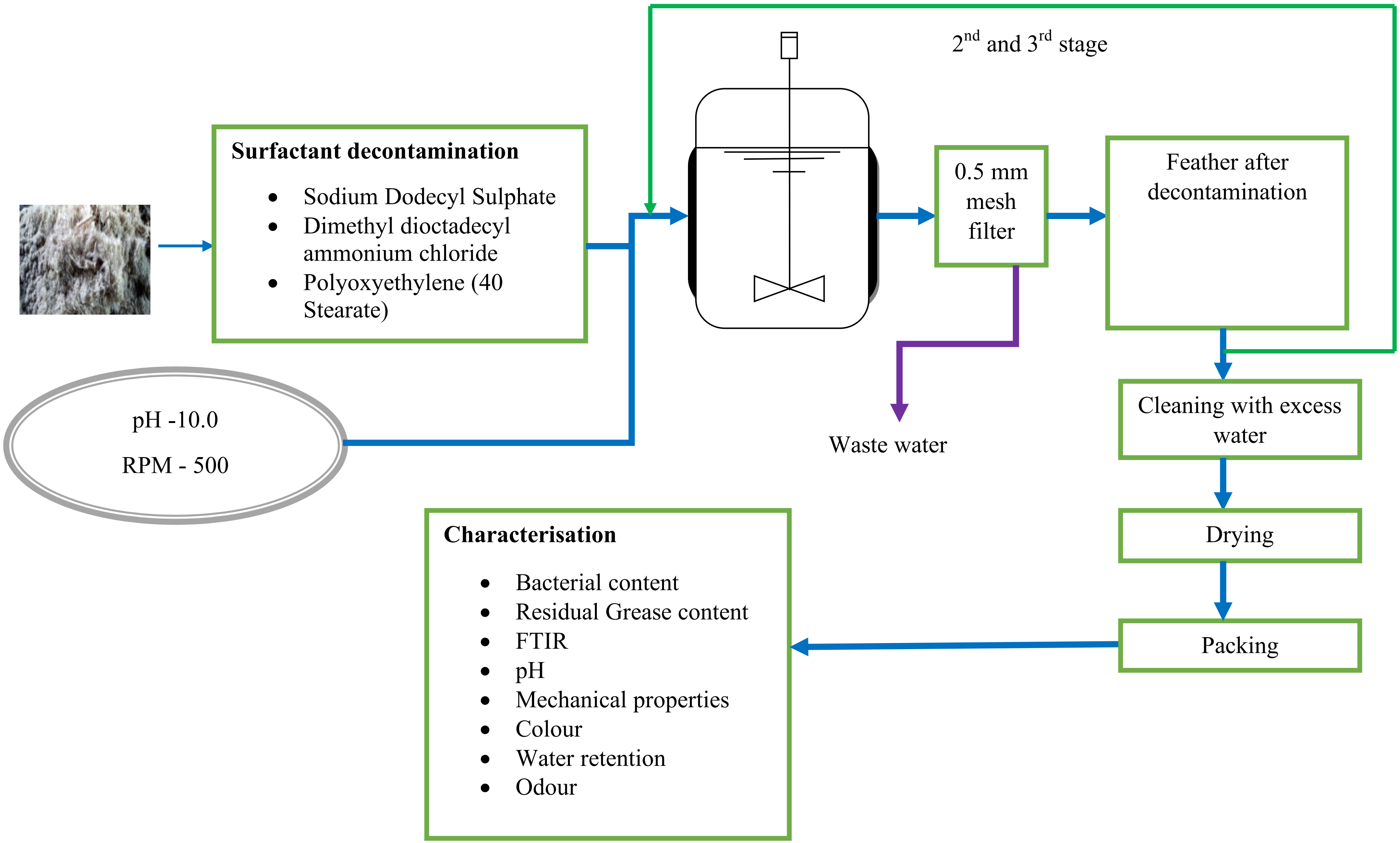


Figure 3.2.1. Decontamination and pre-treatment block diagram

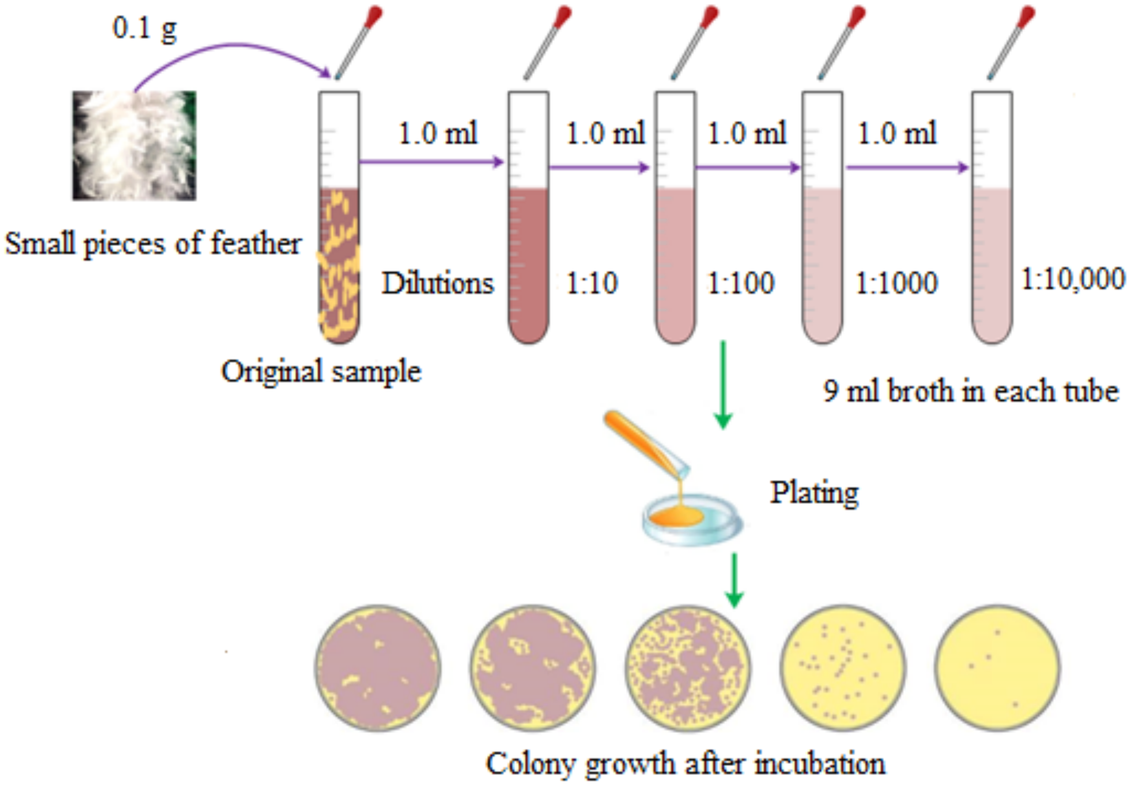


Figure 3.2.2. Pour plate technique for microbial test on treated and untreated chicken feathers

3.2.2.4. The effect of decontamination and pre-treatment on physicochemical and mechanical properties of chicken feathers

Removal of impurities

Impurity removal is a measure of mass lost from the raw chicken feather during pre-treatment and decontamination, represented as a percentage of the weight loss and calculated using Equation 1:

$$Impurity\ removal\ (\%) = \frac{M_1 - M_2}{M1} * 100 \qquad [1]$$

where M_1 is a dry raw chicken feather and M_2 is a dry decontaminated and pretreated feather in grams.

Residual grease content

Residual grease is the grease content of chicken feathers after pre-treatment and decontamination. The residual grease content of treated chicken feather was determined by extracting the washed samples with hexane using a Soxhlet apparatus according to ASTM D1574 (ASTM D1574, 2013). Three replicate samples were measured for each of the decontaminating and pre-treatment techniques.

Fourier transform infrared (FTIR) spectroscopy

FTIR spectroscopy (Frontier Universal ATR-FTIR, from PerkinElmer) was used to ascertain if the decontamination and pre-treatment procedures affected the functional groups of the feathers. A universal attenuated total reflectance (ATR) module was used for all spectra in a wave number range between 400 cm^{-1} and 4000 cm^{-1}.

Whiteness and yellowness indices

The pre-treated and decontaminated feathers were monitored for their colour using a spectrocolorimeter, which was standardised with Hunter lab colour standards. The colour of the chicken feathers in terms of L*, a*, and b* values were measured with a Hunter lab Colorimeter (Greta Macbeth Colour Eye 3100). The whiteness value was obtained according to equation 2:

$$\text{Whiteness } \% = 100 - [(100 - L)^2 + a^2 \ + b^2]^{\frac{1}{2}} \qquad [2]$$

Fibre density: The density of the chicken feather fractions was measured using a liquid pycnometer (Rude et al., 2000). Five replicates were performed for each sample type.

Water retention and moisture regain

Decontaminated and untreated chicken feather samples were dried at 105 ^{o}C for over 4 hours and weighed (W_1) before soaking in distilled water at different temperatures for 5 min. The wet chicken feathers were removed and centrifuged for 5 min at 9000 rpm and weighed again (W_2). Water retention (%) was calculated according to equation 3 and the average of three tests was taken:

$$Water\ retention\ (\%) = \frac{W_2 - W_1}{W_1} * 100 \qquad [3]$$

Morphological and elemental profile analysis

The impact of the decontamination and pre-treatment techniques on the morphology and elemental composition of the feathers was investigated using low-resolution scanning electron microscopy and energy dispersive spectroscopy (EDS). Chicken feathers from experiments that showed superior bactericidal efficacy were further analysed using high-resolution scanning electron microscope (SEM) analysis as well as elemental profile analysis using energy dispersive spectroscopy (EDX) using a Field Emission Gun Scanning Electron Microscope with EDX capability (Carl Zeiss, Oberkochen, Germany).

Mechanical properties

The feather samples were dried and conditioned at a relative humidity of 65 ± 2 % and a temperature of 22 ± 2 ºC and then used to measure their bundle strength tenacity, length, and single feather strength. The feathers were carefully combed with a fine comb, and then 11.8 mm long feathers were prepared. The bundle tensile test was carried out on an Instron Tensile Tester (Model 3345) at 0 mm gauge length.

Thermogravimetric analysis

The thermal properties of untreated and treated samples were measured using a Perkin-Elmer TGA thermogravimetric analyser, under temperatures that ranged between 25 °C and 550 °C, at a heating rate of 20 °C min^{-1} under nitrogen gas purge.

3.2.2.5. Statistical optimisation

The conventional method of experimental design, i.e., changing one factor at a time, is laborious and often ignores the interactive effects of each independent variable (Montgomery, 2008). With this in mind, a Plackett-Burman factorial, design-and-response was used wherein the surface methodology was used for screening and optimisation of the parameters under study. The objective was to evaluate various surfactant pre-treatment and decontamination strategies to purify chicken feathers prior to valorisation. The resultant data can be used to target decontamination applications and to develop financial analysis informed by an understanding of necessary processing costs and potential financial benefits. The heterogeneous properties of chicken feather had to be considered in all decontamination and characterisation processes.

Screening using Plackett-Burman factorial design

A selection of major factors required for the minimum microbial count was performed using a Plackett-Burman design. The effects of seven factors, namely surfactant concentration, the number of treatment stages, time, temperature, pH, feather to liquid ratio, and stirring speed, were investigated at two levels (minimum and maximum). Statistica 13.2 and JMP 13.0 software (Stat-Ease, Minneapolis, USA) were used to generate 12 sets of the experiments (Table 3.2.2). The effect of each factor on microbial count was determined using the calculated p-value of each factor.

Table 3.2.2. Placket-Burman design for screening the significant factors

Run	Variables							Response
	Concentration of surfactant, %w/v	Temperature, ^{o}C	Time, min	Feather to liquid ratio	Number of stage	pH	Stirring speed, RPM	Bacteria content, Cfu/g
1	0.15	100	5	1:50	1	3	500	988
2	0.15	100	5	1:50	3	10	0	597
3	0.15	25	5	1:10	1	3	0	1097
4	1	25	5	1:50	1	10	0	507
5	0.15	25	60	1:10	1	10	500	684
6	1	100	60	1:10	1	10	0	338
7	1	25	60	1:50	1	10	0	449
8	1	100	60	1:50	3	10	500	0
9	1	100	5	1:10	3	10	500	97.3
10	1	25	5	1:10	1	3	500	367
11	0.15	25	60	1:50	3	10	500	233
12	0.15	100	60	1:10	3	3	0	127

Optimisation using response surface methodology (RSM)

The four major factors and their interactions selected by the Plackett-Burman design were analysed and optimised by means of a Box-Behnken design. A Box-Behnken design with four factors (surfactant concentration (0.15-1 % w/v), the number of treatment stages (1–3), treatment time (1-60 min), and temperature (25-100 ^{o}C) with a total number of 27 experimental runs was employed for each type of pre-treatment and decontaminating agent. The coded values of the variables at various levels are given in Table 3.2.3. Microbial count, residual grease content, and impurity removal were determined by the coefficient of determination, analysis of variance, and contour plots. Using multiple regression analysis, the data obtained was fitted into a second-order polynomial equation 4.

$$Y = \beta_0 + \beta_i X_i + \beta_{ij} X_i X_j + \beta_{ii} X^2{}_i \quad [4]$$

where Y is the predicted response variable; β_0, βi, βii, βij are constant regression coefficients of the model; and Xi, Xj ($i=1, 3; j=1, 3; i\neq j$) represent the independent variables in the form of coded values.

Table 3.2.1. Coded values of variables used in Box-Behnken design

Coded value	Independent variables	Level		
		-1	**0**	**1**
X_1	Concentration (% w/v)	0.15	0.58	1.00
X_2	Temperature (^{o}C)	25.00	62.50	100.00
X_3	Time (min)	5.00	32.50	60.00
X_4	Number of stage	1.00	2.00	3.00

3.2.2.7. Feasibility analysis of the pre-treatment and decontamination procedures

A preliminary technoeconomic analysis of the procedures was evaluated considering their efficiency in terms of cost of chemicals, the number of treatment steps, the temperature of treatment, and the treatment time required. The comparison of costs of chemicals for decontamination and pre-treatment of 5 g chicken feather was based on the price of reagent grade surfactants. Further requirements for additional costs were noted (e.g., number of treatment stages, treatment time, and temperature).

3.2.3. Results and Discussions

Experiments were conducted to achieve the objectives of the decontamination and pre-treatment of chicken feather studies. Further aims included determining the optimum washing conditions based on minimum bacterial count and the effect of pre-treatment on physicochemical and mechanical properties of the chicken feathers.

3.2.3.1. Effect of surfactant treatment on appearance and odour of chicken feathers

Visual inspection of the samples showed that the barbs of raw chicken feathers were tangled and stuck to the rachis. When left at room temperature, the raw wet feathers turned dark brown after two days and had a distinct putrid smell - the raw chicken feathers turned dark brown from bacterial decomposition. After washing with water, their barbs opened and appeared white, however the odour remained. The untreated feathers contained blood, which looked pink upon collection but turned brown after drying. This allowed the bacteria to excrete waste material that caused the feathers to darken (Tseng, 2011; Pourjavaheri et al., 2014). The treated feathers exhibited weight loss compared to the raw and autoclaved samples. This indicates that there was a large amount of impurities in the initial sample. The surfactant treatment imparted a soap smell to the feathers and changed their colour from brown to white. Decontamination and pre-treatment require frequent changes of the washing solution to prevent resorption of the contaminants as a result of rapid saturation of the solution with contaminants. The repeated deposition of contaminants can also be caused by the destruction of solvate membranes from molecules of the surfactants as a result of intensive mechanical action (Tadros, 2006; Tseng, 2011). During the final washing stage, the residual surfactant present in the treated feathers had to be completely removed by adequate rinsing with tap water since any residual surfactants would cause chemical degradation of the feathers (Tseng, 2011; Pourjavaheri et al., 2014). The effects of treatment of feathers with surfactants on the visual appearances of the feathers are illustrated in Figure 3.2.3.

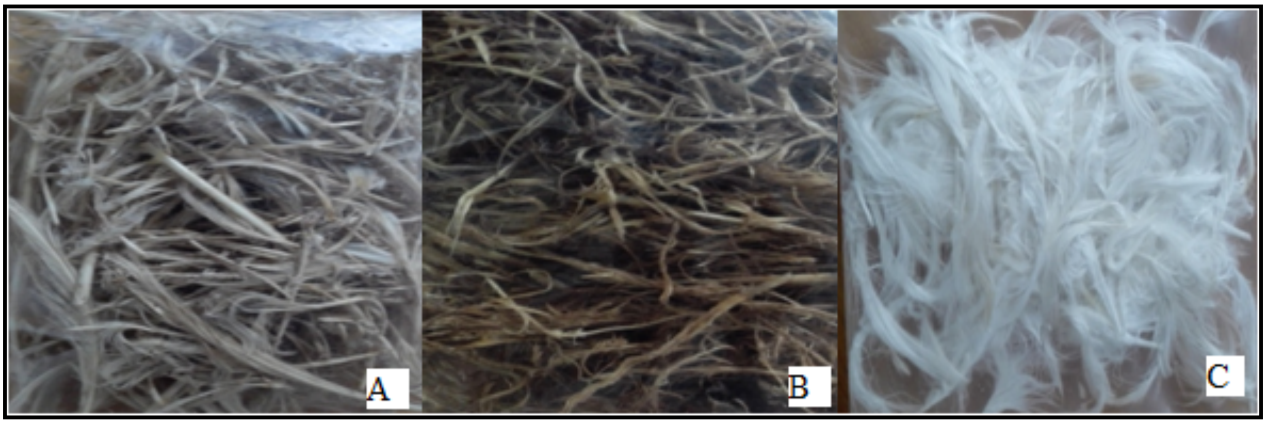


Figure 3.2.3. Chicken feathers upon sampling (A), after storage for 3 days at room temperature (B) and after decontamination and pre-treatment with surfactants (C).

3.2.3.2. Screening of factors using the Placket-Burman design

Using the Placket-Burman design, seven independent variables (i.e., concentration, time, temperature, feather to liquid ratio, the number of stages, pH and steering speed) were screened with regard to their effects on bacterial content and residual grease. The 12 experimental runs generated using the software and corresponding responses (microbial count) are shown in Table 3.2.2. An ANOVA analysis of the Placket-Burman design results is presented in Table 3.2.4. The parameters with p-values of less than 0.05 were considered to have a significant effect on the microbial count. As shown in Table 3.2.4, concentration, time, temperature, and number of stages were the most significant factors ($p<0.05$). Out of the significant variables screened using the Placket-Burman design, concentration, time and number of stages exerted a positive effect on bacterial content, whereas temperature exerted a negative effect.

Table 3.2.4. ANOVA analysis of Placket-Burman design

Code	Term	Estimate	t Ratio	Prob>|t|	Remark
	Intercept	426.475	11.71	<.0001*	
X_1	Concentration	-194.525	-5.34	0.0011*	Significant
X_2	Temperature	25.049		0.0316*	Significant
X_3	Time	-107.4971	-2.96	0.0212*	Significant
X_4	Feather to liquid ratio	43.6		0.0769	Non- significant
X_5	Number of stages	-224.7338	-6.09	0.0005*	Significant
X_6	pH	23.98		0.3569	Non-significant
X_7	Stirring speed	-19.597		0.6547	Non-significant
X_5*X_1	Interaction effect	41.433824	1.12	0.2986	Non-Significant
X_5*X_3		42.997			Significant

3.2.3.3. Microbial counts

As expected the untreated chicken feathers had the highest microbial counts (1.48E+07±6.72E05 Cfu/g) (Table 3.2.5) and decontamination by autoclaving reduced the microbial count by a thousand-fold to 2.81E+06±5.62E04 Cfu/g. Results for microbial counts after treatment of feathers with surfactants are shown in Figures 3.2.4-3.2.6. The results show that the surfactants were effective in removing microorganisms from the feathers. The lower standard microbial counts in the treated samples could be due to the microorganisms being washed away in the surfactant decontamination and pre-treatment processes. Additionally, the lowering of microbial content is due to bactericidal properties of surfactants (Davis, 1960; Huffman, 2002; Kronberg et al., 2014). Decontamination with SDS was the most effective in reducing microbial counts. As shown in Figures 3.2.4-3.2.6, the order for microbial reduction was according to the order POE > DDAC > SDS. This was the same trend observed for corresponding critical micelle concentration and surface tension values of the surfactants (Mandavi et al., 2008). The lower standard microbial counts indicate higher bactericidal removal.

The data in Figures 3.2.4-3.2.6 shows that the microbial counts of the treated chicken feathers were significantly dependent on the number of treatment stages and concentration of surfactant used, followed by time, and temperature. The first treatment stage did not reduce the microbial loads as effectively as the 2nd and 3rd decontamination cycles. However, a single decontamination cycle with all types of surfactants may provide sufficient disinfection if the treated feathers were to be used for the production of composites.

All the decontamination and pre-treatment procedures with all the surfactants studied showed significant decreases in microbial counts (Figure 3.2.4-3.2.6). This is in agreement with literature data that indicate that surface active agents are capable of eliminating a broad range of microorganisms (Mandavi et al., 2008).

3.2.3.4. Optimisation by Box-Behnken design

The microbial count decreased more than a thousand-fold after decontamination and pre-treatment (Table 3.2.5). Four signal factors obtained in Placket-Burman design were further optimised using the Box-Behnken design. Twenty-seven experimental runs were conducted for each surfactant type. In this model, the effect of individual, or a combination/interaction of independent variables on microbial count were assessed. The processed data from the experimental design enabled calculation of the coefficients of the regression equation - which characterise the dependency of microbial count on the independent variables. After the exclusion of insignificant coefficients of the regression equation, a multiple mathematical model regression analysis of the observed responses can be predicted by the quadratic model below (Equation (5, 6 and 7)):

Table 3.2.5. The characteristics of chicken feather before and after treatment

Pre-treatment	Microbial count
Control	1.48E+07±6.72E05 Cfu/g
Autoclave	2.81E+06±5.62E04 Cfu/g

$$(\mathbf{MC\ (SSD)})^{\mathbf{0.35}} = +2.682 - 0.973 * X_1 - 0.089 * X_2 - 0.003 * X_3 - 0.003 * X_4 - 0.922 * X_1 * X_2 + 0.005 * X_1 * X_3 - 0.002 * X_1 * X_4 + 7.2e - 005 * X_2 * X_3 - 0.0003 * X_2 * X_4 - 4.4e - 005 * X_3 * X_4 \quad [5]$$

$$(\mathbf{MC(POE)})^{\mathbf{0.26}} = +24.609 - 6.441 * X_1 - 5.79176 * X_2 - 0.021 * X_3 - 4.179e - 003 * X_4 \quad [6]$$

$$(\mathbf{MC(DDAC)})^{\mathbf{0.13}} = +4.210 - 0.925 * X_1 - 0.723 * X_2 - 2.689e - 003 * X_3 - 2.668e - 003 * X_4 \quad [7]$$

Analysis of the equation of regression allows us to draw a conclusion that the criterion of optimisation (microbial count) in the selected factor space is influenced by four factors – the concentration of surfactant (X_1), time (X_2), temperature (X_3) and number of stage (X_4). The negative values of coefficients of the regression equation confirm that an increase in the value of any of the factors will lead to a decrease in the value of microbial count. The mathematical model (Eq. 5-7) of the decontamination and pre-treatment of chicken feather attests that the desired value of microbial count is within the limits of the tested factor space. The statistical significance of the model equations 5-7 and the model terms were evaluated by the F-test for analysis of variance (ANOVA), which indicated that the regressions were statistically significant.

Table 3.2.6. Analysis of variance (ANOVA) for the fitted linear model for optimisation of microbial count

Type of surfactant	Source	Sum of Squares	Degree of freedom	Mean Square	F Value	p-value Prob >F	
SDS	Model	506.67	4	126.67	180.53	< 0.0001	*Significant*
	Concentration (%v/v)	*97.86*	*1*	*97.86*	*139.46*	*< 0.0001*	
	Number of stage	*404.38*	*1*	*404.38*	*576.31*	*< 0.0001*	
	Time (min)	*4.40*	*1*	*4.40*	*6.28*	*0.0201*	
	Temperature (^oC)	*0.037*	*1*	*0.037*	*0.053*	*0.8201*	
	Residual	15.44	22	0.70			
	Lack of Fit	*14.02*	*20*	*0.70*	*0.99*	*0.6176*	*Not significant*
	Pure Error	*1.41*	*2*	*0.71*			
	R^2=0.970, Adjusted R^2=0.965, Predicted R^2=0.955, Adequate Precision= 48.052; CV=11.05%						
POE	Model	496.84	4	124.21	137.01	< 0.0001	*Significant*
	Concentration (%v/v)	*89.93*	*1*	*89.93*	*99.20*	*< 0.0001*	
	Number of stage	*402.53*	*1*	*402.53*	*444.01*	*< 0.0001*	
	Time (min)	*4.08*	*1*	*4.08*	*4.50*	*0.0455*	
	Temperature (^oC)	*0.29*	*1*	*0.29*	*0.33*	*0.5743*	
	Residual	19.94	22	0.91			
	Lack of Fit	*19.03*	*20*	*0.95*	*2.08*	*0.3743*	*Not significant*
	Pure Error	*0.91*	*2*	*0.46*			
	R^2=0.961, Adjusted R^2=0.954, Predicted R^2=0.941, Adequate Precision= 41.633; CV=11.37%						
DDAC	Model	8.19	4	2.05	27.17	< 0.0001	*Significant*
	Concentration (%v/v)	*1.85*	*1*	*1.85*	*24.62*	*< 0.0001*	
	Number of stage	*6.27*	*1*	*6.27*	*83.16*	*< 0.0001*	
	Time (min)	*0.066*	*1*	*0.066*	*0.87*	*0.3606*	
	Temperature (^oC)	*1.2E-003*	*1*	*1.2E-003*	*0.016*	*0.9007*	
	Residual	1.66	22	0.075			
	Lack of Fit	*1.66*	*20*	*0.083*	*190.25*	*0.0052*	*Significant*
	Pure Error	*8.7E-004*	*2*	*4.4E-004*			
	R^2=0.832, Adjusted R^2=0.801, Predicted R^2=0.735, Adequate Precision= 18.892; CV=12.89%						

Sodium dodecyl sulphate: The model F-value of 180.53 implies the model is significant, and there is only a 0.01 % chance that a model F-value this large could occur due to noise. From Table 3.2.6, it can be observed that concentration, number of stage and time of the model were significant to the response, indicating that low microbial count depends on the interactions between these four factors. The "Lack of Fit F-value" of 0.99 implies the Lack of Fit is not significant relative to the pure error. There is a 61.76 % chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good for process optimisation to fit the model. The fit of the model was checked by the coefficient of determination R^2, which was 0.9704, indicating that 97.04 % of the variability in the response could be explained by the model. A high R^2 coefficient (0.9704), as a measure of a number of reductions in the variability of the response, obtained using the independent factors within the model confirms a satisfactory adjustment of the proposed model to the experimental data. The "Predicted R-Squared" of 0.9558 is in reasonable agreement with the "Adjusted R-Squared" of 0.9651; i.e., the difference is less than 0.2. "Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case, the ratio of 48.052 indicates an adequate signal so this model can be used to navigate the design space. The optimised process parameter for SDS treatment is a concentration of 0.5, number of stage 2, time of treatment 30 min and temperature of 80 ^{o}C.

Polyoxyethylene (40) Stearate): The Model F-value of 137.01 implies the model is significant. There is only a 0.01 % chance that an F-value this large could occur due to noise. According to the p-values of the model term (Table 3.2.6), number of stage, concentration and time were significant model terms. The "Lack of Fit F-value" of 2.08 implies the Lack of Fit is not significant relative to the pure error. There is a 37.43 % chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good for process optimisation to fit the model. The coefficients of determination (R^2) of the model was 0.9614, which further indicates that the model was suitable for adequate representation of the real relationships among the variables. The "Predicted R-Squared" of 0.9409 is in reasonable agreement with the "Adjusted R-Squared" of 0.9544; i.e., the difference is less than 0.2. The optimised process parameter for PEE treatment is a concentration of 0.75, number of stage 2, time of treatment 40 min and temperature of 80 ^{o}C.

Dimethyl dioctadecyl ammonium chloride: The model F-value of 27.17 implies that the model is significant. There is only a 0.01 % chance that an F-value this large could occur due to noise. From Table 3.2.6, it can be observed that concentration and number of stage of the model were significant to the response, indicating that low microbial count depends on the interactions between these four factors. The "Lack of Fit F-value" of 190.25 implies the Lack of Fit is significant relative to the pure error. There is only a 0.52 % chance that a "Lack of Fit F-value" this large could occur due to noise. Significant lack of fit is bad for process optimisation to fit the model. The fit of the model was checked by the coefficient of determination R^2, which was 0.8316, indicating that 83.16 % of the variability in the response could be explained by the model. The "Predicted R-Squared" of 0.7345 is in reasonable agreement with the "Adjusted R-Squared" of 0.8010; i.e., the difference is less than 0.2. "Adequate Precision" measures the signal to noise ratio. In this case, the ratio of 18.892 indicates an adequate signal so this model can be used to navigate the design space. The optimised process parameter for DDAC treatment is a concentration of 0.5, number of stage 2, time of treatment 50 min and temperature of 90 ^oC.

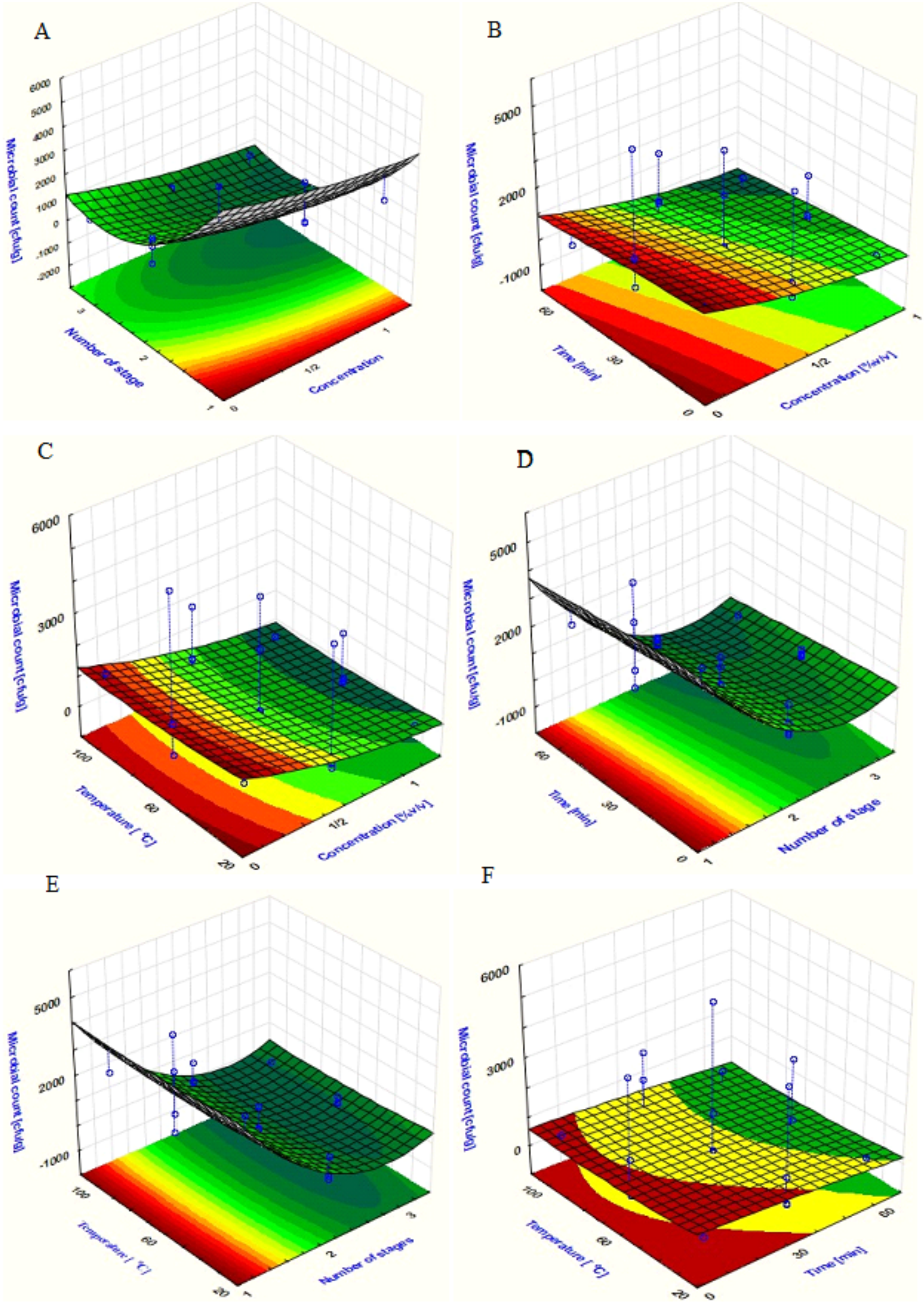


Figure 3.2. 4. Three-dimensional plots of the effect of four variables on the microbial count (SDS). Interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) Number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

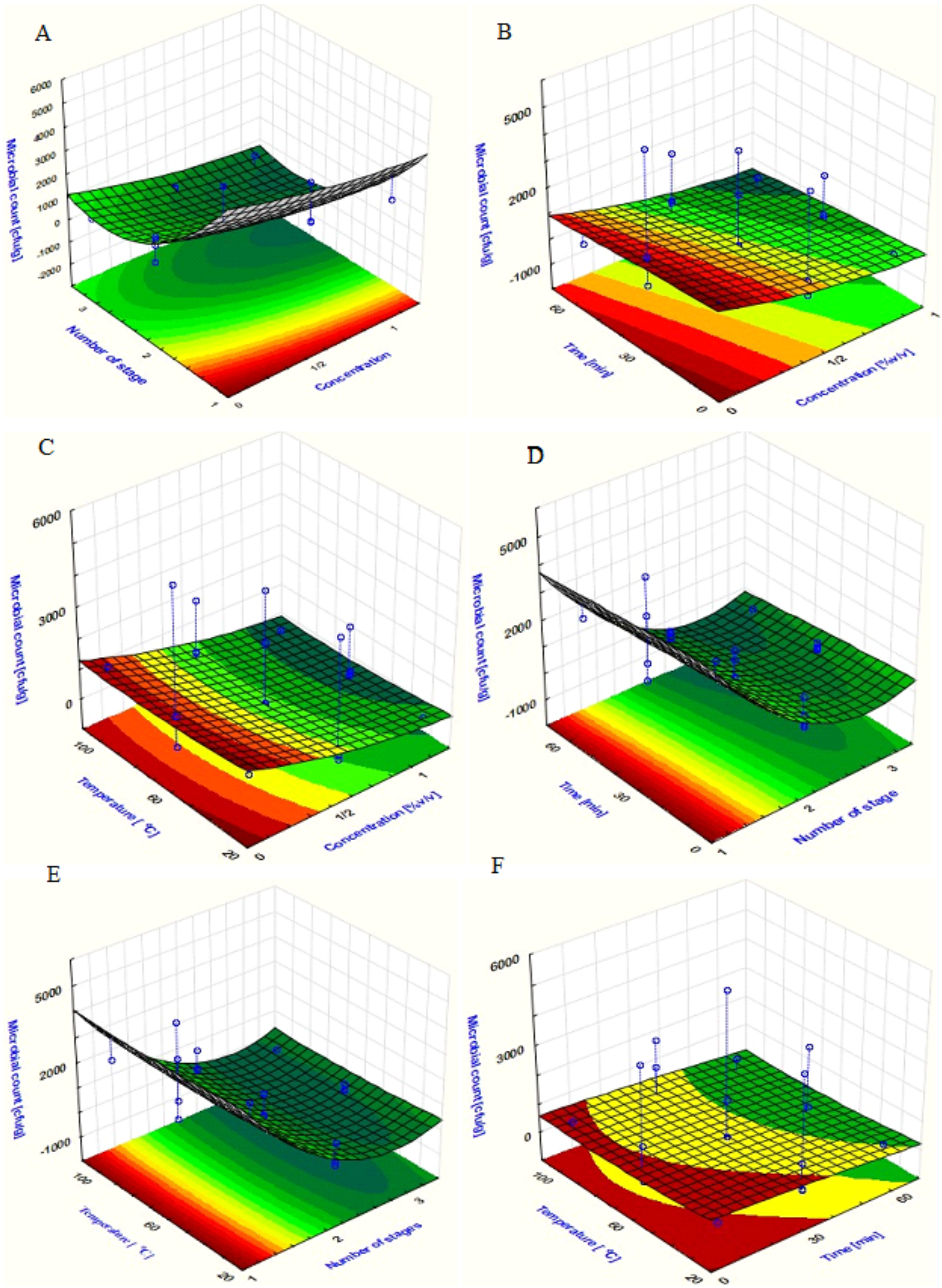


Figure 3.2.5. Three-dimensional plots of the effect of four variables on the microbial count (POE). Interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) Number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

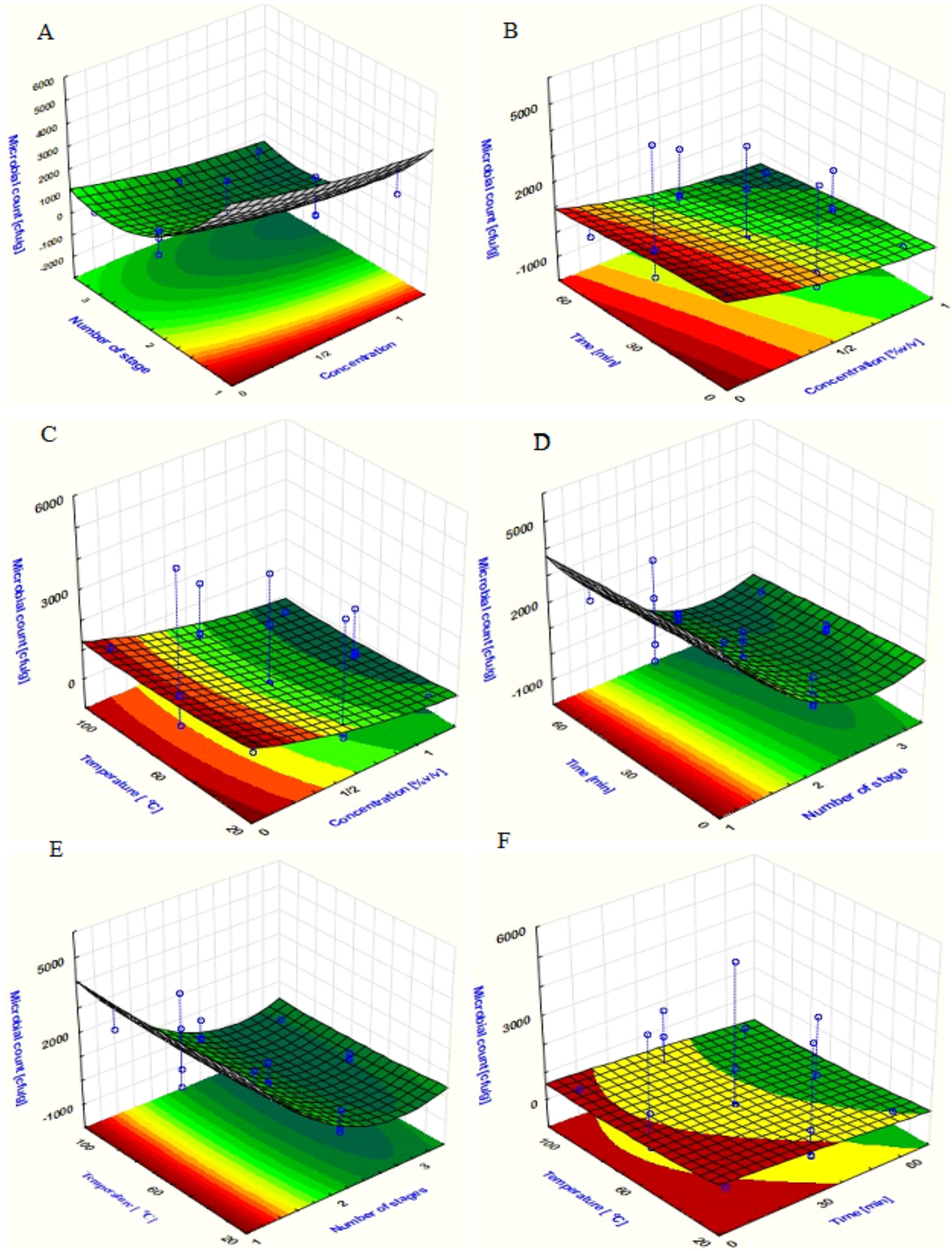


Figure 3.2. 6. Three-dimensional plots of the effect of four variables on the microbial count (DDAC). The interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) Number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

3.2.3.5. Coefficient of variation: The coefficient of variation (Cv) indicates the ratio of the standard error of the estimate to the mean value of the observed response. Generally, a model can be considered reasonably reproducible if the Cv is not greater than 15 % (Montgomery, 2008). Here, the Cv value was 11.05 % (SDS), 12.03 % (DDAC), and 10.31 % (POE) indicating a high degree of precision in the experiment. From Table 3.2.7 the negative sign for the coefficients of factors in the fitted models for microbial count indicated that the level of microbial count decreased with increasing levels of factors. Also, the greatest coefficients of factor, number of stage, revealed the high sensitivities of the response to this factor. Adequate precision is a measure of the range in predicted response relative to its associated error, which provides a measure of the "signal-to-noise ratio". In the present study, the ratio of 11.05 % (SDS), 12.03 % (DDAC), and 10.31% (POE) indicates an adequate signal, so this model can be used to navigate the design space. Simultaneously, low values of the coefficient of variation (Cv) (11.37 %) indicated good precision, reproducibility and reliability of the experiments.

Table 3.2.7. Coefficient of estimate for the fitted linear model for optimisation of microbial count

Type of surfactant	Factor	Coefficient Estimate	Degree of freedom	Standard Error	95% CI Low	95% CI High
SDS	Intercept	7.86	1	0.41	7.00	8.72
	Concentration (%v/v)	-2.74	1	0.27	-3.31	-2.17
	Number of stage	-5.79	1	0.27	-6.36	-5.22
	Time (min)	-0.79	1	0.37	-1.57	-0.017
	Temperature (^oC)	-0.11	1	0.20	-0.53	0.30
POE	Intercept	7.86	1	0.41	7.00	8.72
	Concentration (%v/v)	-2.74	1	0.27	-3.31	-2.17
	Number of stage	-5.79	1	0.27	-6.36	-5.22
	Time (min)	-0.79	1	0.37	-1.57	-0.017
	Temperature (^oC)	-0.11	1	0.20	-0.53	0.30
DDAC	Intercept	2.06	1	0.12	1.81	2.30
	Concentration (%v/v)	-0.39	1	0.079	-0.56	-0.23
	Number of stage	-0.72	1	0.079	-0.89	-0.56
	Time (min)	-0.10	1	0.11	-0.32	0.12
	Temperature (^oC)	-7.33E-003	1	0.058	-0.13	0.11

The three-dimensional response surfaces illustrate the interactions between two variables by keeping another variable constant (Figures 3.2.4-3.2.6). It has been reported that elliptical contours mean perfect interactions between the independent variables (Haji et el., 2014). As shown in Figure 3.2.4, the shapes of the contour plots are all elliptical except for Figure 3.2.4C and 3.2.4F, indicating that the mutual interactions between every two variables were significant. As shown in Figure 3.2.5, the shapes of the contour plots are all elliptical except for Figures 3.2.5C and 3.2.5F, indicating that the mutual interactions between every two variables were significant. As shown in Figure 3.2.6, the shapes of the contour plots are all elliptical, indicating that the mutual interactions between every two variables were significant.

3.2.3.6. The effect of decontamination and pre-treatment on physicochemical and mechanical properties of chicken feathers

Evaluation of impurities

The removal of impurities in decontaminated and pre-treated chicken feathers was plotted against concentration, number of stages, time, and temperature as shown in Figure 3.2.7. The impurity removal after washing was about 8-25 %. This impurity removal is due to the washing out of short fibres and foreign materials such as vegetation, suints, blood, dust and some other contaminants from the poultry industry and proves that the impurity removal has direct dependency on the cleaning agents. From Figure 3.2.7 it can be seen that there is a significant reduction in impurity content compared to the untreated chicken feather. The result in Figure 3.2.7 would suggest that a single stage would be insufficient in reducing impurities to an acceptable level, so it requires more than one stage of cleaning. From the figure, it can be seen that using all of the surfactant cleaning methods at a concentration from 0.1-0.57 % was ineffective at reducing all the impurities. But increasing the concentration to 1 % improves the removal of impurities.

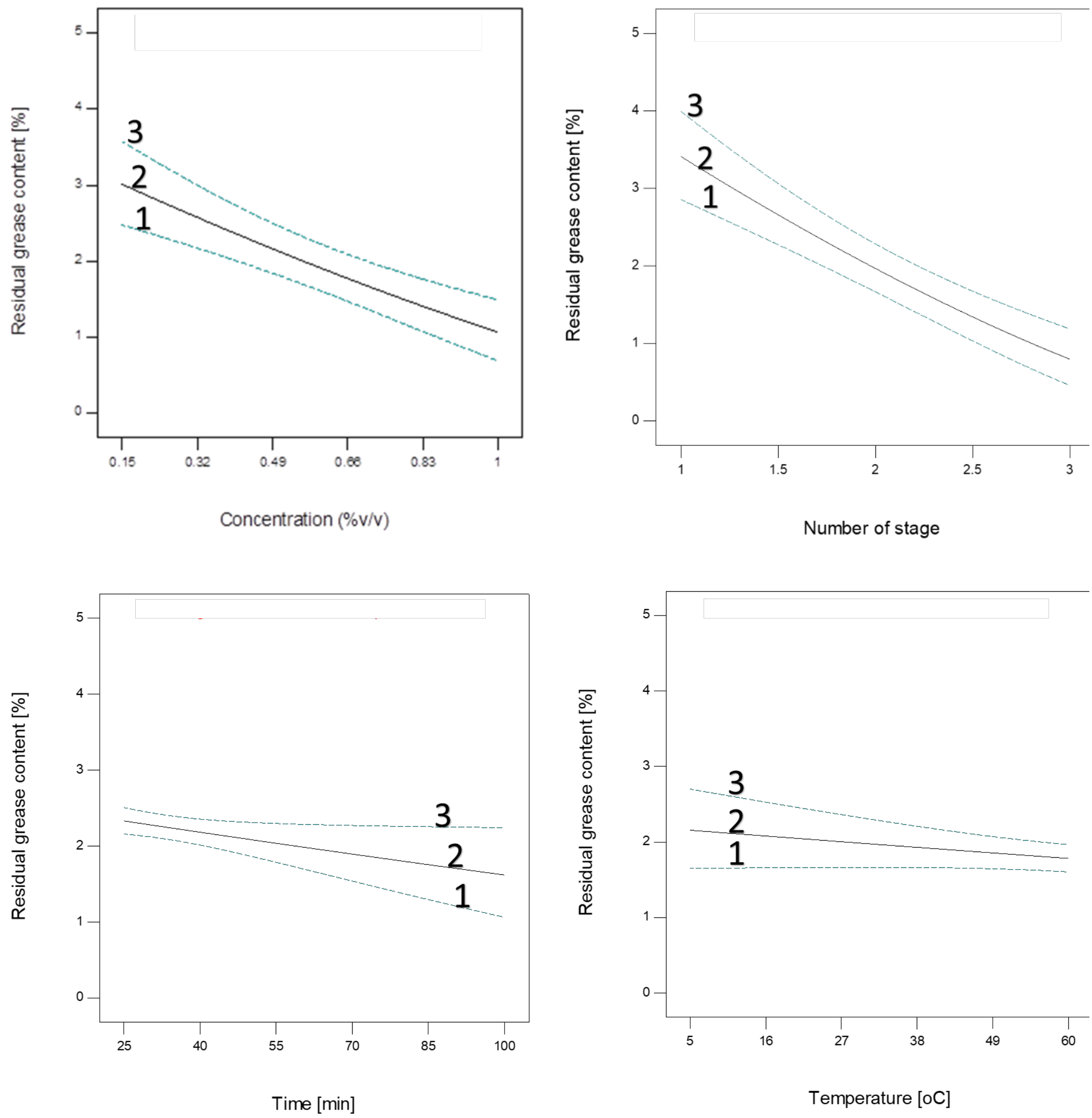


Figure 3.2.7. The effect of independent variables on residual grease content [%] (1=SDS; 2=DDAC; 3=POE treated feather)

Residual grease content

Figure 3.2.8 shows the residual grease content after hexane extraction of the decontaminated and pre-treated chicken feathers at 60 ^{o}C. The anionic surfactant SDS had the best outcome since it was effective at removing oily dirt and stains in pure water at the three lower detergent concentrations. DDAC surfactant was the next most effective, followed by POE. As can be seen from Figure 3.2.8 the increase in concentration and number of stages significantly reduces the residual grease content of the treated chicken feathers. The higher number of stages improves emulsification and removes the grease more effectively. This is evident even at the lower treatment concentrations. The greatest scouring ability of all surfactants significantly depends on the number of stages and concentration. This eliminates more than 90 % of the grease content of the chicken feathers. The residual grease content of a chicken feather needs to be below 2 % to make processing easier during further valorisation activities (Bateup, 1986; Bateup and Warner, 1986). The second and third stage decontamination and pretreatment cycles, especially at higher surfactant concentrations, produced feathers with low residual grease content. As can be seen from Figure 3.2.8, the reduction of decontamination and pretreatment time and temperature affects the level of residual grease on the feather. However, the effect of time and temperature is not as significant as the number of stage and concentration.

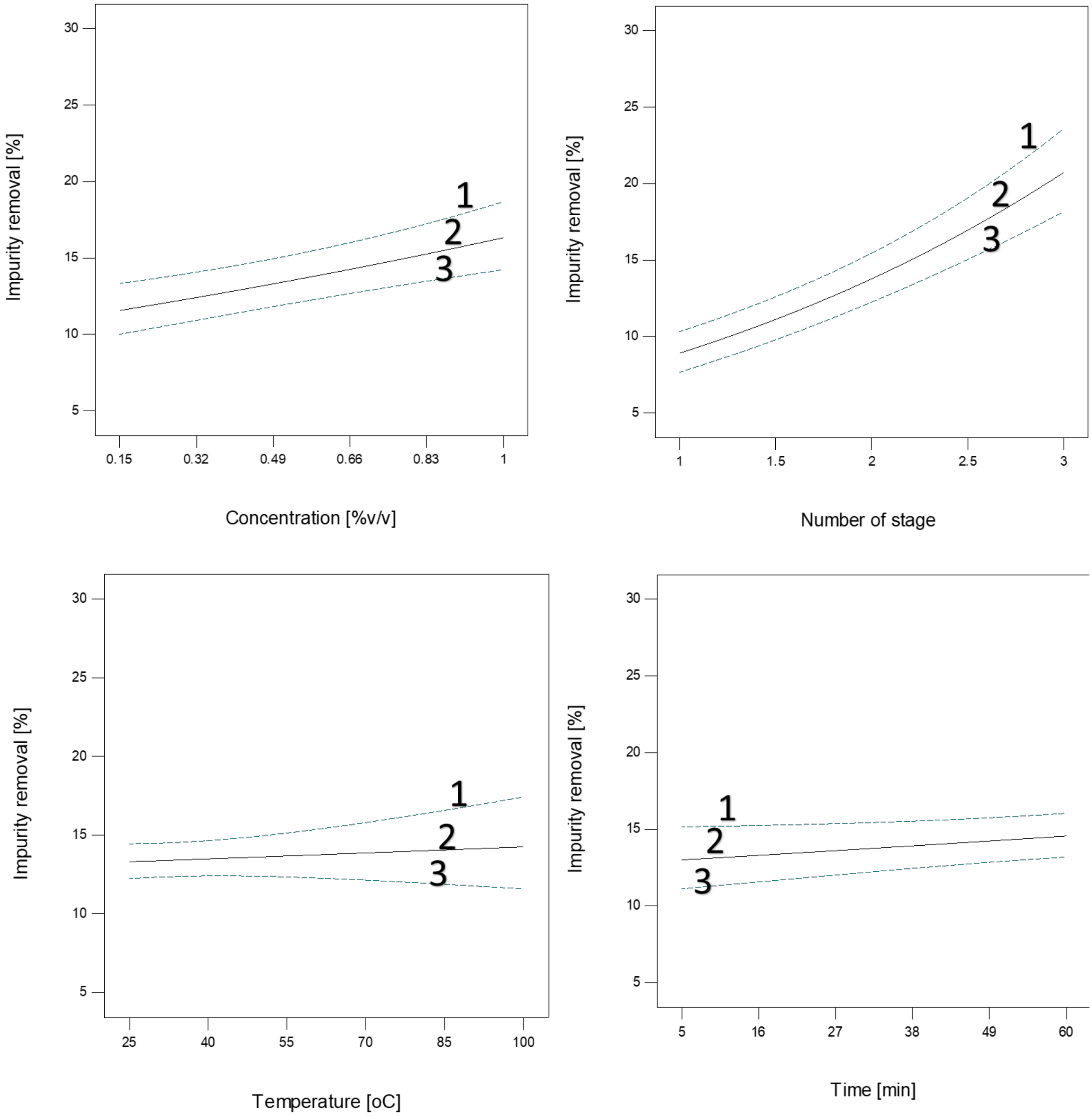


Figure 3.2.8. The effect of independent variables on impurity removal [%] (1=SDS; 2=DDAC; 3=POE)

Ash Content

Figure 3.2.9 shows the effect of surfactant decontamination and pre-treatment on the ash content of chicken feathers. From the results, it was observed that the ash content of decontaminated and pre-treated samples were higher than those of untreated samples (12.15% vs 1.25%). This is due to removal of non-ash impurities from waste chicken feathers in the treatment processes (in effect the ash content becomes higher due to the lower amounts of non- ash impurities in the samples). This is also an indication of the efficiency of the treatment process. The effect of treatment of feathers on ash content has also been reported in the literature where it was reported that that higher concentration of treatment chemicals aided the removal or reduction of the proportion of the ash content of the fibres whereas lower concentrations of the alkaline treatment improved the development of ash content in the fibres (Anderson, and JR Christoe, 1984; Oladele, I., 2016).

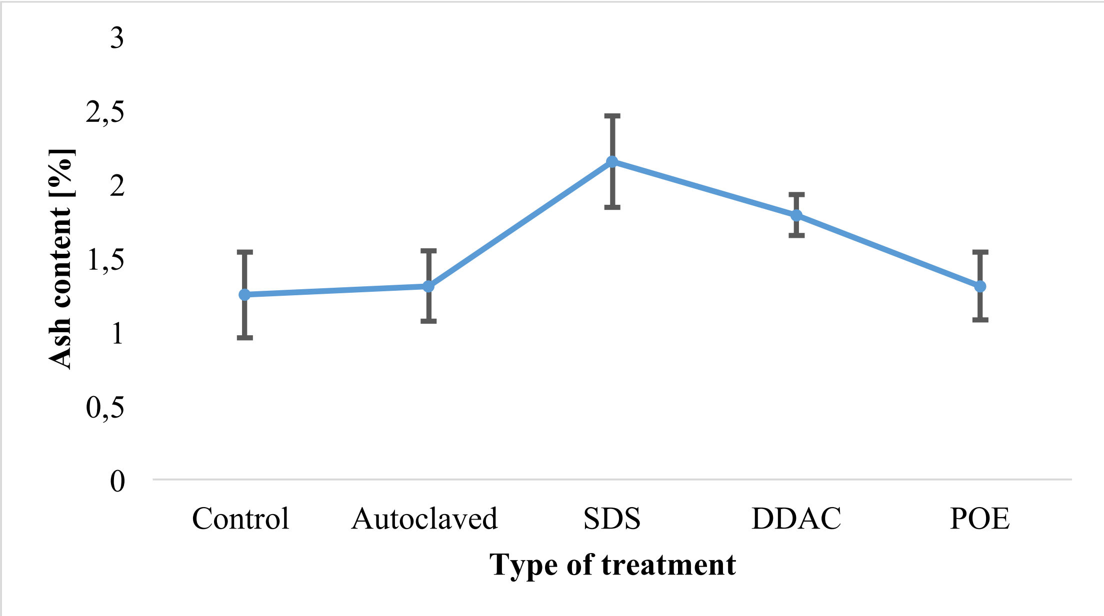


Figure 3.2.9. Effect of decontamination and pretreatment on the ash content of chicken feathers.

FTIR spectroscopy

In order to examine the effects of decontamination and pre-treatment processes on chicken feathers, FTIR spectra of untreated and decontaminated and pre-treated chicken feathers were obtained (Figure 3.2.10). There were no significant differences in the chemical composition and structure of surfactant decontaminated and pre-treated chicken feathers, except for the autoclaved sample. However, the autoclaved technique did not significantly remove adhered waste materials and fats as the FTIR spectrum of the autoclaved sample was the same as that of the untreated feathers.

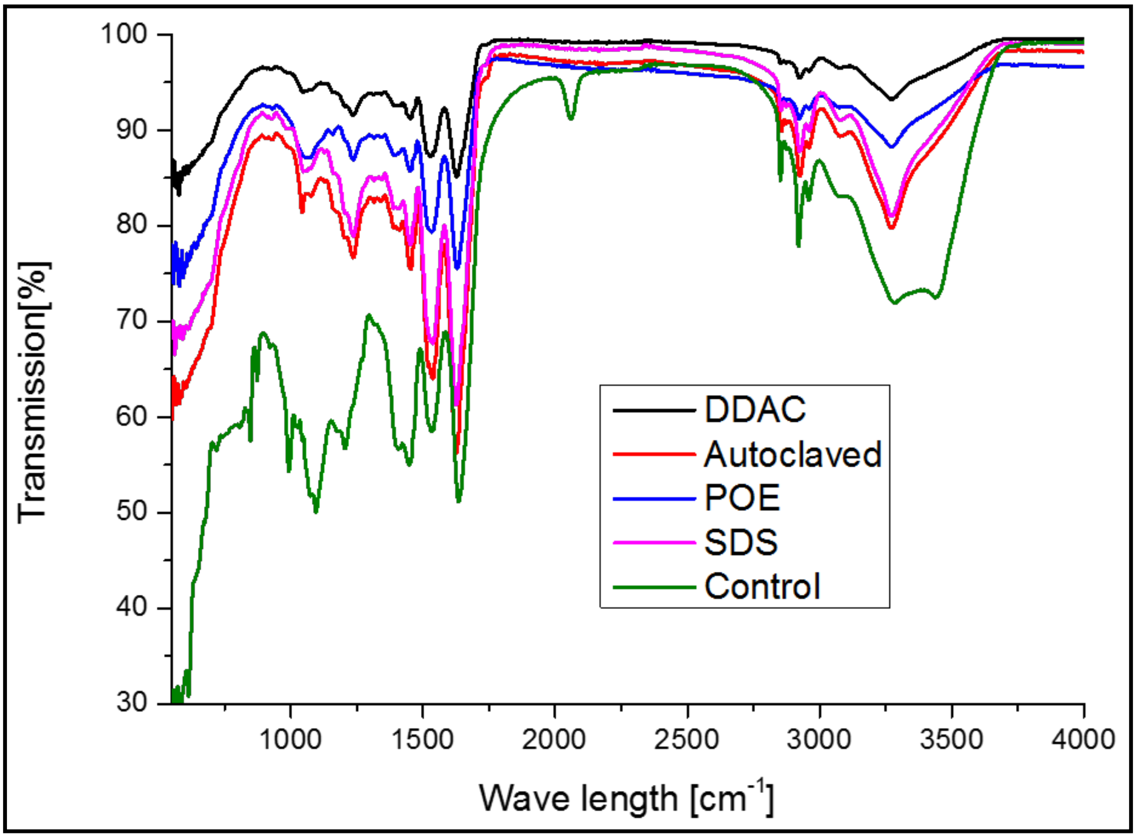


Figure 3.2.10. FTIR spectra of treated and untreated chicken feathers.

Water retention and moisture regain

The water retention properties of the chicken feather barbs are presented in Table 3.2.8. There were no significant differences found for all samples regardless of the type of decontamination, pre-treatment methods and water temperature. The amount of water retained by a chicken feather barb increases with an increase in the hydrophilic tendency of the fibre.

Table 3.2.8. pH and water retention of treated and untreated chicken feathers.

	Untreated	**Autoclaved**	**SDS**	**DDAC**	**POE**
pH	5.36	5.26	5.50	4.72	4.41
Water retention	46.63	51.24	61.28	56.81	58.75

Figure 3.2.11 illustrates the interaction of a surfactant compound with a chicken feather surface showing an intact lipid. Hydrophobic interactions exist between the chicken feather surface lipid and hydrophobic tail of the surfactant. Figure 3.2.11 illustrates that the outermost surfaces of surfactant-chicken feather interface by creating a more hydrophilic surface.

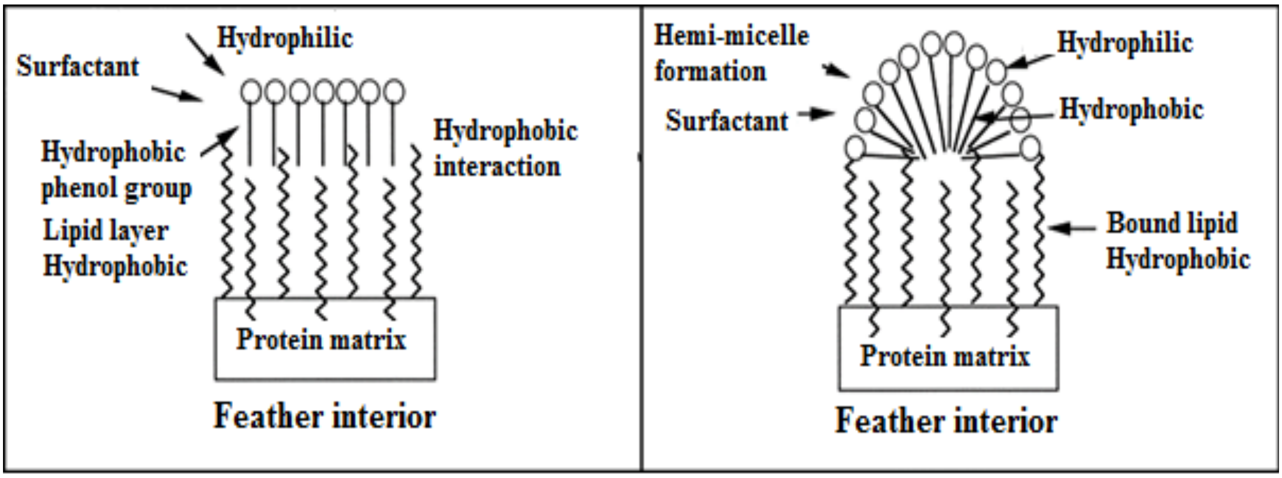


Figure 3.2.11. Illustrations of the hydrophobic/hydrophilic interaction between surfactants and the feather surface showing the formation of hemimicelles (adapted from Kronberg et al., 2014)

In this study, the surfactant either forms a continuous layer or hemimicelles on the chicken feather surface. Due to the hydrophobicity of chicken feathers, electrostatic and hydrophobic interactions are also found between the surfactant and chicken feathers (Brack et al., 1999; Kronberg et al., 2014). After the lipid is removed, the surfactant molecules are orientated in such a manner that the polar region forms the outermost surface. The wettability of chicken feather barbs can increase due to this phenomenon.

Removal of grease, dirt, suints, burrs and woody fragments and mineral matter from chicken feathers can also result in moisture regain change due to surface modification of treated chicken feathers (Freeland et al., 1985; Tseng, 2011). Pre-treated and decontaminated chicken feathers absorbed water from the atmosphere quickly whereas the saturation values after 24 hours were not as large as that for untreated feathers (Figure 3.2.12). The reduction of the polar groups after pre-treatment and decontamination reduced regain saturation values. As can be seen in Figure 3.2.12, the moisture is attracted to the polar groups present in the treated chicken feathers. A practical implication of this observation is that increase in moisture regain will cause reduction in the electrical resistance of chicken feathers resulting – this, in turn, will induce static electricity on the feathers (Hearle and Morton, 2008).

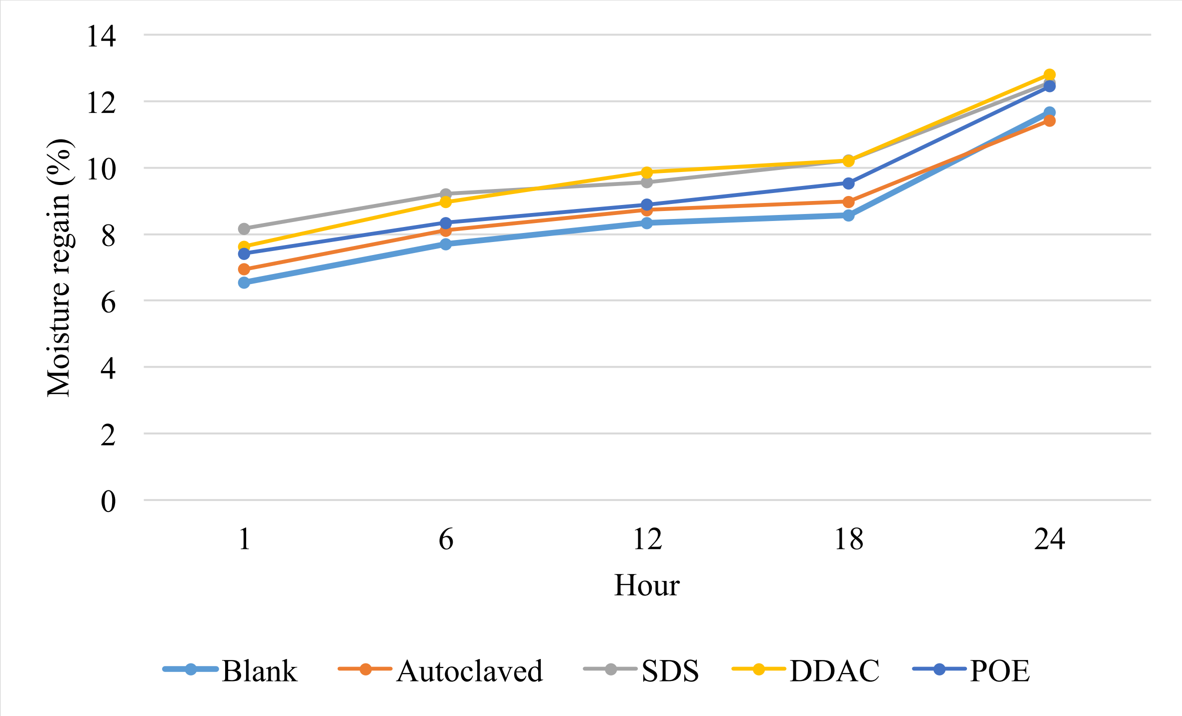


Figure 3.2.12. Moisture regain differences between treated and untreated feathers

Whiteness and yellowness indices

The colour of feathers varies not only in terms of the type of pretreatment used but also in terms of the variation in age of the chicken, individual nature of the poultry, and the slaughtering processes used (Sheffield and Doyle, 2005). Varying amounts of preen, particulates from dust bathing, faecal matter, and type of feed, all contribute to variation in colour of chicken feathers. Since raw chicken feathers contain blood and may have been collected several hours before decontamination, their colour becomes dark brown due to bacterial development. The whiteness index and yellowness index for both untreated and treated chicken feathers as a result of different decontamination and pre-treatment methods were measured. Table 3.2.9 illustrates the colour variations that were obtained. There were no significant differences in the whiteness indices of the feather treatment methods using surfactants (Table 3.2.9). SDS produced the whitest feathers. The improvement of the whiteness and yellowness indices in treated and untreated samples depended on the concentration of surfactant, number of treatment stages, and time of treatment (Bateup, 1985). It was noticed that the increase in each factor led to an increase of whiteness index and a decrease in yellowness index.

Table 3.2.9. CIE tristimulus values, whiteness index and colour differences (ΔE) for treated and untreated chicken feathers

Type of feather	L^*	a^*	b^*	ΔE	WI CIE	YI E313
Control	75.36	2.81	19.59	77.91	-57.75	43.18
Autoclaved	81.49	1.89	18.29	6.13	-34.36	37.70
SDS	94.85	0.07	4.36	24.89	67.49	8.28
DDAC	92.35	0.06	4.25	23.03	61.60	10.56
POE	94.48	-0.01	4.32	24.64	65.00	9.31

Density

Density measurements of whole chicken feathers and fractions (rachis and barb) showed clear differences, almost two-fold, between barb and rachis fractions for treated and untreated chicken feathers. The density of whole feathers was closer to that of the barb fraction in almost all cases whereas values for untreated chicken feathers showed noticeably higher dispersions due to inhomogeneity of the sample. On the contrary, there were no significant differences in densities of the treatment samples, irrespective of the treatment method used (Figure 3.2.13). The density of chicken feathers was lower than 1 g/cm^3 with the exception of the untreated and autoclaved sample. This value is a lower value than the density of cellulosic and other protein fibres such as wool. Generally, the density values for chicken feathers were in agreement with those reported in the literature (0.8-0.89 g/cm^3) (Pourjavaheri et al., 2014).

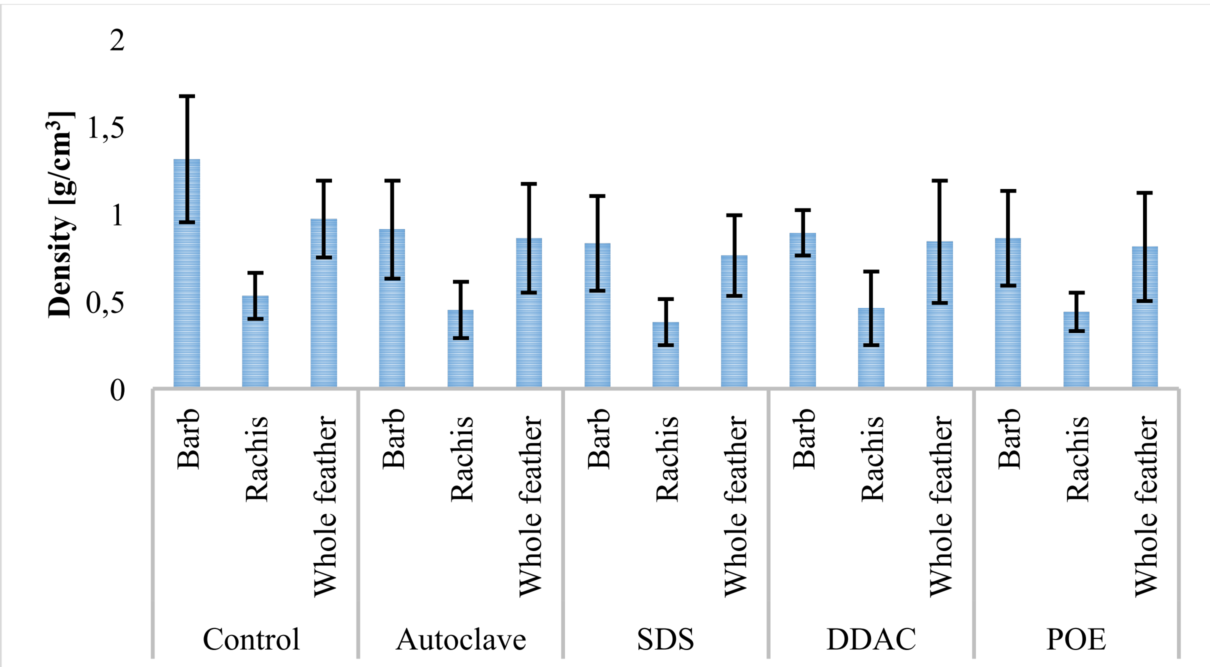


Figure 3.2.13. Density measurement for untreated and treated chicken feathers

Mechanical properties

Chicken feathers suffer reversible loss of tensile strength when wet (Wang et al., 2003). This could be due to the hydrogen bonds which are dissociated in aqueous conditions resulting in reduction of disulphide bonds in the feathers. In aqueous media, protein chains can be ionised and attract charged molecules – hence chicken feathers are susceptible to chemical damage (strong alkali and strong acids) in aqueous media (Tesfaye et al., 2017 (c)). The alkaline nature of suint is critical for setting the conditions for pre-treatment. Prolonged treatment time and high temperatures will lead to strength loss and yellowing. The effect of bacteria removal from chicken feathers was evaluated after decontamination and pre-treatment of the feathers.

Table 3.2.2. Tensile properties of treated and untreated chicken feathers

	Maximum load [cN]	**Tenacity at maximum load [cN/tex]**	**Tensile extension [%]**	**Tensile strain at maximum load [%]**	**Tensile stress at maximum load [MPa]**
Untreated	375.79	8.39	2.45	2708.53	0.38
Autoclaved	485.06	10.25	2.54	2797.33	0.49
SDS	1000.77	12.40	6.09	6744.38	1.00
POE	662.75	12.58	3.36	3703.99	0.66
DDAC	488.37	11.42	4.45	4908.01	0.49

The analyses of the mechanical properties of treated and untreated chicken feather barbs are shown in Table 3.2.10. In some cases, decontamination of feathers results in minimal fibre damage whereas treatments with surfactants enhanced the tensile strength of barbs. From the results, SDS treatment best influenced the improvement of tensile stress at maximum load. This indicates that the chemical treatment can enhance the tensile properties of animal fibres (Feughelman, 2002). The enhanced strength observed in treated samples may be due to increase in protein content of the treated samples due to the removal of other impurities. This is in agreement with literature results where the presence of a high amount of protein content led to enhancement of tensile properties (Pourjavaheri et al., 2014). From Table 3.2.10, it is clear that enhancement of strain ability of treated samples has been achieved compared to untreated feathers. This suggests that treated feathers can withstand more strain thus delaying failure of materials made from them. Consequently, potentially chicken feather barbs could be used as materials for reinforcement in natural fibre composites.

Scanning electron microscopy, energy dispersive spectroscopy, SEM/EDX

The morphology and elemental profile analyses of the feathers were studied by SEM/EDX in order to ascertain if the decontamination and pre-treatment procedures had any effects on the feathers. The images in Figures 3.2.14 reveal that the detergents used washed the chicken feathers cleanly, leaving them free from dust with their naturally smooth surfaces. This is probably due to the removal of dirt and lipid layer that coated the chicken feather as a result of the detergency action. The bulk of the decontaminated and pre-treated chicken feather became white and fluffy. The tangled and curled chicken feathers started to unfurl after decontamination and pre-treatment. Feather whiteness and unfolding of the barb from the rachis increased as the number of pre-treatment stages increased. The autoclave treated samples remain folded due to lipid residues whereas the untreated chicken feathers had an abundant amount of contaminants, lipids, and closely linked barbules on the surface. These observations are similar to those reported for pre-treatment of alpaca and hair fibres (Mendes and Angela, 2003; Wang et al., 2003).

All surfactant treatments show a good level of contaminant removal. However, Figure 3.2.14 shows that there was cracking on the surface of the feathers. The feather microstructure was not damaged after decontamination and pre-treatment and barbules were found intact. The treated chicken feathers had a hard texture. The feathers treated using the autoclave technique had the same appearance and texture as the unwashed feathers. However, the surfactant solution softened the texture in the rachis parts and made them more brittle. The level of feather entanglement and fibre length are also important factors if the feather fractions are to be used for textile applications.

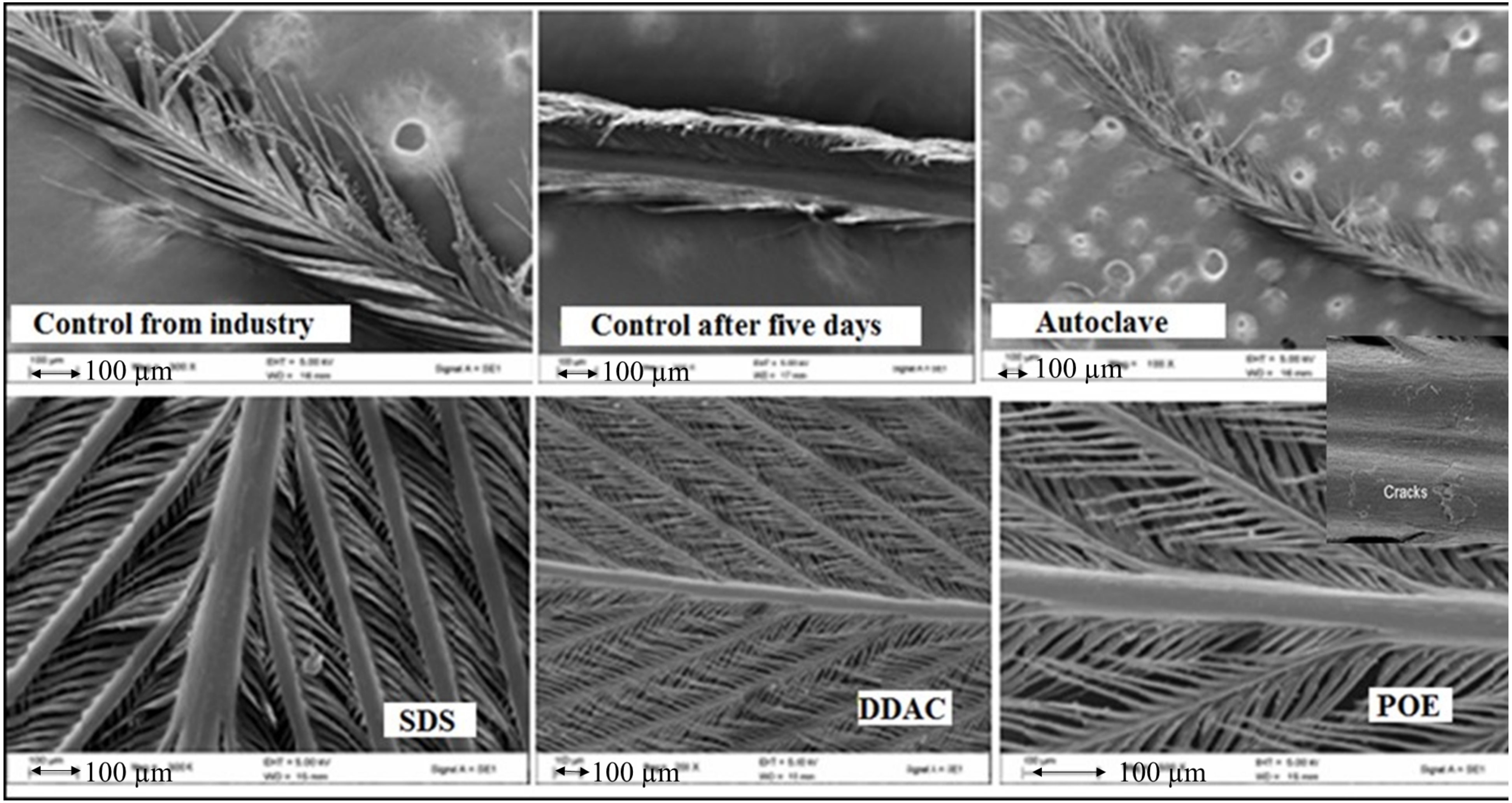


Figure 3.2.14. The SEM structure of treated and untreated chicken feathers (at 100 µm scale)

Figure 3.2.15 shows the SEM-EDX images and the elemental analysis of the samples. The relative proportions of the sulphur element decreased where the carbon content increased in all the treated samples. This may be due to the removal of dirt and decontaminates (blood, skin and other dirt) from the surface of the chicken feather.

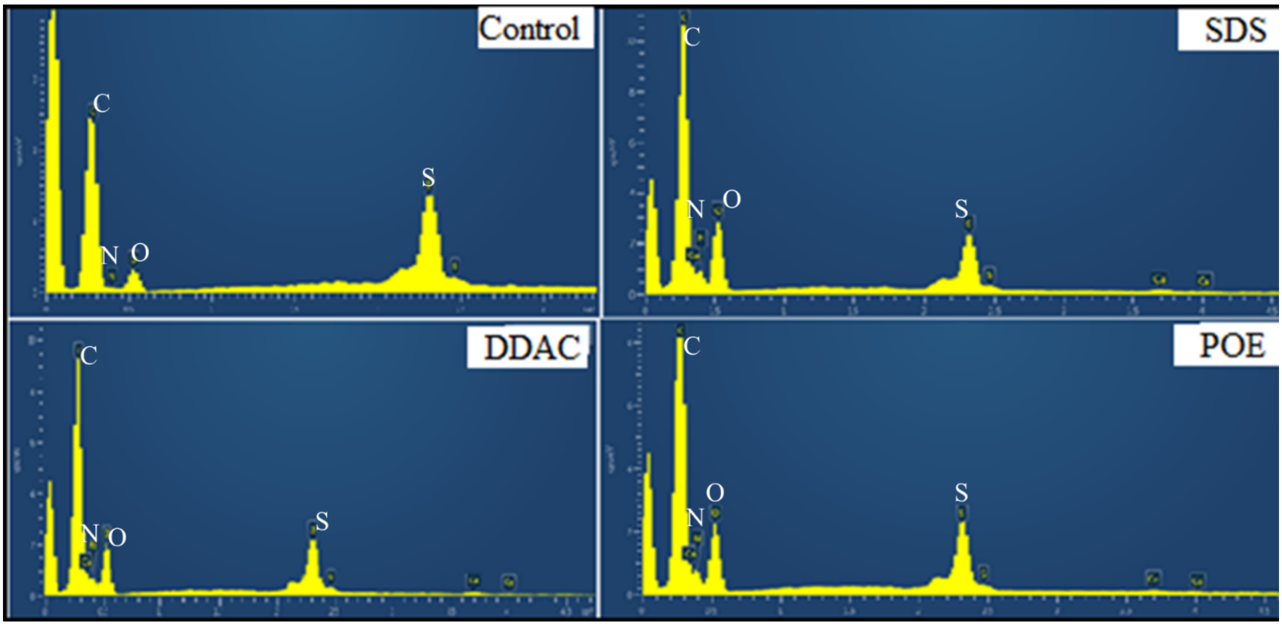


Figure 3.2.15. SEM-EDX and elemental data drived from treated and untreated chicken feathers

Thermogravimetric analysis

Although the mass loss profiles for treated and untreated chicken feathers were very similar a closer examination of the derivative diagram shows significant differences in the profiles (Figure 3.2.16). The first mass loss observed in the temperature range of 25–235 °C can be attributed to water release. The second and third mass loss stages (around 235–350 °C and 350–550 °C respectively) are related to denaturation of chicken feathers. The complete degradation of the chicken feather carbonic chain takes places in the temperature range of 350–550 °C (Figure 3.2.16A). Figure 3.2.16 A shows rapid decomposition in the temperature range between 235–550 °C.

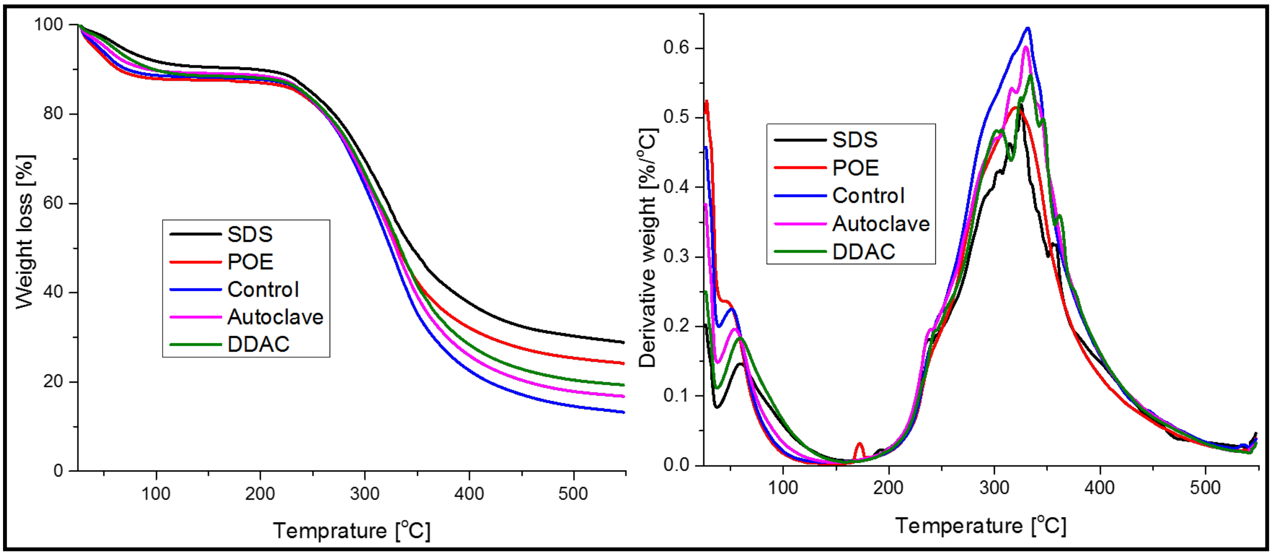


Figure 3.2.16. Thermogravimetric (A) and derivative curves (B) for treated and untreated chicken feathers

In Figure 3.2.16B the denaturation temperature increases after decontamination and pre-treatment. Decontamination and pre-treatment of chicken feathers promote stability of the structure and shifts the denaturation temperatures higher by increasing the ionic interactions (Monteiro et al., 2005). Disinfecting and pre-treatment of chicken feathers shows a large degradation of the cystine disulphide bonds inside and between the chains (Pourjavaheri et al., 2014), and therefore exhibits higher denaturation temperatures, compared to the control chicken feathers. It is apparent that more energy is spent to disorganise the structure of untreated chicken feathers than in the treated chicken feathers. This fact is supported by the increase of the denaturation temperature and the decrease in the denaturation enthalpy of chicken feather (Monteiro et al., 2005) (Figure 3.2.16B).

3.2.3.7. Commercial feasibility analysis

For bench scale application, all of the decontamination and pre-treatment methods are practical, in terms of energy input, the cost of materials, and time at the laboratory scale. Table 3.2.11 shows the differences between each type of treatment to scale the method up to the pilot plant industry. For this study, the filtration, final wash and drying steps that are common to all methods have been ignored. The DDAC decontamination and pre-treatment methods have the highest costs in terms of chemical and energy input. The lowest input costs are for POE methods where chemical prices are the lowest, therefore this method is recommended for the bactericidal effect of the surfactant in the biomedical application area.

Table 3.2.3. Economic comparison.

Method	**Price**[a]	**Time**	**Steps**	**Temprature**[b]	**Scale**[c]
SDS	2	1	2	RT	++
POE	1	1	2	RT	+++
DDAC	3	2	2	RT	+

[a] Relative cost of chemicals on a 5 g of chicken feather basis; [b]Required temperature in ˚C; [c]Feasibility of scaling up the method, (+++ means most feasible, +means least feasible).

3.2.4. Conclusions

This study has investigated the effectiveness of surfactants for removal of contaminants and microbial content of waste chicken feathers from a poultry processing facility. Treatment of feathers with surfactants was effective in removing lipid matter from the feathers. Although not as effective as combined pot surfactant treatments, autoclaving was also effective in removing microbial matter from the feathers to levels that rendered the feathers safe to handle and use. The physicochemical properties of the chicken feathers were not adversely affected by the treatments. A preliminary commercial feasibility analysis of the technologies indicates that using POE for decontamination of waste feathers was more cost effective than using SDS and DDAC.

ACKNOWLEDGMENTS

The authors are highly grateful to the Thermodynamics Research Unit and the Biorefinery Industry Development Facility/CSIR for providing funding and necessary laboratory facilities and technical support to complete this work. The Department of Science and Technology's Waste Roadmap (South Africa) and Ethiopian Institute of Textile and Fashion Technology is also acknowledged for financial support.

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CHAPTER 4

CHARACTERISATION OF WASTE CHICKEN FEATHERS

Chapter overview

Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decreased reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. The world poultry industry has struggled with this question: what to do with more than $40x10^9$ kg of poultry feather waste their business generates each year? Can features and properties of feathers allow for valorisation of chicken feathers?

In order to determine the suitability of using waste chicken feathers as a renewable resource for production of high-value materials, it is important to understand their physical, chemical, thermal, mechanical, electrical properties and also their morphological structures. In this chapter, results of such comprehensive characterisation are reported: the properties of the whole chicken feather and of the component parts of the feather (barbules, barbs and rachis) were used to evaluate the possibilities for beneficiation of waste chicken feathers.

This chapter is composed of three different research articles: valorisation of chicken feathers; characterisation of physical properties and morphological structure, valorisation of chicken feathers; and characterisation of chemical properties and valorisation of chicken feathers: characterisation of mechanical, thermal and electrical properties.

4.1. VALORISATION OF CHICKEN FEATHERS: CHARACTERISATION OF PHYSICAL PROPERTIES AND MORPHOLOGICAL STRUCTURE

(BASED ON PAPER THREE)

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ABSTRACT

The physical properties and morphological structure of chicken feathers were examined in order to identify possible avenues for the valorisation of waste chicken feathers. The physical properties ascertained were fibre length, fineness, diameter, colour, ash content, moisture content, moisture regain, density, aspect ratio and dimensional measurement. The morphologies of the whole feather and its fractions (barb and rachis) were characterised by scanning electron microscopy. The results indicate that a chicken feather has unique features. The barb, unlike any other natural or synthetic fibre, is a protein fibre that has low density, high flexibility, good spinning length and a hollow honeycomb structure. The rachis has low density, low rigidity, and a hollow honeycomb structure. These characteristics indicate that chicken feather barbs can be utilised to manufacture textile products either on their own or by structural interaction with other fibres. The characteristics of both the barb and the rachis, make them suitable for the manufacture of composite materials. These results illustrate the possibilities of chicken feathers as a valuable raw material. The collection and processing of the chicken feathers from poultry can be a new source of employment and provide income generation opportunities.

Keywords: - barbs, characterisation, chicken feathers, morphology, protein fibres, rachis, whole feathers

4.1.1. Introduction

The disposal of waste in an economically and environmentally acceptable manner is a critical issue facing most modern industries. This is mainly due to increased difficulties in locating disposal works and complying with stringent environmental quality requirements imposed by waste management and disposal legislations. Worldwide, the poultry–processing industry generates large quantities of feather by-products that amount to $40x10^9$ kg annually (Compassion in World Farming, 2013). According to some available figures of the USA Foreign Agricultural Service post reports, the total domestic per capita consumption of chickens is 59 kg in the United States; 48.0 kg in the Saudi Arabia, 67.1 kg in Hong Kong, 69.7 kg in Israel, and 35.4 kg in Canada (USDA Foreign Agricultural Service, 2014) – in South Africa the consumption rate in 2011 was 36.27 kg (DAFF, 2014). Considering that feathers represent 5-10 % of the total weight of mature chickens (Rahayu and Bata, 2015), it is evident that the industry generates a large amount of feathers as a waste product, e.g., more than $258x10^6$ kg of chicken feathers are produced in the Republic of South Africa alone (DAFF, 2014) (Figure 4.1.1). This large consumption of chicken results in generation of huge amounts of chicken feathers.

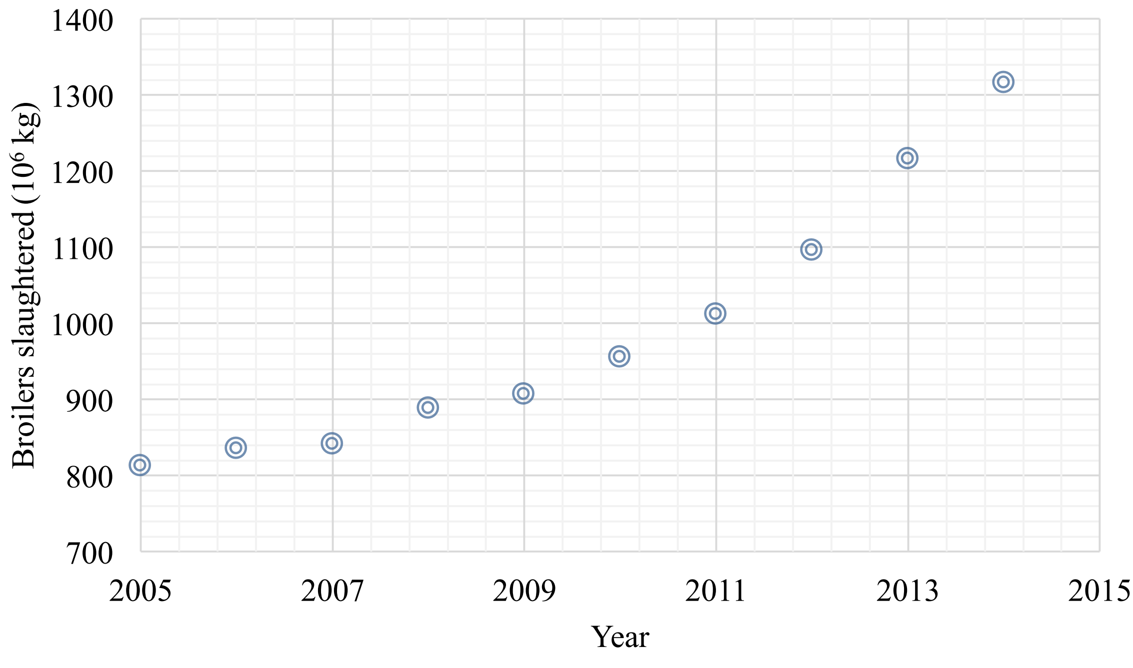


Figure 4.1.2. Annual slaughter of broilers in South Africa (adapted from DAFF, 2014).

The feathers are considered wastes and different approaches have been used for disposing of waste feathers, including land-filling and incineration (Veerabadran et al., 2012; Stingone and Wing, 2011). However, improper disposal of these biological wastes by landfilling contributes to environmental damage and transmission of diseases (Tronina and Bubel, 2008). Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. Burning poultry wastes may actually produce as much or more toxic air emissions than coal plants. For example, analysis conducted by the North Carolina Department of Environment and Natural Resources found that a 57 MW poultry waste combustion plant emitted levels of carbon monoxide, particulate matter, nitrogen oxides, and carbon dioxide per unit of power generated that were higher than those for new coal plants (Stingone and Wing, 2011). An alternative to reduce these environmentally unfavourable disposal options is the utilisation of feather constituents as animal feed. Traditional methods to degrade feathers for subsequent use as animal feed include alkali hydrolysis and cooking under steam pressure. For example, the feathers may be hydrolysed, dried and ground to a powder to be used as a feed supplement for a variety of livestock, primarily pigs (Park et al., 2000). This is a fairly expensive process, however, and results in a protein product of low quality for which the demand is low (Veerabadran et al., 2012). These methods are not ideal in that they not only destroy the amino acids in the feathers but also consume large amounts of energy.

The world poultry industry has struggled with this question: what to do with more than $40x10^9$ of poultry feather waste their business generates each year? A closer look at a chicken feather reveals that it is comprised of the rachis or quill, its primary structure, the barbs, its secondary structure, and the barbules, the tertiary structure (Figure 4.2.2).

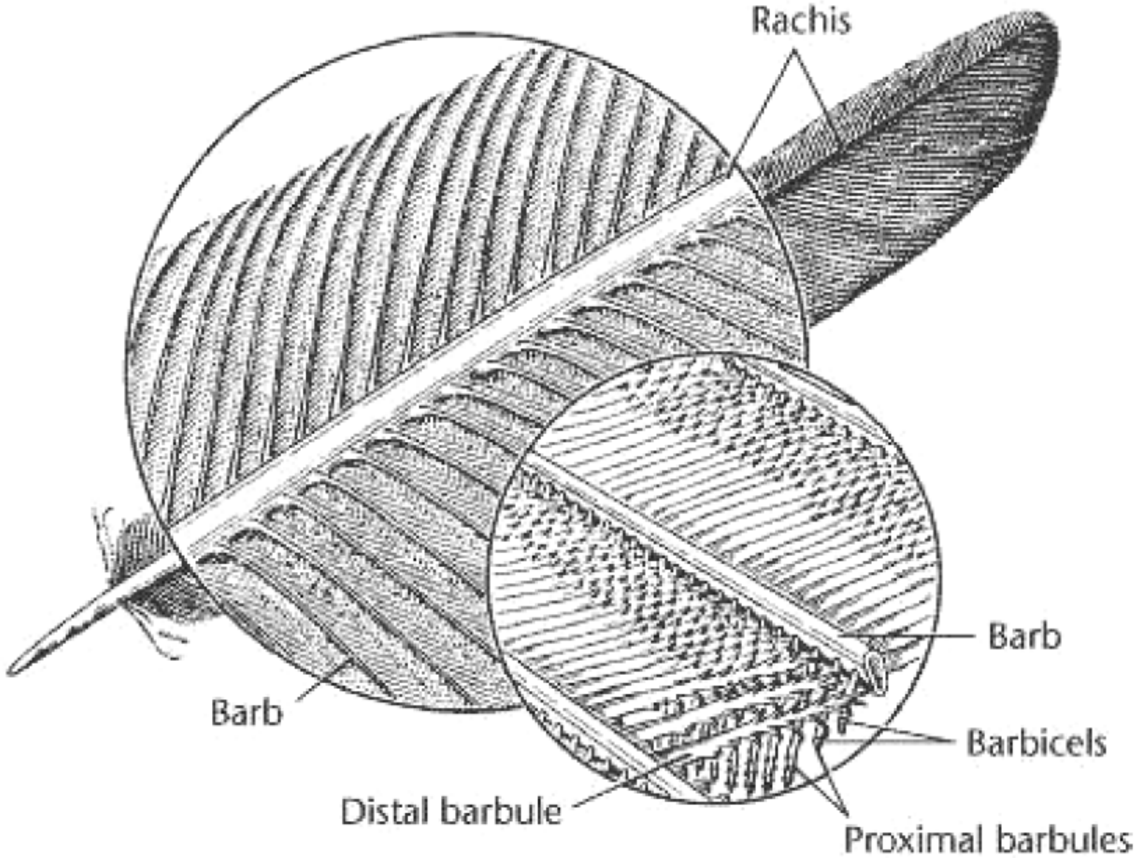


Figure 4.1.3. Structures of a chicken feather (adapted from Bartels, 2003).

Can these features and properties of these structures allow for valorisation of chicken feathers? The applications mentioned in the preceding paragraphs utilise only a small portion of waste feathers generated by the poultry processing industry. Therefore, there is need to find or develop valorisation technologies for the waste.

Characterisation and analysis of chicken feathers fraction to assess their suitability for valorisation as a source of protein fibre for high-value applications and the textile market is the first step for valorisation. In order to determine their suitability for these applications, it is important to understand the physical properties and the morphological structure of chicken feathers. Studies have been done in this topic, however, the studies were focused on specific applications upfront, e.g., textile applications (Reddy and Yang, 2005; Paul et al., 2014; Reddy et al., 2014), composite building applications (Jeffrey, 2006), biobased plastic resins containing chicken feather fibres (Roh et al., 2012), removal of heavy metals from wastewater (Al-Asheh and Banat, 2003), and a general description of feathers in domesticated birds (Bartels, 2003) none have focused on comprehensive evaluation of physical and morphological properties of feathers to help ascertain their possible valorisation. In this research, results of such comprehensive studies are reported: the morphological structure and physical properties of the whole chicken feather and of the component parts of the feather (barbules, barbs and rachis) were used to evaluate the possibilities for beneficiation of waste chicken feathers.

4.1.2. Materials and methods

Sample collection: Chicken feathers were obtained from a slaughterhouse in the province of KwaZulu-Natal, South Africa.

4.1.2.1. Sample preparation: The feathers were dried and conditioned at a relative of humidity 65±2 % and a temperature of 20±2 °C. The barbs were separated from the rachis manually by cutting with scissors. The cutting of fibres was performed near the rachis so as not to lose length and the natural properties due to the format of the fibre along the extension. For all samples prepared, their characterisations were conducted in a lab environment (temperature of 20±2 °C and a relative humidity of 65±2 %).

4.1.2.2. Measurement of physical properties: The chicken feathers were characterised for their physical properties and morphological structures. The methods used for the physical characterisation were adapted from those used for fibre characterisation of wool and other textile fibres. The parameters studied were fibre length, fineness, diameter, colour, ash content, moisture content, moisture regain, density, aspect ratio and dimensional properties.

4.1.2.3. Fibre length: Fibre length was determined by the "Oiled plate method" (ASTM, 2012) adapted from ASTM D5103-07. This is an individual fibre method that is used to measure the length distribution of short staple fibres. The requirements for the measurement of individual fibres makes this method the most accurate available. A sheet glass sheet was smeared with liquid paraffin, and some fibres were placed on its far-left corner. The fibres were then drawn out one at a time manually and straightened out and smoothed out over a centimetre scale etched on the underside of the glass sheet. The paraffin served to prevent the fibres from being blown away and assisted in keeping the fibres flat and straight for measurement. The lengths of 100 individual samples were noted.

4.1.2.4. Fibre diameter: The diameter of the feather fractions were measured at three different points along each fraction using an optical microscope (Nikon H600L). The average diameter of each fraction was calculated and was considered as the fibre diameter.

4.1.2.5. Fibre dimensions: For each chicken feather 25 samples were randomly chosen for measurement and the mean was calculated. Wall thickness and medulla width were measured using a light microscope. The following derived values were calculated from the data:

$$Slenderness\ ratio = \frac{Length\ of sample}{Diameter\ of\ sample} \quad [1]$$

$$Flexibility\ ratio = \frac{Lumen\ width\ of sample}{Diameter\ of\ sample} \quad [2]$$

4.1.2.6. Linear density of the barbs: The conditioned feathers were carefully combed with a fine comb, and 11.8 mm long bundles were cut with scissors. The bundles were weighed and the linear density was calculated.

4.1.2.7. Fibre density: Whole chicken feathers and feather fractions were prepared as blends of carbon tetrachloride (1.592 g/cc) and xylene (0.866 g/cc) density gradient. The samples were placed in a liquid pycnometer column for measurement of density. The density of the column increased linearly from top to bottom. A sample placed within the column comes to rest in a position which corresponds to its density. Five replicates were performed for each sample type.

4.1.2.8. Moisture content and moisture regain: A hot air oven was used to determine the moisture content of the samples. Two-gram samples were processed according to ASTM D1576-90 using the formula:

$$Moisture\ content = \frac{W_1 - W_2}{W_1} * 100 \qquad [3]$$

$$Moisture\ Regain = \frac{W_1 - W_2}{W_2} * 100 \qquad [4]$$

W_1 = Original mass of sample (g), and W_2 = Oven dry mass of sample (g)

4.1.2.9. Longitudinal and Cross-sectional areas: The longitudinal and cross-sectional areas of the feather barbs and rachis were measured using a Hitachi TM1000 scanning electron microscope (Hitachi High Technologies, Japan). The samples were cut to about 0.5–1 mm using a blade and the cut flat ends were used to measure the cross-sectional area, fine structure, appearance, microstructure and longitudinal views of the samples.

4.1.2.10. Surface area analysis: Surface areas of the samples were determined via Brunauer-Emmett-Teller/BET analyser. The BET surface area and micropore volume are determined using the nitrogen adsorption/desorption isotherms collected at liquid nitrogen temperature (77K) using a Micromeritics TriStar II surface area and porosity analyser (USA). Prior to analysis, the samples are degassed at desired temperature for a particular time under a vacuum of more than 2 µm He with a nitrogen gas flow to ensure absence of moisture in the sample. The desorption branch of the isotherm is used to determine the Barret-Joyner-Halenda (BJH) pore size distributions of the material.

4.1.2.11. Atomic Force Microscopy (AFM): Atomic Force Microscopy was performed with a Solver P47H base with a SMENA head, manufactured by NT-MDT. The cantilever of choice was a SuperSharpSilicon™ SPM-Sensor (SSS-NCLR, Nanosensors™) with a resonance frequency of 146-236 kHz; Force constant of 21-98 N/m; Tip radius 2nm (typical), the scan rate ranged from 0.6-1.6 Hz. Scans were taken in both height mode, in which the deflection of the cantilever was directly used to measure the z position (Height image) and in phase mode, where the phase lag of the cantilever was used to determine the differences in material stiffness (Phase image). All scans were conducted in air (climate controlled) at 256x256 pixels.

4.1.2.12. Colour: The colour of the samples was determined by using a Konica Minolta CR-410 Chroma instrument. The metre was calibrated with a white plate. Absolute colour readings were recorded in L*, a* and b* space (ASTM, 1998). The measurement were done in triplicate.

$$\Delta \boldsymbol{E} = [\Delta \boldsymbol{L}^{*2} + \Delta \boldsymbol{a}^{*2} + \Delta \boldsymbol{b}^{*2}]^{\frac{1}{2}} \qquad [5]$$

Where: L^*, a^*, b^* = CIE tristimulus values. ΔE = CIELAB colour difference

4.1.2.13. Sampling of chicken feathers for characterisation: Feathers differ in size depending on their location on the body of the chicken. Feathers can be distinguished as primary and auxiliary feathers in relation to body area from which they originated. Primary feathers are in the area of the wings and are not uniform in size. Therefore, to optimise measurements of weight and diameter, a random sampling technique was used. For measurement purposes, five different sampling positions were marked at specific distances along the length of the specimen as illustrated in Figure 4.1.3: the average of three replicates was considered as one measurement for each test except for length measurements.

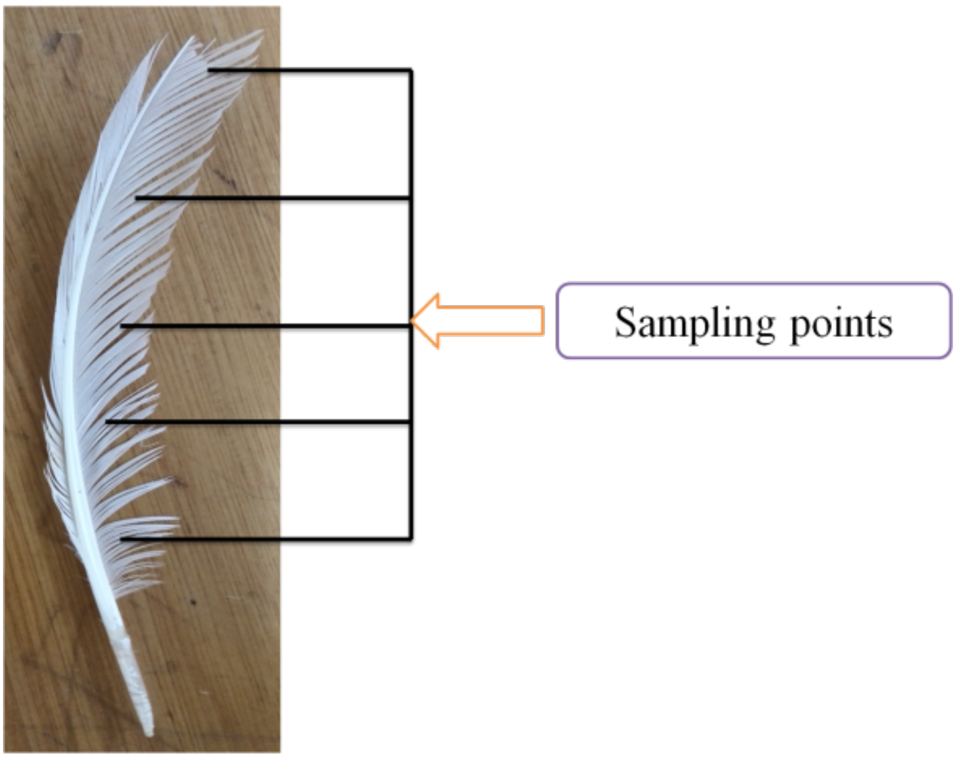


Figure 4.1.4. Selection of sampling points for measurement along a chicken feather.

Statistical analysis: Data on dimensions, analytical studies and physical parameters were subjected to statistical analyses. Microsoft Excel and Origin were used to analyse for the mean, standard deviation (SD) and coefficient of variation (Cv). Arithmetic mean and SD were calculated for all the data on barb, rachis and whole feather.

4.1.3. Results and discussions

4.1.3.1. Length: - Figures 4.1.4, 4.1.5 and 4.1.6 and Table 4.1.1 show the fibre length distribution of chicken feather barbules, barb and rachis. The averages of 100 readings at different sampling positions for a total of 100 samples were noted. The results show that the order of fibre lengths of the samples was barbules>rachis>barbs.

Table 4.1.1. Fibre length distribution of chicken feather fractions

	Barbules	Barb	Rachis
Mean	398.00 µm	24.75 mm	92.13 mm
SD	154.58 µm	19.14 mm	55.28 mm
Median	379.79 µm	25.31 mm	124.85 mm
Cv	38.84%	77.31%	60.01%

Rachis: The length of the chicken feather rachis ranged between 40 mm to 150 mm. This gave the range of the chicken feather rachis as 110 mm. The range was high, due to the different sizes of the rachis at different sampling position of the chicken body. The median length was 124.85 mm and the mean length was 92.13 mm with a SD of 55.28 mm. The length distribution of chicken feather rachis was not normal and showed a positive degree of kurtosis from 121-140 mm (Figure 4.1.4). From the data, it can be deduced that the chicken feather rachis is of lengths that can be spun since spinning is applicable for fibres with lengths of greater than 12.7 mm (May, 2002).

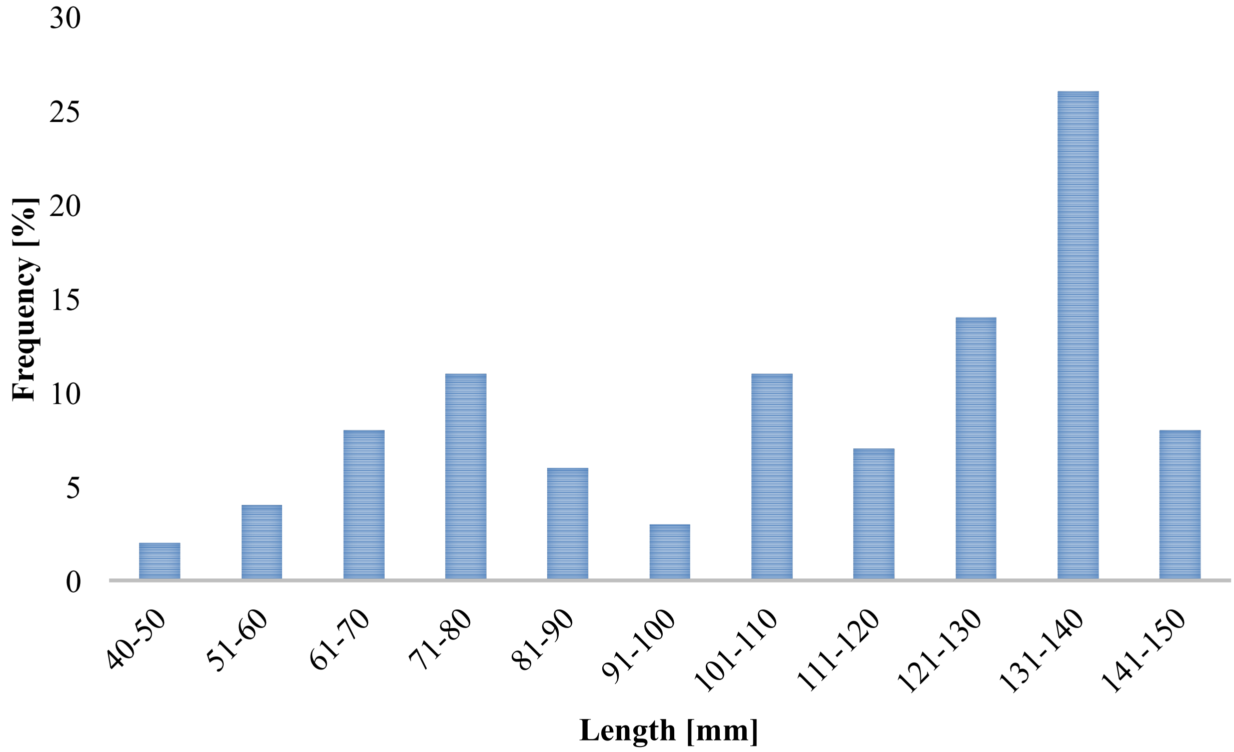


Figure 4.1.5. Fibre length distribution of chicken feather rachis

Barbs: The distributions of chicken feather barb fraction were not normal but rather showed a positive degree of kurtosis from 21-30 mm (Figure 4.1.5). The lengths of the barbs ranged between 1 mm to 45 mm. This gave the range of the fibres as 44 mm.

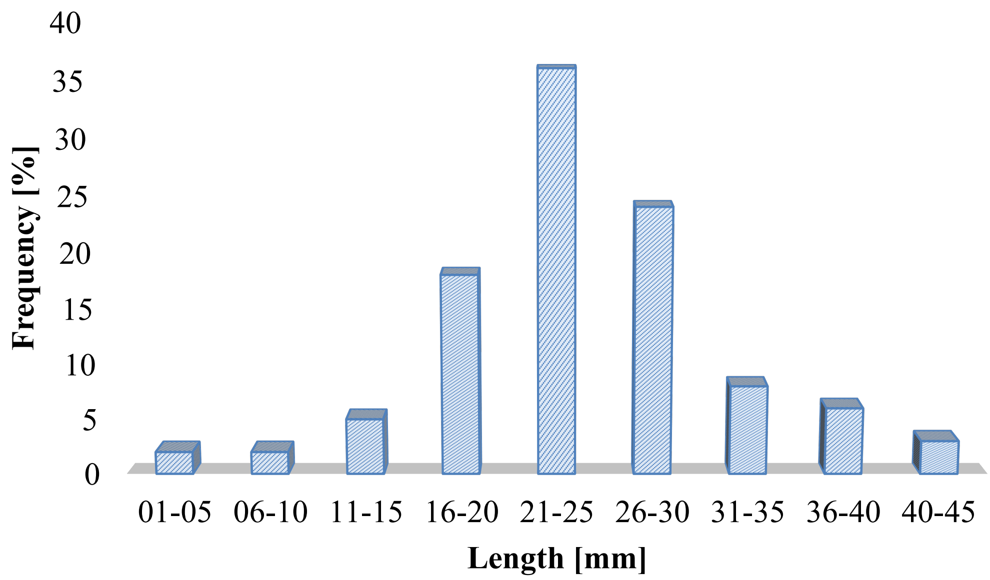


Figure 4.1.6. Fibre length distribution of chicken feather barbs

The data in Table 4.1.1 indicate that barbs of chicken feathers are of a length that is suitable for spinning into yarn fibres (Hearle, and Morton, 2008). However, the fibre lengths of the barbs lie between short staple and medium staple textile fibres: this will affect the spinning limit, handling of the product, the lustre of the product, quality of the yarn. The higher the amount of short fibres the more end breakage will occur during processing, which negatively affects the quality of the product and the production rate. The length distributions of each chicken feather barb along the length of one rachis were not consistent along their lengths; the mean Cv for ten samples at five sampling positions was 53.53% demonstrating the heterogeneity of the sample. However, variations of barb length up to the third sampling position were consistent varying by less than 15%.

Barbules: The fibre length distributions of chicken feather barbules were approximately normal (Figure 4.1.6) and ranged between 1 to 800 μm. The data indicate that barbules of chicken feathers are of a length that is not suitable for spinning.

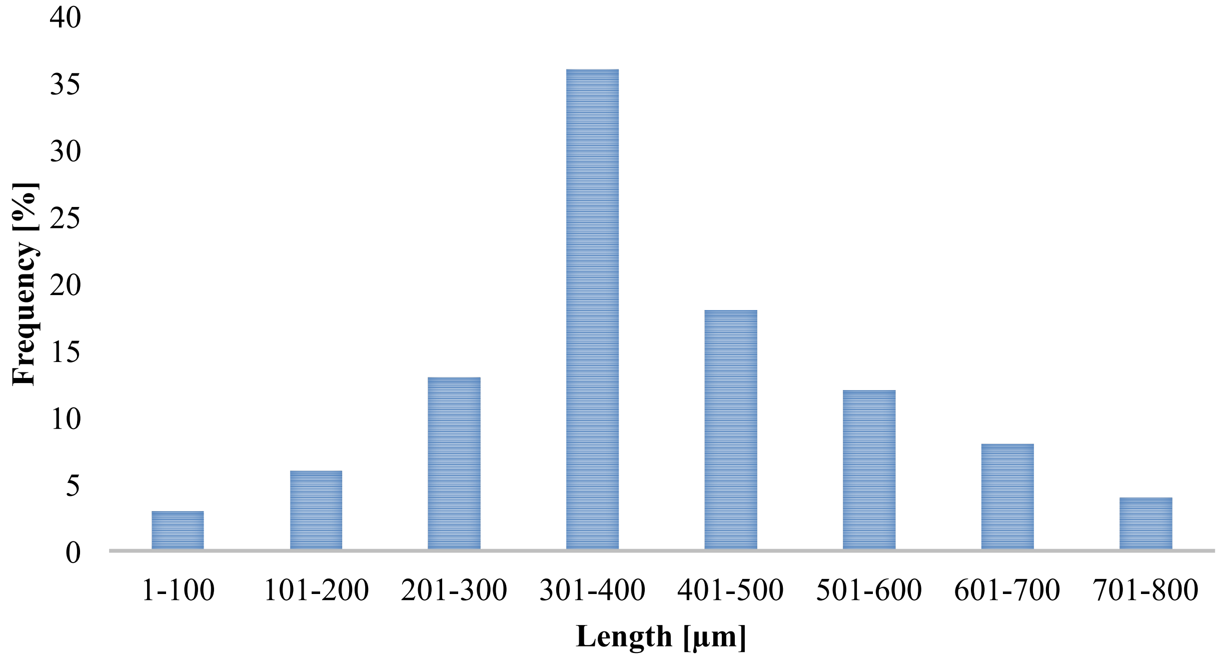


Figure 4.1.7. Fibre length distribution of chicken feather barbules

4.1.3.2. Fibre diameter: The data in Table 4.1.2 illustrate the diameter of the barbules, barbs and rachis of chicken feathers. The averages of three readings from different places along a single sample were used for 25 samples, for a total of 75 readings.

As can be seen from Table 4.1.2, the mean diameter of the chicken feather barbules was 4.93 µm, with a SD of 1.73 µm and a Cv of 35.12 %. The diameter of the barb was relatively small: the mean diameter was 46.65 µm, with a SD of 34.37 µm and a Cv of 73 %. The variation in diameter was high indicating that the barbs were of widely different diameters. Uniformity of barb width is an important aspect in the quality and flexibility of yarn spinning. Due to its contribution to softness and to the fact that finer fibre generates fibre yarns which produce lightweight fabrics, fibre diameter is the first requirement in yarn production. As the demand by the modern consumer is to seek comfort and enjoyment in wear, this is critical in the modern textile industry which is found especially in light weight fabrics.

Table 4.1.2. Diameter of chicken feather barbules, barb and rachis

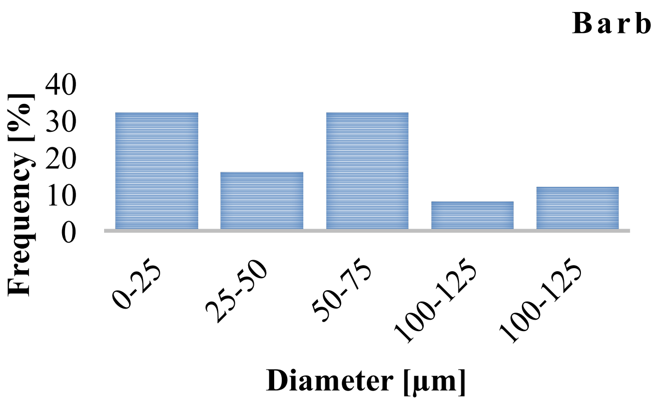
	Barbules	Barb	Rachis
Mean	4.92 µm	46.65 µm	2.26 mm
SD	1.73 µm	34.37 µm	1.17 mm
Cv	35.12 %	73.66 %	51.65 %

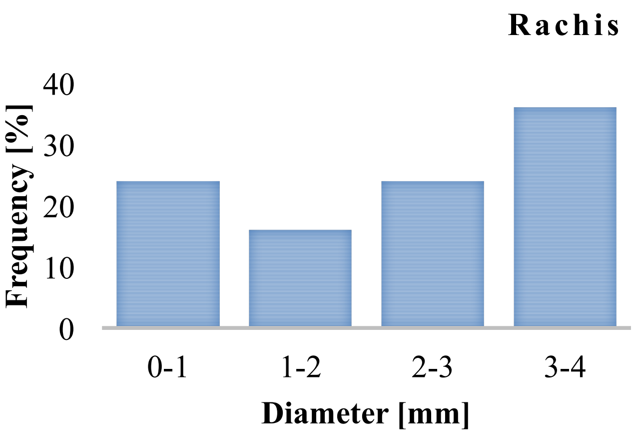
The mean diameter of the rachis of the chicken feathers was 2.26 mm, with a SD of 1.17 mm and a Cv of 51.65 %. The Cv of the measurement was relatively high and the diameter of the rachis was very high. The diameter of fibres affects the spinning quality and flexibility of the fibre: the finer the fibre the better the spinning quality. The diameter of the barb of the chicken feathers were in the range of spinnable diameter for the textile application (Hearle, and Morton, 2008: Jones, et al., 1998). Our results indicate that the rachis of chicken feathers will not be suitable for spinning into textile yarns.

The distributions of diameter widths of chicken feather barb and barbules were very consistent along their length, varying by less than 10% and 4%: only the extreme distal ends of the barb and barbules differed in diameter from the rest of the samples. The distribution of the diameter widths of the rachis was not consistent along the length of the rachis, varying by greater than 40%: the extreme distal end of the rachis is wider but the apex of the shaft is thinner than the rest of the rachis.

As shown in Figure 4.1.7, the fibre diameter widths distributions of barbules were approximately normal; however, the diameters of the barb and rachis were narrower (i.e., exhibited a negative degree of kurtosis from 5-50 μm and a positive degree of kurtosis from 3-4 mm). ANOVA statistics showed that the diameter width distributions of the different feather fractions were significantly different from each another.

The variation in fibre length and diameter of the barbs and rachis was very large, most probably because the feather samples originated from different positions on the chickens and from different sized chickens. Barbs and rachis from big chickens are longer than those from smaller chickens whereas barbs and rachis of small chickens are fluffier than those from large chickens. Also, barbs and rachis from big chicken feathers originating from the outer body of a chicken are much longer than those of small feathers from the inner body part of a chicken.





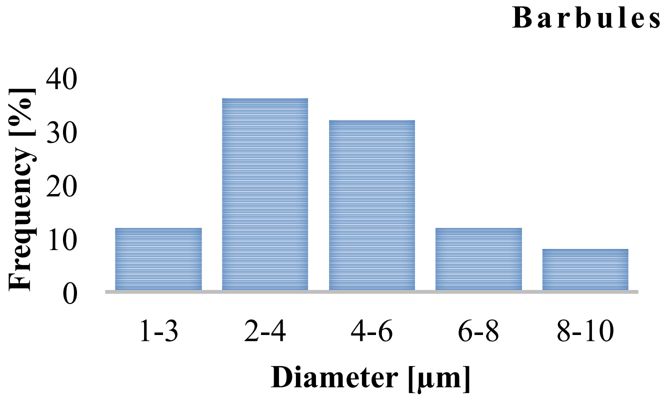


Figure 4.1.8. The distributions of diameter widths of chicken feather fractions

4.1.3.3. Linear density of barbs: The diameter dimensions of chicken feather barbs show that they are very fine fibres – determination of the linear density of this fraction is very complicated. However, the measurements were done and the results in Table 4.1.3 show that the linear density of a chicken feather barb bundle is 0.92 Tex with a SD of 0.69 Tex. The Cv of the linear density was 29.66 % and this low variation indicates that the sample was naturally homogeneous. Possible applications for this type of linear density include composites for applications in diverse areas such as automotive, aerospace, geotextile, decorative, and even textile industries (e.g., fabrics blended with wool or cotton).

Table 4.1.3. Linear density and fineness of chicken feather barb

	Linear density
Mean	0.92 Tex
SD	0.69 Tex
Cv	29.66 %

4.1.3.4. Dimensional measurements: Data for medulla diameter, cell wall thickness and length and diameter results for barbs are shown in Figure 4.1.8 and summarised in Table 4.1.4. The data for rachis were much bigger than that for barbs. Higher cell wall thickness/cortex of fibres causes more flexibility of fibres in further processing of fibres, e.g., in textile applications. The increase of cell wall thickness has a direct positive effect on strength properties of fibres.

The calculated values for aspect ratio/slenderness ratio and flexibility ratio are shown in Table 4.1.4: the barbs exhibited higher slenderness ratio flexibility ratio than the rachis. Table 4.1.6 shows that the corresponding average aspect ratio for barb was 530.55 whereas that for rachis was approximately 40.77. Slenderness ratio/aspect ratio is related to the dimensional parameters of fibres such as length and breadth. The preferred length to width ratio for use in textile industries is between 200–600 (Fathima and Balasubramanian, 2006). The results from the present work suggest that chicken feather barbs can be used as fibres in textile industries whereas rachis may not be used for such applications.

The use of any type of textile fibre for composite applications is dictated by its geometric dimensions, specifically a very high length-to-diameter ratio. In weight-sensitive applications such as automotive, aircraft and space vehicles strength-to-density and stiffness-to-density ratios are commonly used as indicators of the effectiveness of a fibre (Ververis, et al., 2004). The longer the fibre, the lower the number of ends, and the higher will be the load carrying capability. In general, the strength of fibre composites is dictated by the critical length of the fibre: the strength will be higher if the fibre length exceeds its critical length. If the aspect ratio is greater than 15, the fibre is termed continuous; otherwise, it is termed discontinuous (Gejo et al., 2010).

In this study, chicken feather can be considered as continuous fibre with average aspect ratio greater than 15, but their diameters and lengths varied depending on their location on the body of the chicken. Chicken feather fibres are naturally of short length which allows for accommodation of a number of fibres for the same volume fraction; increase in surface area improves the efficiency of load carrying (Fatima and Balasubramanian, 2006). The workability-reducing effect of fibres depends largely on aspect ratio. Ideally, the aspect ratio should be as small as possible to minimise the loss of workability and as large as possible to maximise the resistance of fibres to pull-out from the matrix and maximising their reinforcing effectiveness.

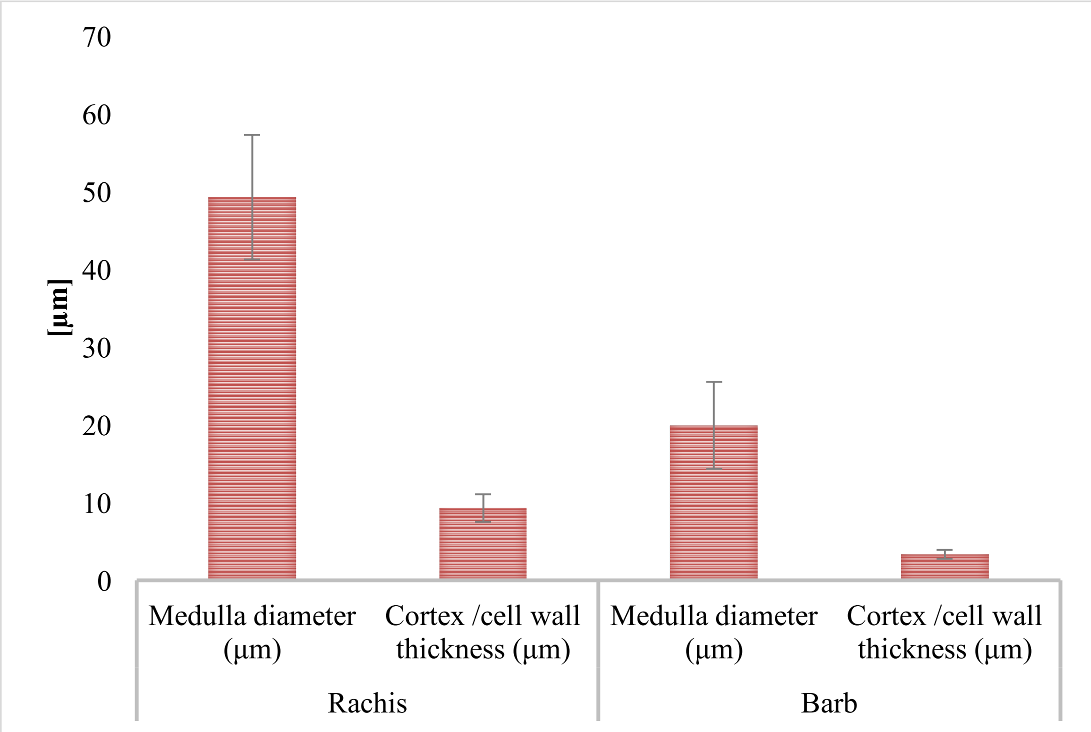


Figure 4.1.9. The dimensional measurements of chicken feather barbs and rachis

Fibres with high aspect ratios are thin and long whereas fibres with low aspect ratio are shorter and broader in the transverse direction. It is advantageous to retain as much fibre length as possible since higher aspect ratios give rise to good surface contact and fibre-to-fibre bonding. Long fibre lengths (up to 500 aspect ratio); result in high strength (Fowler et al., 2006). Short and thick fibres produce a poor slenderness ratio which in turn negatively affects the quality of the final products. This is partly because short and thick fibres do not produce good surface contact and fibre to fibre bonding.

Table 4.1.4. Dimensions of chicken feather fractions

Part of feather	Length (mm)	Diameter (µm)	Medulla diameter (µm)	Wall thickness (µm)	Slenderness ratio	Flexibility ratio
Barbs	24.75	46.65	26.88	3.31	530.55	57.62
Rachis	92.13	2,260	49.25	9.27	40.77	0.58

The flexibility ratio of chicken feather barbs was 57.62 while that of rachis was 0.58. According to the classification of textile fibres with respect to their flexibility ratio, the flexibility coefficient of chicken feather barbs places them in the elastic fibres group, whereas the rachis is included in the highly rigid fibre group. The flexibility and ability of the barbs to twist and bend will provide good strength, cohesiveness, and spinnability to yarns and fabrics made from them. If barbs are blended with other fibres, the morphological structures of the barbs, barbules and the hooks in the barbules will provide better cohesiveness to the blended yarns.

Fibre diameter and wall thickness govern fibre flexibility. A thick-walled fibre adversely affects burst strength, tensile strength, and folding endurance of the final product (e.g., textile fabric, composites, and paper). Product manufactured from thick-walled fibres will be bulky, coarse-surfaced and will contain a large amount of void volume whereas products from thin walled fibres will be dense and well formed.

4.1.3.5. Moisture content and regain: The data in Figure 4.1.9, illustrate the results of the moisture content of chicken feathers and fractions thereof. Moisture regain values are more commonly used in textile business transactions than moisture content values since buyers of fabrics are concerned with the weight of fibres and excess moisture impacts the weight of the purchased fabrics (fabrics with higher moister regain values will weigh more that those with low regain values). The results of the proximate analyses of chicken feathers (barb, whole feather and rachis) from different sampling positions of the feathers are presented in Figure 4.1.9. The moisture content of the barbs was the highest at 12.33 %, followed by that for whole feathers at 10.54 % and rachis at 8.75 %. From the data in Figure 4.1.9, the Cv for all samples is very low indicating that the sample was homogeneous. The moisture content values followed the same trend as the regain values except that the values were about 15 % smaller.

The ability of chicken feathers and fractions to absorb moisture from the environment has important implications for processing, storage, transportation, and durability of chicken feather containing composite materials, since increases in moisture content may interfere with processing or bonding, increase weight of the products (and transportation costs), or lead to rapid deterioration of the product. However, the average moisture content of the chicken feathers did not exceed 10.54 %: this implies that the material could be safely stored for long time periods with no concerns of deterioration. Moisture contents of 8%-13 % indicate that chicken feather is hygroscopic. The hygroscopicity increases in chicken feather barbs. This implies that they can absorb enough water to prevent static build-up – useful in applications where static build-up is of importance.

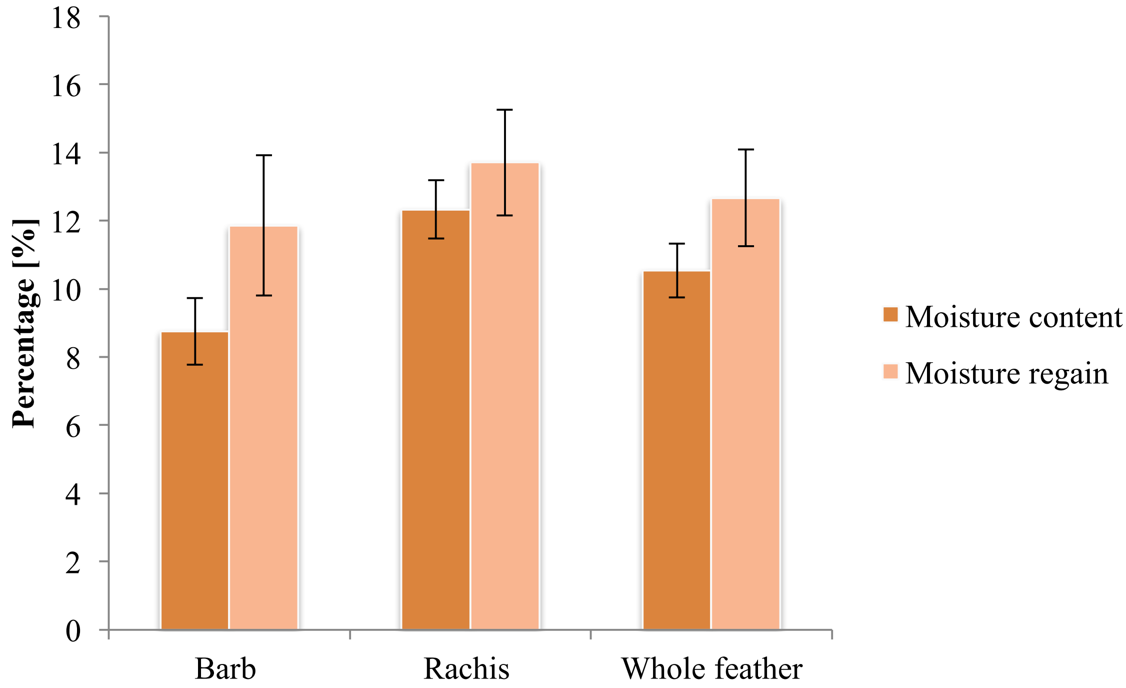


Figure 4.1.10. Moisture contents and regain of chicken feather fractions

In structural morphology considerations, the presence of a honeycomb structure will provide for the accumulation of liquids in its interior, in addition to the amount of water already absorbed by the dry material: 3.11 % for barbs, 1.39 % for rachis and 2.13 % for whole feathers. Chicken feather fractions could be a good opportunity for several types of applications that require liquid retention. For example, in the medical area, it is possible to insert drugs in microfibrous materials and, with body heat, the drug may be released to the body of the individual.

Fibres with greater regain values probably have more amorphous regions. The value of moisture regain of the chicken feathers was considered low compared to other fibres that have a moisture regain of up to 20 %. This probably implies that fabric products made from this material will provide comfort in texture to the end users.

The comfort of textile fabrics are influenced by moisture content and fibres with good moisture regain accept dyes and finishes more readily than fibres with low regain (Freddi, et, al., 2003); therefore, water-born dyes and finishes can be applied on the chicken feather fabrics. Further research is required to determine the maximum suitable moisture content of chicken feathers and also to assess the effect of variations in moisture on processing, storage, transportation, and durability of the fibres.

4.1.3.6. Morphological Structure: The morphological features of chicken feather fractions are shown in Figure 4.1.10. As can be seen in Figure 4.1.10a the chicken feather is composed of three distinct units: the rachis, the central shaft of the feather that runs the entire length of the feather to which is attached the secondary structures, the barbs and the tertiary structures, the barbules. The length of the rachis varies depending on the sampling position of the feathers on the body of the chicken; however, the lengths of barbs and barbules do not vary much except that sometimes barbs and barbules at the base of the rachis are longer than those at the tip of the rachis. The lengths of the rachis are about 1-150 mm and barbs are about 1-45 mm. The barbules are about 1- 800 μm long and have hook-like structures at their tips as can be seen in Figures 4.1.10a and 4.1.10b. Barbs display a fibrillar surface but no scales. From this information, it can be postulated that mechanical properties of fibrous composites made from feathers will be improved due to the entanglement of barbules with other fibres. Also, the occurrences of microfibrils in chicken feathers that are twisted form helixes imply that their use will impart high mechanical strength to the fibres.

The thickness and stiffness characteristics of chicken feather rachis indicate that rachis fibres are not suitable for use as natural protein fibres. In contrast, the flexibility and length of feather barbs make them suitable to be used as natural protein fibres. As can be seen in Figure 4.1.10c feather barbs show honeycomb shaped hollow cells in the cross-section direction. These honeycomb structure can act as a raw material for light weight high tech materials. The voids inside chicken feathers may be more accessible to fluids or air as length decreases. The presence of hollow honeycomb structures provides high resistance to compressibility and also imparts light-weightiness to barbs and rachis.

The honeycomb structure in the cross-sectional view of the chicken feathers, as shown in Figure 4.1.10d,e, confirms the existence of extensive air pockets in the feathers: this contributes to the high thermal resistance and good moisture transport characteristics of feathers. The presence of two different structures inside the bio-fibres are evident: they are microfibrils and protofibrils. The former have a more ordered and crystalline structure than the feather matrix. The protofibrils exist inside the microfibrils and are also surrounded by the matrix. The images in Figure 4.1.10e confirm that the microstructure of feathers is nearly round; the medulla in coarse fibres are concentric and irregular in size.

The presence of extensive air pockets in the structure of feathers imply that feathers can be used in the preparation of good thermal retention materials (Birbeck and Mercer, 1957; Das and Ramaswamy, 2006). This property imparts good resilience features to feathers and explains why feathers are good materials for preparation of products with good heat insulation capacity, e.g., winter outerwear coats.

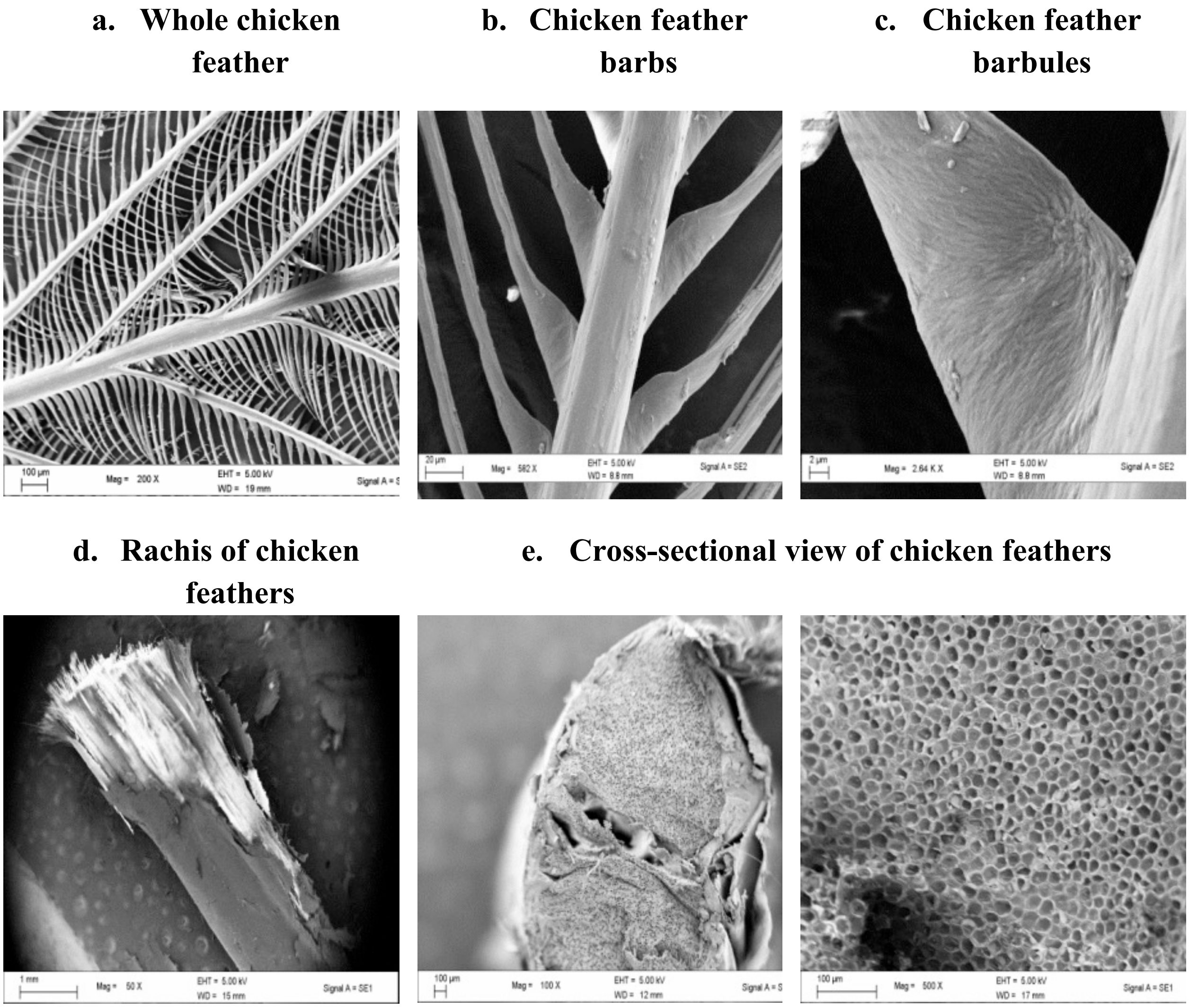


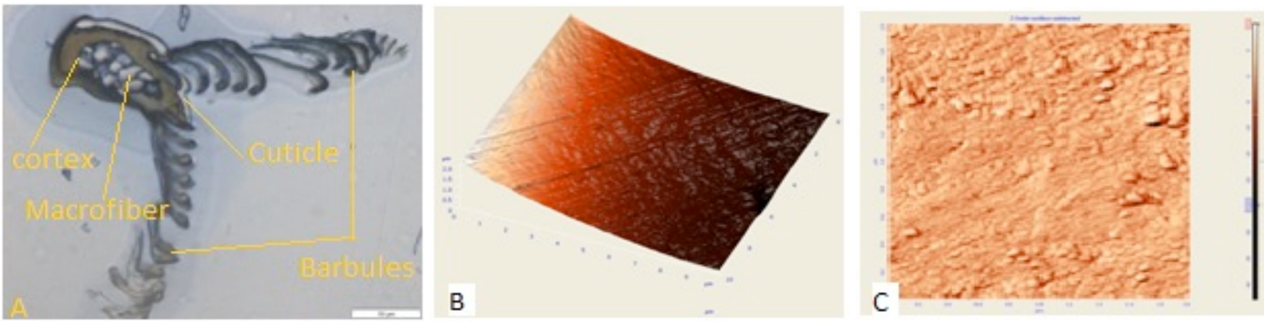
Figure 4.1.11. Morphological structures of chicken feathers (whole chicken feather, chicken barbs, chicken barbules, chicken rachis).

4.1.3.7. Fine details of chicken feather fractions cellular structures: From the AFM images of barb and rachis cross-section image, the cuticle, cortex, and epoxy resin regions can be easily recognised (Figure 4.1.11 and 4.1.12). Morphologically, the chicken feather barb and rachis consists of two components, outside layers of protecting cells, called cuticles which surround the cortex that consist of macrofibrils (Figure 4.1.11 and 4.1.12). The cell membrane complex separates cortex from those of the cuticle and a group of cortical cells were also linked together by cell membrane complex. In rachis of chicken feathers, there is also a central medulla (Figure 4.1.12.3). The cross-sectional shape of the rachis was greatly varied from sample to sample; some were approximately circular, whereas others were oval-shaped whereas the shape of the barbs were less varied in shape and were approximately oval-shaped. Figure 4.1.11.1 (a), the cross-section of the barbules were approximately a hooked/helical structure.

Cuticle: As it is seen in Figure 4.1.11 (4.1.11.1 (a) and (b)) and 4.1.12 (4.1.12.1 (a) and 4.1.12.2), a dark region surrounded the barb and rachis cross-section represented the cuticle. The cuticle, which were plate-shaped, form the outer part of the barb and rachis surrounding the cortical cells in layers of flat scales and was only one scale in thickness over most of its area (Figure 4.1.11 and 4.1.12). The cuticle of chicken feather fractions were smooth with low scales, indicates the lusterity of the fibre is good. As it is also observed in wool fibre, all interactions with the environment occur through the cuticle, providing resistance to potentially harmful agents that may come into contact. Since the cuticle is such a small part of both barb and rachis cross section, it is unlikely to contribute to the tensile properties.

Cortex: The cortex forms the central/principal part of both the barb and rachis cross-section of the chicken feather and two different morphological regions can be seen: the macrofibril and cell membrane complex (Figure 4.1.11 (4.1.11.1 (a) and (b - 3x3 μm)) and 4.1.12 (4.1.12.1 (a - 500x500 μm) and 4.1.12.2). It consists of small spindle-shaped cells which are a bundle of the intermediate filaments, oriented parallel to each other (Figure 4.1.11 and 4.1.12). As the diameter of the rachis greater than the barb, so the proportion of cortex in rachis is higher than rachis (Figure 4.1.11 and 4.1.12). Unlike in barb, the division of macrofibrils in rachis was quite clear, as fibril matrix divided them (Figure 4.1.12). A cortex cell of both barb and rachis contains a group of macrofibrils and they were separated by fibril matrix and between macrofibrils, there were nuclear remnants of keratinocytes (Figure 4.1.11.2 and 4.1.12.4). In the cortex, the nuclear remnants: which are not mature macrofibrils (Figure 4.1.12.1 (a)) were either found in stretched into dendrites or the centre of the macrofibrils. The shape and staining of the nuclear remnants seemed highly probable that they were melanin. The surface roughness is thought to be indicative of immature macrofibrils. Microfibrils are a relatively early stage of development, organised to form macrofibril structures which were also observed (Figure 4.1.11.2 (c - 1x1 µm) and 4.1.12.5 (b -8x8 µm)) and they consist of protofibrils (Figure 4.1.12.5 (c - 1x1 µm)).

4.1.11.1. Cross-sectional image of barb (a), Cuticle (b-3x3 µm) and the cortex (c- 2x2 µm*)*



4.1.11.2. Ultrastructure of chicken feather barb (cortex, macrofibrils, fibril matrix, and microfibrils), a-3x3 µm, b-2x2 µm, and c-1x1 µm.

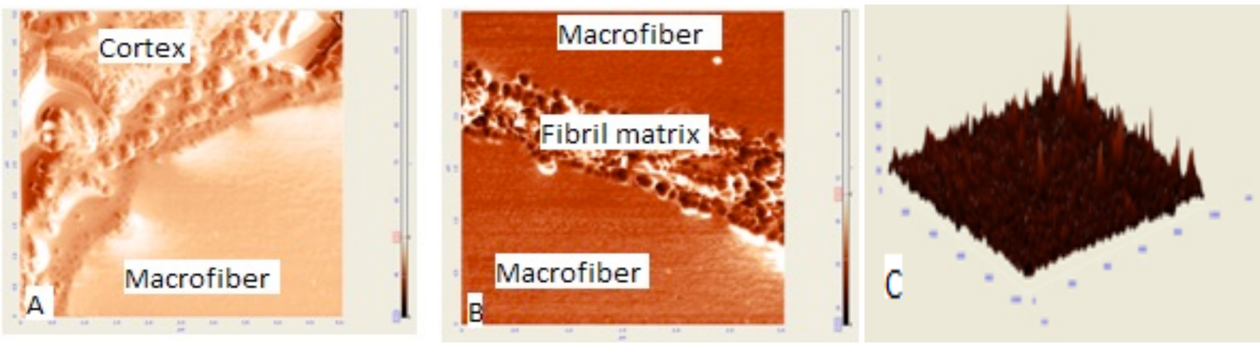
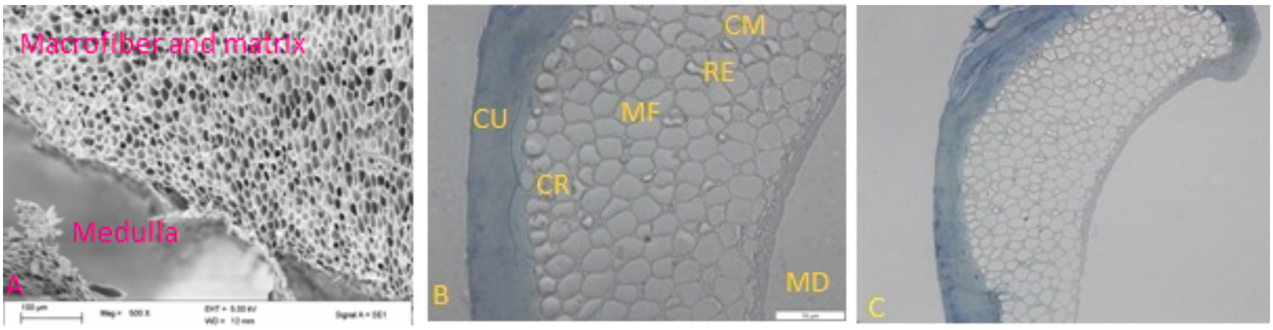


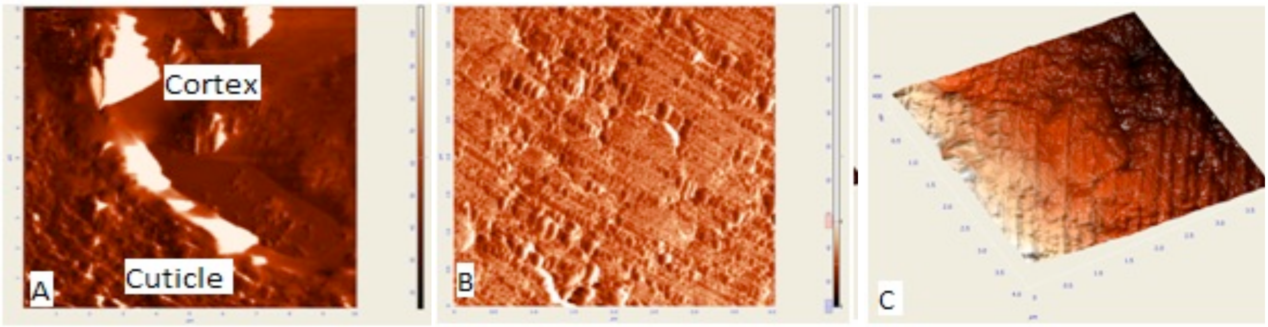
Figure 4.1.12. Cross-sectional images of chicken feather barb and fine detailed images of the cuticle region and cortex region.

4.1.12.1. Cross-sectional image of chicken feather rachis

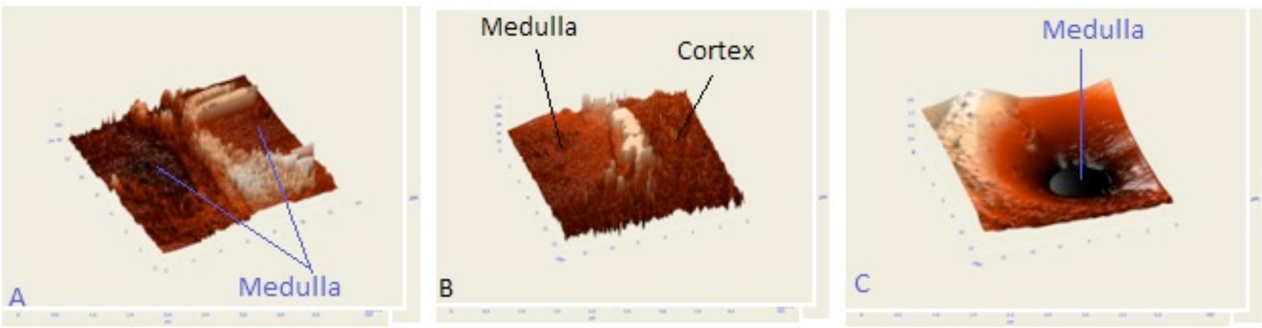


CU; cuticle, CR; cortex, MF; macrofibrils, RE; nuclear remnants, MD; medulla and CM; Cell membrane complex

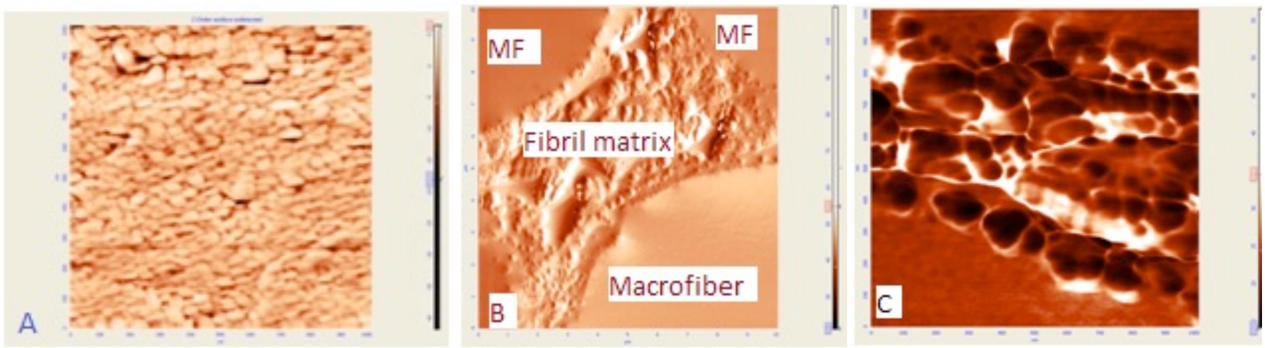
4.1.12.2. Cuticle (a - 10x10 µm), (b - 4x4 µm) and (c - 3x3 µm)



4.1.12.3. Medulla (a - 12x12 µm), (b - 12x12 µm) and (c - 12x12 µm)



4.1.12.4. Cortex (a - 1x1 µm*), Macrofibre and fibril matrix (b* - 10x10 µm*) and fibril matrix (c*- 1x1 µm*)*



4.1.12.5. Macrofibrils (a- 10x10 µm*), microfibrils (b*- 8x8 µm*) and protofibrils (c*- 1x1 µm*)*

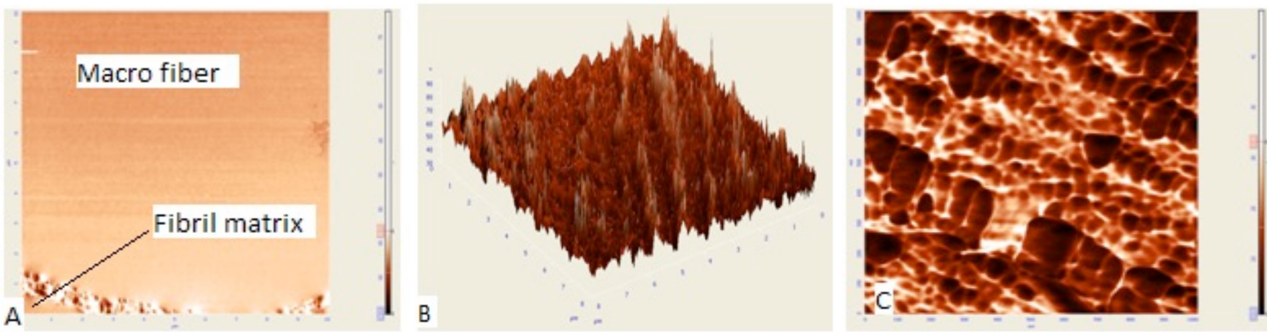


Figure 4.1.13. Cross-sectional images of chicken feather rachis and fine detailed images of the cuticle region and cortex region.

4.1.3.8. Density of chicken feathers: The density of whole feathers and feather fractions showed clear differences among them but that of the whole feather was very close to that of the barb density in almost all cases. The mean relative density of the barbs was 0.91 g/cm^3 with a SD of 0.22 g/cm^3 and Cv 24.29 %, a relatively low variation indicative of sample homogeneity. The density of chicken feather barbs varied between 0.5 g/cm^3 and 1.5 g/cm^3. The variation in results may be related to the composition differences in the barb samples studied.

The data in Figure 4.1.13 show that the mean recorded relative density of rachis was 0.44 g/cm^3 with a SD of 0.13 g/cm^3 and Cv 28.99 %, a relatively low variation indicative of sample homogeneity. The mean density of whole chicken feathers was 0.68 g/cm^3 with a SD of 0.13 g/cm^3 and Cv 18.91 % again, the Cv was relatively low and indicative of sample homogeneity. Chicken feather barbs consist of a large concentration of alpha helices whereas the quill or rachis is mainly composed of beta sheets and/or disordered structures. SEM micrographs of cross sections of a rachis (Figure 4.1.10) show an open cell porous structure, which very probably, is responsible for the low-density value of the rachis. The images of chicken feather barbs are typical of feather barbs, barbules, and hooklets.

The mean wet density of rachis was 0.76 g/cm^3 with a SD of 0.23 g/cm^3 and Cv 27.48 %, a relatively low variation indicative of sample homogeneity. The mean density of whole chicken feathers was 0.97 g/cm^3 (SD of 0.31 g/cm^3 and Cv 31.96 %) and barb was 1.31 g/cm^3 (SD of 0.36 g/cm^3 and Cv 30.26 %): again the Cv is relatively low and indicative of sample homogeneity. The result from Figure 4.1.13 shows that the density of chicken feather fractions after drying, indicating that a significant amount of moisture was present in the fractions. The low SD values confirmed the similarities of the density of the samples.

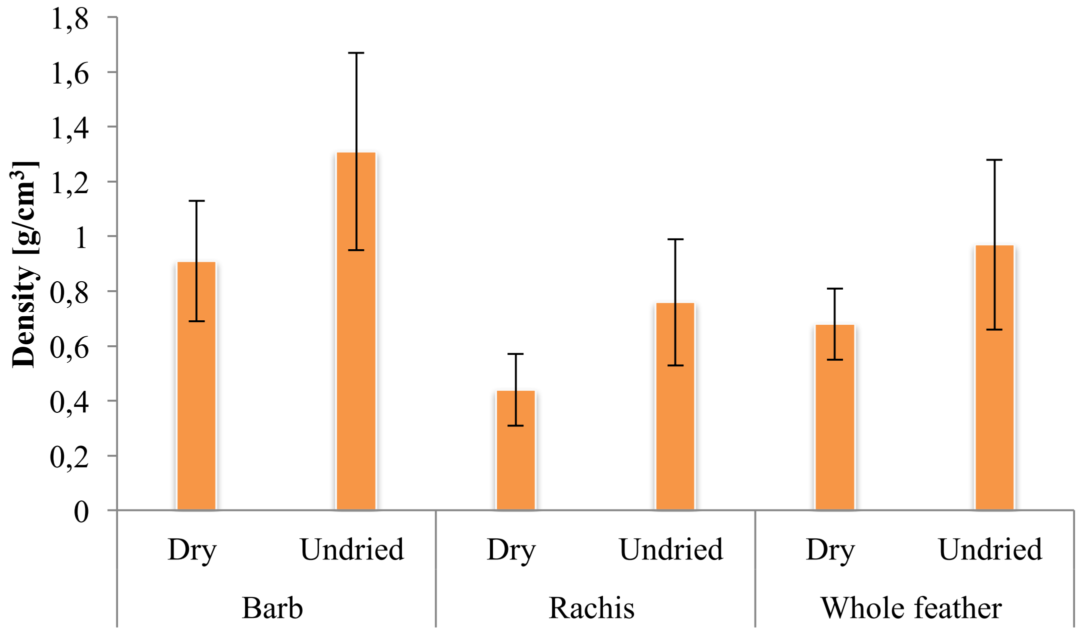


Figure 4.1.14. Density of chicken feather fractions

Considering that the chicken feathers used in this study were collected from one chicken processing plant, it is plausible that the density of the chicken feather fractions is likely to be influenced by the effectiveness of the waste chicken feather segregation process employed at the plant. Therefore, density measurements may be used to gauge the degree of the segregation process. Such properties are important in the valorisation of feathers into many applications such as textile yarn and composites.

The density of chicken feathers and fractions thereof, were measured to be 0.44-0.91 g/cm^3: these values correlated well with literature values for protein and cellulosic fibre but were lower than those of animal and plant fibres such as wool (1.31 g/cm^3), silk (1.27 g/cm^3), jute (1.3 g/cm^3), coir (1.2 g/cm^3), and cotton (1.5-1.6 g/cm^3), etc. (Hearle, and Morton, 2008). Considering that the density of composite materials increases as the amount of reinforcing fibre content increases, the inclusion of chicken feather fractions in a composite could potentially lower the density of the resultant composites. This implies that production of lightweight composites containing chicken feather fractions will result in substantial savings in terms of transportation and construction costs due to the inclusion of the lightweight feather fractions. No natural or commercially available synthetic fibres today have a density as low as that of chicken feathers.

4.1.3.9. Mass of chicken feather fractions: The mass distribution of chicken feather fraction and single barbs were significantly different among the fractions as can be seen in Table 4.1.5 and Figure 4.1.14. Box and whisker plots of the mass distribution for chicken feather fractions are shown in Figure 4.1.14. The result confirmed that mean weight of the chicken feather rachis was 48.28 mg with a SD of 25.12 mg and Cv at 52.03 % having a total percentage of 52.13 % of the whole feather. The Cv was relatively high due to the heterogeneity of chicken feather rachis at different positions on the body part of the chicken. The mean weight of barb in a chicken feather was 44.27 mg with a SD of 24.52 mg and Cv 55.39 %. The Cv is relatively high due to the heterogeneity of chicken feather barbs at different positions on the body parts of the chicken and rachis. The mean weight of a single barb was 0.10 mg with a SD of 0.05 mg and Cv at 55.02 %. The Cv is relatively high due to the heterogeneity of chicken feather barbs length distribution at different positions along the length of the rachis.

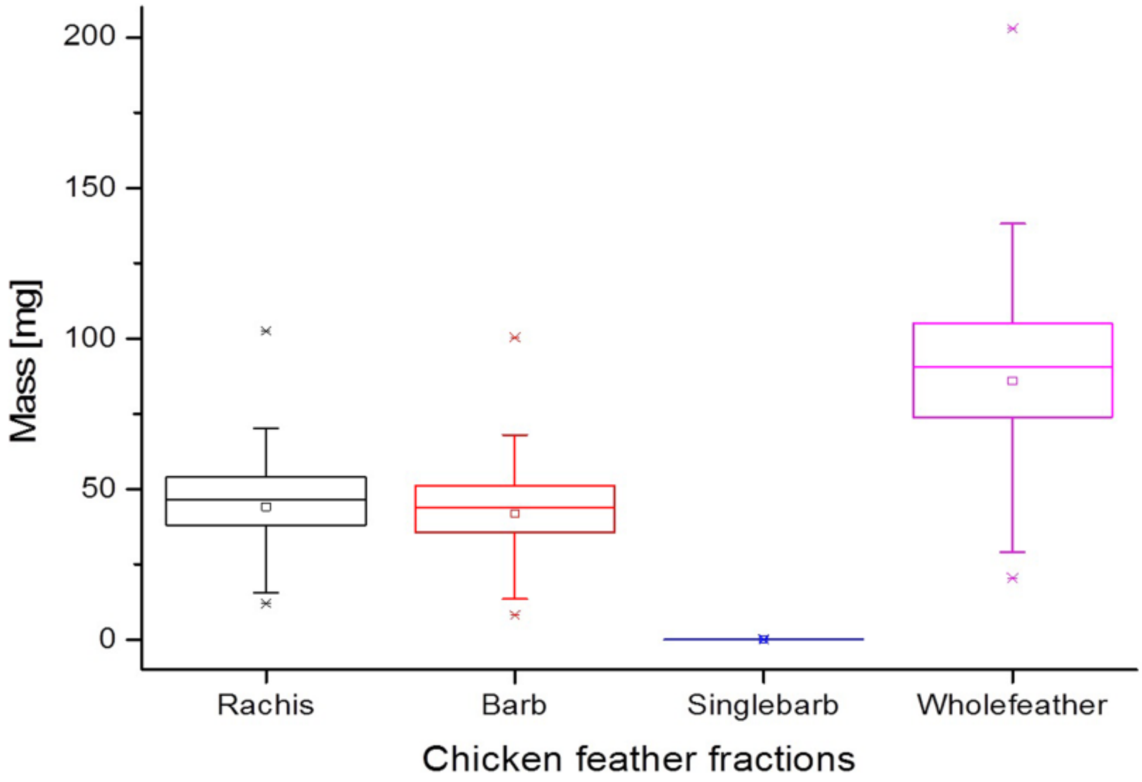


Figure 4.1.15. Box and whisker plots of mass distributions of chicken feather fractions (rachis, barb, single barb and whole feather). * refers to the highest and lowest values, the lower whisker represents the 10th percentile, the □ represents the mean value, the bottom of the box represents the 25th percentile, the line inside the box represents the median value, the top of the box represents the 75th percentile and the top whisker represents the 90th percentile.

Table 4.1.5. The mass distributions of chicken feather fractions

	Whole feather	**Rachis**	**Barb in the whole feather**	**Single barb**
Mean (mg)	95.356	48.28	44.27	0.10
SD (mg)	56.14	25.12	24.52	0.05
Cv (%)	58.87	52.03	55.39	55.02
% age	100	52.13	48.87	-

4.1.3.10. Colour measurements: Table 4.1.6 shows the colour measurement data for chicken feather barb and rachis. Chicken feather colour varies due to the biological nature of the chicken and how it was processed. The amount of preen oil in chicken feather contributes to the yellowness of the feather and these fatty acid compositions varies for different age intervals. Particulates from dust bathing, pieces of feed and faecal matter may also be present in chicken feathers. Unprocessed white chicken feather collected from poultry industries appeared straw-like and the barbs were stuck to the rachis in a greasy tangle and turned dark brown after 2 days when left at room temperature. A malodorous smell was also evident due to the development of bacteria and the bacterial excrement caused the feathers to darken (Figure 4.1.15). As it is shown in Figure 4.1.15, the untreated white chicken feather also contains blood, which looks pink just after collection but turns brown as it dries. The method of transporting the feather, in the poultry industry (from the section to temporary waste storage area) may also affect the colour of the chicken feather and the amount of impurities. The CIE tristimulus (L*, a* and b*) values, whiteness index, yellowness index and colour difference result from Table 4.1.6 shows that there is a need to pre-treat the chicken feather in order to improve the colour of the chicken feather before valorisation.

a b

Figure 4.1.16. Chicken feather from poultry industry (a: during collection; b: after three days)

Table 4.1.6. CIE tristimulus values, whiteness index and colour differences (ΔE) for chicken feathers

Fraction of chicken feather	L^*	a^*	b^*	ΔE	WI CIE	YI E313
Barb	75.36	2.81	19.59	77.91	-57.75	43.18
Rachis	78.54	1.43	11.32	79.36	48.34	41.62

4.1.3.11. BET analysis: As it is seen from Table 4.1.7 and 4.1.8, the physiosorption property of the chicken feather fractions (barb and rachis) shows a significant difference of BET surface area. The difference in surface area of both samples may be due to the microstructural difference between the two samples as it is seen in the morphology section. Since the pore size of both fractions falls in between 2-150 nm, it can be concluded that the chicken feather fractions were mesoporous and microporous material (Weber et al., 2010: Gil, and Montes, 1994).

Rachis: The surface area of the rachis was 1.2528 m^2/g with a single point surface area at P/Po = 0.200876844: 1.2912 m^2/g (Table 4.1.7). The pore volume of barb for single point adsorption total pore volume of pores less than 168.9074 nm diameter at P/Po = 0.988792338 was 0.017373 cm^3/g. The chicken feather rachis has a pore size of adsorption average pore width (4V/A by BET) 55.47121 nm, BJH adsorption average pore diameter (4V/A): 42.9203 nm and BJH desorption average pore diameter (4V/A): 28.7849 nm.

Table 4.1.7. Physiosorption property of the chicken feather rachis

	Surface Area
Single point surface area at P/Po = 0.200876844:	1.2912 m^2/g
BET Surface Area:	1.2528 m^2/g
BJH Adsorption cumulative surface area of pores between 1.7000 nm and 300.0000 nm diameter:	2.171 m^2/g
BJH Desorption cumulative surface area of pores between 1.7000 nm and 300.0000 nm diameter:	3.3714 m^2/g
	Pore Volume
Single point adsorption total pore volume of pores less than 168.9074 nm diameter at P/Po = 0.988792338:	0.017373 cm^3/g
BJH Adsorption cumulative volume of pores between 1.7000 nm and 300.0000 nm diameter:	0.023291 cm^3/g
BJH Desorption cumulative volume of pores between 1.7000 nm and 300.0000 nm diameter:	0.024261 cm^3/g
	Pore Size
Adsorption average pore width (4V/A by BET):	55.47121 nm
BJH Adsorption average pore diameter (4V/A):	42.9203 nm
BJH Desorption average pore diameter (4V/A):	28.7849 nm

Barb: The surface area of the barb was 0.7845 m^2/g with a single point surface area at P/Po = 0.201083043: 0.8712 m^2/g (Table 4.1.8). The pore volume of barb for single point adsorption total pore volume of pores less than 139.3977 nm diameter at P/Po = 0.986439263 was 0.007904 cm^3/g. The chicken feather barb has a pore size of adsorption average pore width (4V/A by BET): 40.29871 nm, BJH adsorption average pore diameter (4V/A): 87.0263 nm and BJH desorption average pore diameter (4V/A): 25.8096 nm.

Table 4.1.8. Physiosorption property of the chicken feather barb

	Surface Area
Single point surface area at P/Po = 0.201083043:	0.8712 m^2/g
BET Surface Area:	0.7845 m^2/g
BJH Adsorption cumulative surface area of pores between 1.7000 nm and 300.0000 nm diameter:	0.615 m^2/g
BJH Desorption cumulative surface area of pores between 1.7000 nm and 300.0000 nm diameter:	2.1358 m^2/g
	Pore Volume
Single point adsorption total pore volume of pores less than 139.3977 nm diameter at P/Po = 0.986439263:	0.007904 cm^3/g
BJH Adsorption cumulative volume of pores between 1.7000 nm and 300.0000 nm diameter:	0.013389 cm^3/g
BJH Desorption cumulative volume of pores between 1.7000 nm and 300.0000 nm diameter:	0.013781 cm^3/g
	Pore Size
Adsorption average pore width (4V/A by BET):	40.29871 nm
BJH Adsorption average pore diameter (4V/A):	87.0263 nm
BJH Desorption average pore diameter (4V/A):	25.8096 nm

Figure 4.1.16 shows the BET specific surface area of chicken feather fractions. It can be seen from the Figure 4.1.16 that the rachis were much more linear and the data is uniformly distributed compared to the barb of chicken feathers. Figure 4.1.16 demonstrates that the amount of the adsorbed nitrogen is noticeably lower for barb compared to the rachis part. This region is the representative of adsorption in micropores, which are the internal adsorption sites inside the chicken feather fraction. These results showed that the material produced from rachis have very stable adsorption and desorption resulting in the higher surface area compared to material produced from chicken feather barb.

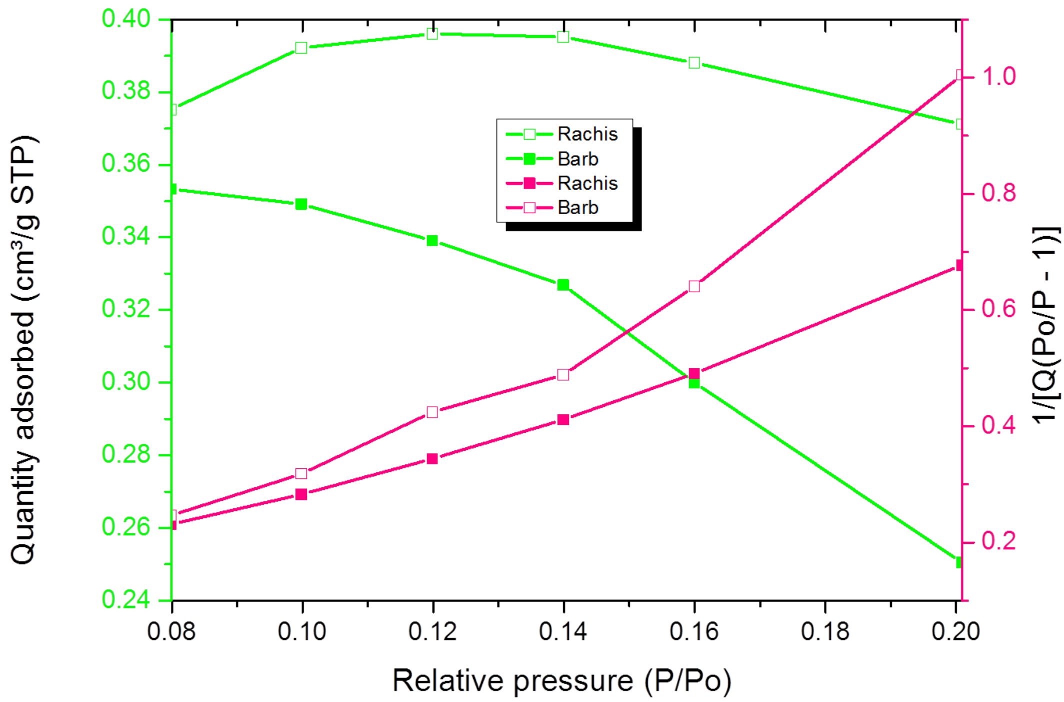


Figure 4.1.17. BET Specific surface area analysis of chicken feather fractions

Nitrogen adsorption/desorption isotherms at 77 K of the barb and rachis of the chicken feather samples are shown in Figure 4.1.17. Both fractions exhibited the type-III isotherms and explains the formation of multilayers. Figure 4.1.17 shows considerable differences between the adsorption/desorption isotherms of barb and rachis of the chicken feather: the uptake amount at low pressure by rachis were much higher than barb this is the indication for the presence of more mesopores. The uptake of nitrogen at very low pressures is due to mesopore and micropores filling from the enhanced adsorbent–adsorbate interactions in the mesopores and is distinct from adsorption in macropores because adsorption in mesopores material is due to multilayer adsorption and capillary condensation (Weber et al., 2010; Gil and Montes, 1994).

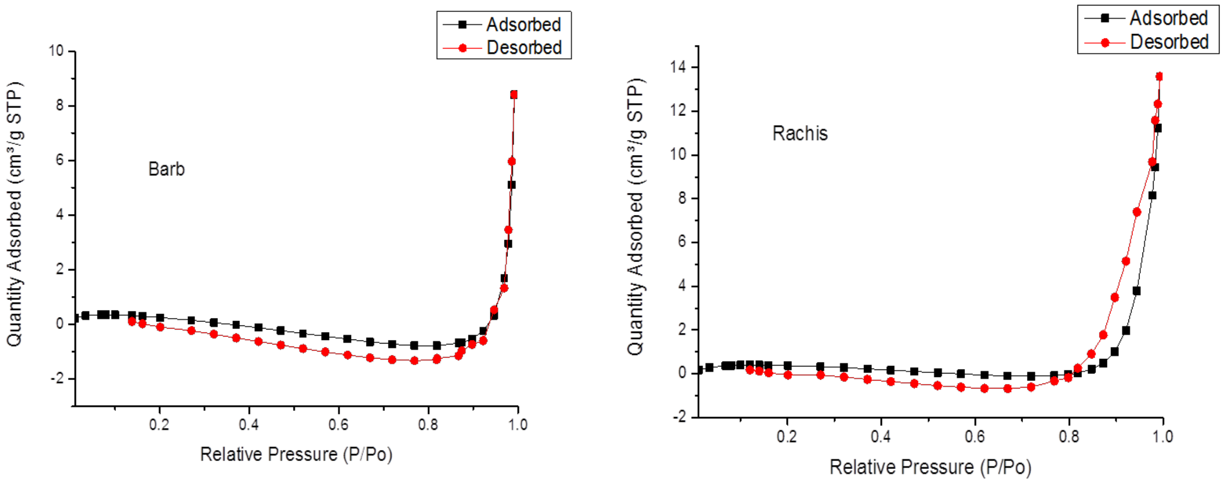


Figure 4.1.18. Adsorption/Desorption isotherm of chicken feather fraction

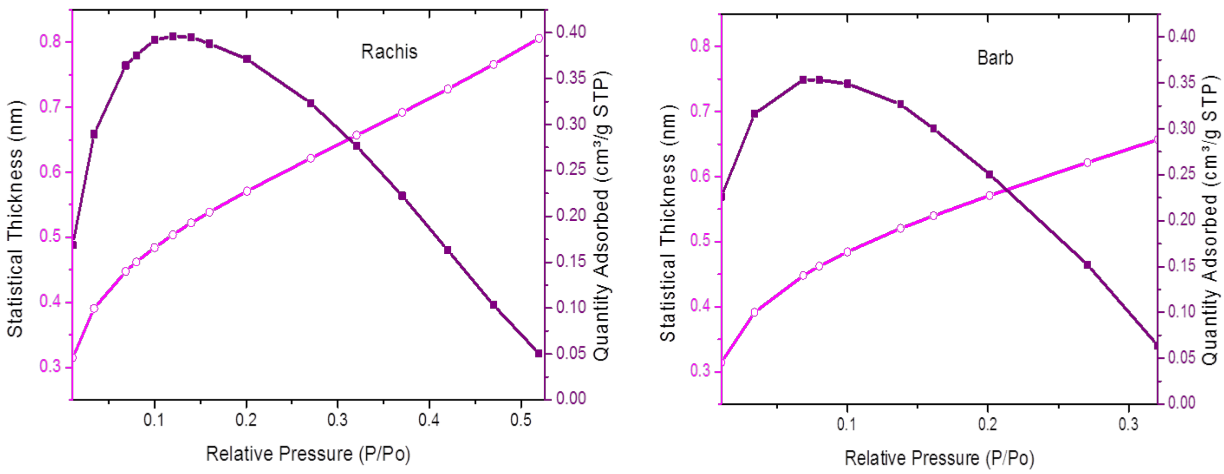


Figure 4.1.19. Thickness curve of chicken feather fraction

Figure 4.1.18 and 4.1.19 shows the t-plots of chicken feather fraction and indicates that there is a strong deviation in t-plots between the fractions. But the t-plot of the fractions were identical (Figure 4.1.18 and 4.1.19). The vertical line indicates the presence of mesopores and the horizontal line from the straight line indicate the presence of micropores (Weber et al., 2010; Storck et al., 1998).

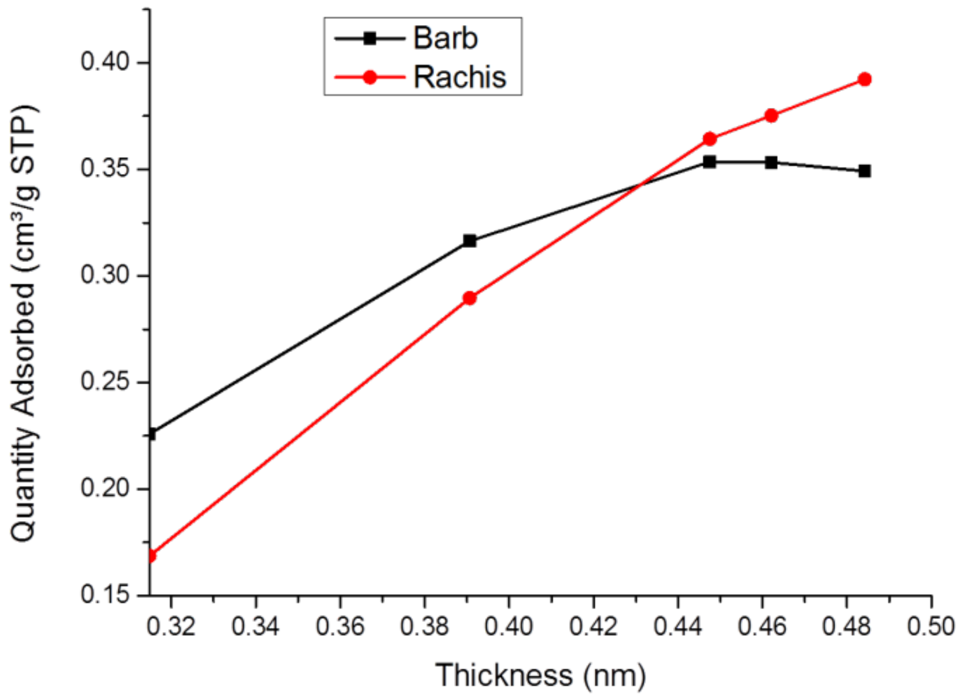


Figure 4.1.20. t-Plots of chicken feather fractions

Figure 4.1.20-4.1.23 shows the obtained pore size distribution of chicken feather fractions. The chicken feather fractions have both micropores and mesopores. The pore size distribution shows a maximum at the pore size of 11.8 nm for rachis and 2.89 nm for barb. There is a secondary maximum at a pore size of around 13.95 nm for rachis and 37.55 nm for barb and there are pores in the larger microporous and mesoporous regions, but all these pore distributions are much smaller than the primary maximum.

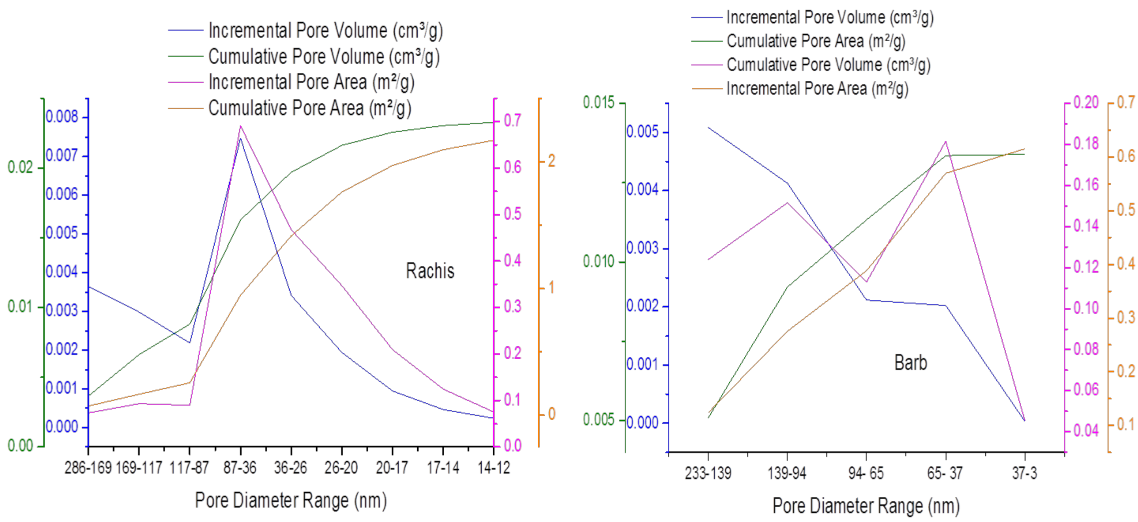


Figure 4.1.21. BJH adsorption pore distribution of chicken feather fractions

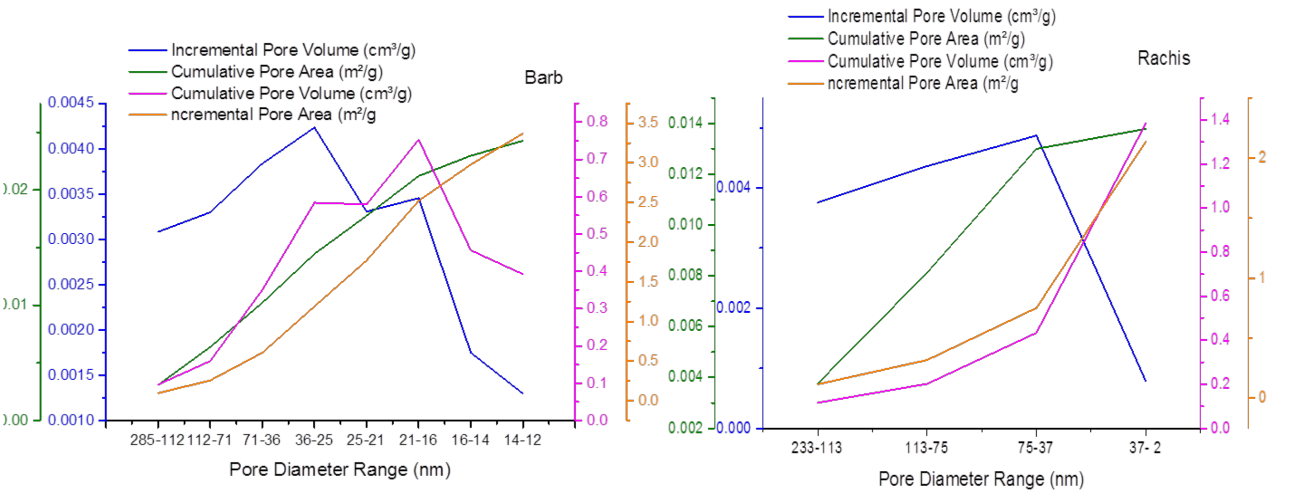


Figure 4.1.22. BJH desorption pore distribution of chicken feather fractions

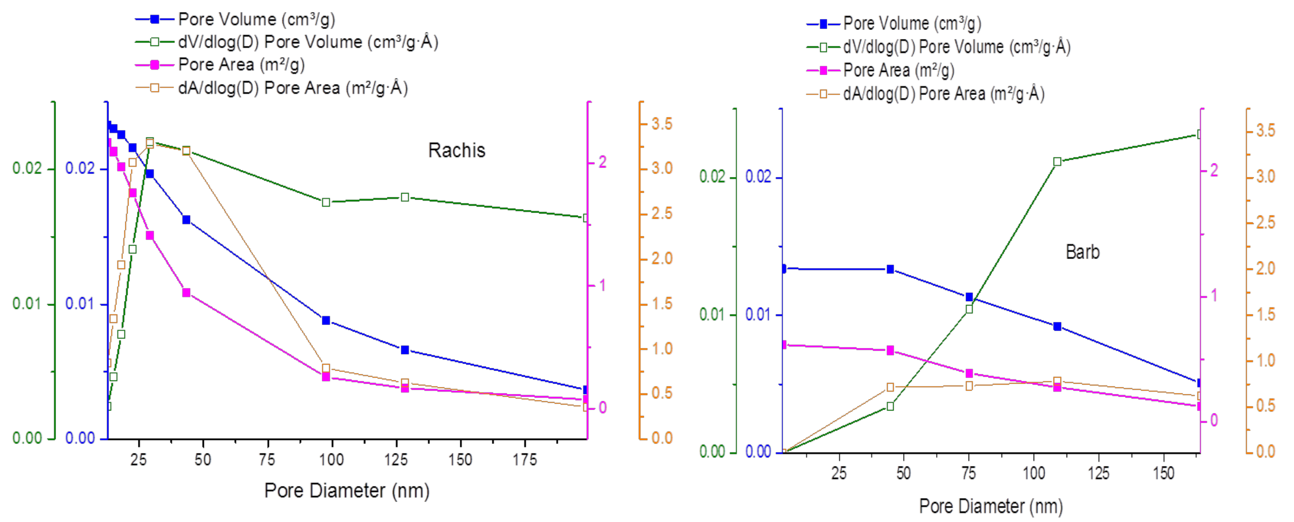


Figure 4.1.23. BJH adsorption cumulative pore volume, pore area, dV/dlog(D) pore volume and dA/dlog(D) pore area of chicken feather fractions

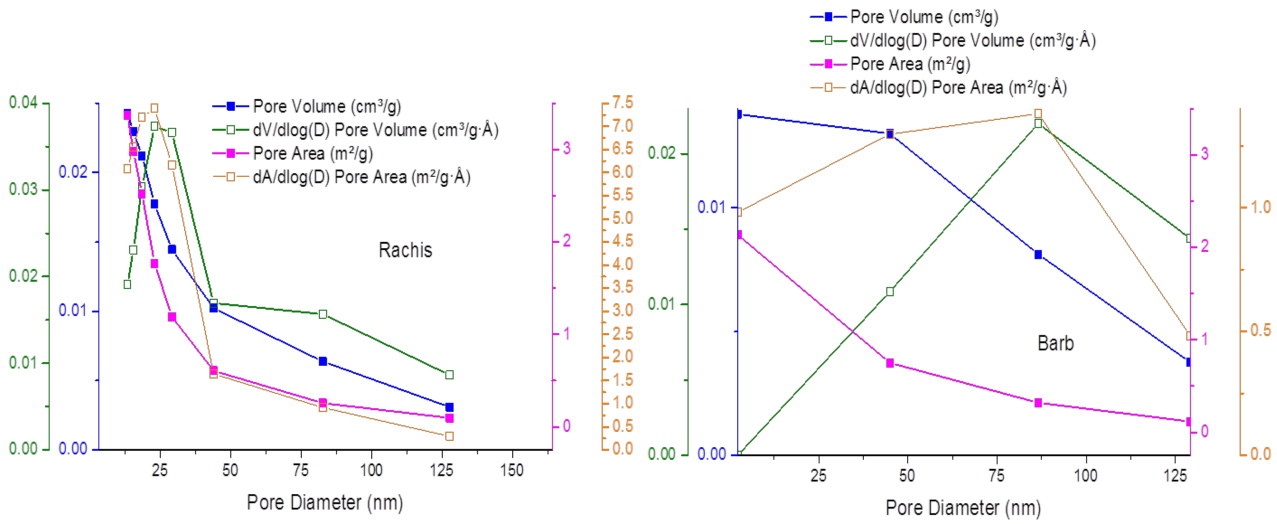


Figure 4.1.24. BJH desorption cumulative pore volume, pore area, dV/dlog(D) pore volume and dA/dlog(D) pore area of chicken feather fractions

4.1.4. Possibilities for valorisation of chicken feather fractions based on physical and morphological structure

The whole chicken feather, due to its complex structure, cannot be processed into protein fibre; however, its unique properties provide possibilities for valorisation into many applications. One such application is in the manufacture of composites for the construction, automotive and aerospace industries. Other applications could be keratin protein extraction for use in cosmetic, paper and pulp, and biodegradable plastic manufacturing. An added advantage is that chicken feathers are an abundant, renewable, waste-product of the poultry industry. In the textile industry chicken feathers could offer a cost-effective alternative source of raw material to the commonly used natural protein fibres, namely, wool and silk.

4.1.4.1. Composites in automobile and aeroplane industries: Currently, most automobile and aeroplane parts are made from petroleum-based raw materials. Owing to remarkable strength (due to the high cysteine content of the keratin protein, and low-priced properties), lightweight nature, and better quality (Figure 4.1.10, 4.1.11, 4.1.12), feathers could be used to produce composites for use in automobile and aeroplane industries such as in dashboards, car parts, seats and cushioning, interior linings etc. to reduce their weight while strengthening them.

4.1.4.2. Fibres in yarns and fabrics: It is estimated that there are $67x10^9$ kg of synthetic and natural fibres currently in use worldwide (Reddy and Yang, 2005). Due to the diminishing accessibility and expected cost increases of the raw materials and natural resources required to manufacture textiles and composite products, it is important to discover alternative sources. Endeavours are being made to utilise renewable agricultural by-products such as pineapple leaves, soybean husks, corn husks, and rice husk, as unconventional sources for cellulosic fibres (Reddy and Yang, 2006). The production of regenerated fibres from agricultural by-products containing proteins such as zein in soya has been tried (Boyer, 1940). However, none of the attempts to produce high-quality protein fibres from agricultural by-products have been commercially successful.

The rachis of feathers comprises approximately half of the weight of the feather while the barbs make up the other half: more than 30 % of the barbs are longer than the 20 mm fibre length required for textile applications (Figure 4.1.5). This means that, on an annual basis, approximately $12x10^9$ kg of barbs could be available as natural protein fibres worldwide, with $77.4x10^6$ kg of barbs obtainable in South Africa (Table 4.1.9). This translates into an availability of 14 percent of the natural and synthetic fibre consumed annually.

Table 4.1.9. Availability of chicken feathers

	World	**South Africa**
Chicken feathers	$>40x10^9$ kg	$>258x10^6$ kg
Barbs	$20x10^9$ kg	$129x10^6$ kg
Barbs > 20mm	$12x10^9$ kg	$77.4x10^6$ kg
Barbs < 20mm and Rachis	$28x10^9$ kg	$180.6x10^6$ kg

4.1.4.3. Construction materials: Feathers could be used as reinforcement materials after prior separation of the feathers into long fibres, short fibres and powdered rachis (Figure 4.1.4, 4.1.5, 4.1.6, 4.1.8 and 4.1.9; Table 4.1.4). Although more research needs to be done, composites made of chicken feathers can be used in panelling or ceiling applications, and for thermal and sound insulation, but not for walls or pillars. Using chicken feather composites in the construction industry could be a major breakthrough to replace wood and plastic-based construction materials.

4.1.4.4. Geotextile materials: Geotextile materials are often used on road construction sites, building operation sites, and for coverage of agricultural areas and other uncovered land where stabilisation of soil is required. The materials are necessary for the conservation of landscapes to avoid removal or loss of sediment during rainfall and to help keep soil nutrients in place. There is a need for low-cost, biodegradable geotextile materials due to the high cost and environmental impact of synthetic erosion control geomaterials currently in use. One possibility is the development of yarns, knitted, and non-woven fabrics from feather fibres. Chicken feather geotextile materials would be strong and very stiff because of the tough keratin property of the feathers (Figure 4.1.4, 4.1.5, 4.1.6, 4.1.8 and 4.1.9; Table 4.1.4). Geotextiles prepared from feathers could be used to preserve the soil environments. Because of the water holding capacity of feather fibres, the materials could increase the moisture content of the soil and also decrease compaction of the soil due to the bulking properties of feathers.

4.1.4.5. Fuel storage applications: Hydrogen, the simplest and most plenteous component in the universe, has long been touted as a clean and ample alternative energy option to fossil fuels (Cheng et al., 2001). Unfortunately, due to its physical properties (lightest element and very low volumetric energy density), it is difficult to store and transport hydrogen. Researchers have been endeavouring to engineer ways to store hydrogen gas on board vehicles at reasonable weights, pressure, and temperatures, to significantly reduce the expenses of a hydrogen infrastructure. However, the alternatives used to store hydrogen, such as metal hybrids and carbon nanotubes, are often very costly (Cheng et al., 2001).

A light-weight and economic material is needed that can bind and release hydrogen, to assist automobiles to use hydrogen fuel; one of these materials could be chicken feathers. Chicken feathers are composed of mainly keratin protein, a natural protein that forms lightweight, strong, hollow tubes (Figure 4.1.10). Seeing that the morphological structure and the adsorption/desorption isotherm of the chicken feather fraction chicken feather could be used as an alternative source for storing hydrogen gas. When pyrolysed, keratin becomes more permeable, expanding its surface, forming hollow tubes between the fibres, and creating crosslinks, which strengthen its structure and become carbon nanotubes. These features increase the ability to bind and store hydrogen. For example, to store and release the gas, one can pump hydrogen gas into feathers at high pressure, and then de-pressurize them, or raise the temperature, in order to release the gas.

4.1.4.6. Water purification: Chicken feathers could be used for water purification due to their inherent properties: structural toughness, stability over a wide range of pH, water insolubility, and high tensile strength. Their sorption characteristics will be satisfactory for the removal of heavy metals (e.g., copper, selenium, and zinc), toxic organic compounds and colourants in water, because of the hygroscopic nature of keratin protein (Kar and Misra, 2004). After extraction of keratin from chicken feathers, sponges could be prepared using dilution of the extracted keratin followed by lyophilisation. The sponge can be useful for example, in cleaning up of oil spills in water.

4.1.4.7. Filtration applications: The super fine size and shape of feather fibres imply that they may be used in filtration applications. Seeing that the morphological analysis and the BET analysis of chicken feather fractions, nonwovens made out of these fractions will exhibit very good porosity (Figure 4.1.10 and 4.1.16-4.1.23), good resistance to mild acids and alkaline media, and light weight characteristics leading to a promising future in the chemical industries. Feather fibres could replace wood pulp-based paper products such as filter papers and decorative papers. Wood pulps are the raw material for most paper-based products, but feather fibres have an advantage in full or partial replacement of wood pulp, as they are finer in diameter than wood pulp.

4.1.5. Conclusions

The physical and morphological structure studies of chicken feather fractions indicate that feathers can be used as reinforcing materials for composites and as textile fibres for the production of yarns and fabric. Because of the presence of hollow honeycomb structures and a very low-density, chicken feather rachis and barbs could be used for applications that require excellent compressibility and resiliency, warmth retention, fluid absorption, light weight composites and sound protection applications. Results of this study indicate that incorporation of chicken feathers can be beneficial in various industries including construction, automotive, aerospace and plastics to make products that are lightweight, improve sound attenuation, and offer insulate from heat loss. Future studies will entail studies on chemical properties of chicken feathers to ascertain their valorisation pathways.

ACKNOWLEDGMENTS

Funding and laboratory facilities were provided by the Thermodynamics Research unit, and the Biorefinery Industry Development Faciity/CSIR, Department of Science and Technology Waste Road Map; editorial assistance was provided by Ms Fiona Higginson.

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4.2. VALORISATION OF WASTE CHICKEN FEATHERS: CHARACTERISATION OF CHEMICAL PROPERTIES

(BASED ON PAPER FOUR)

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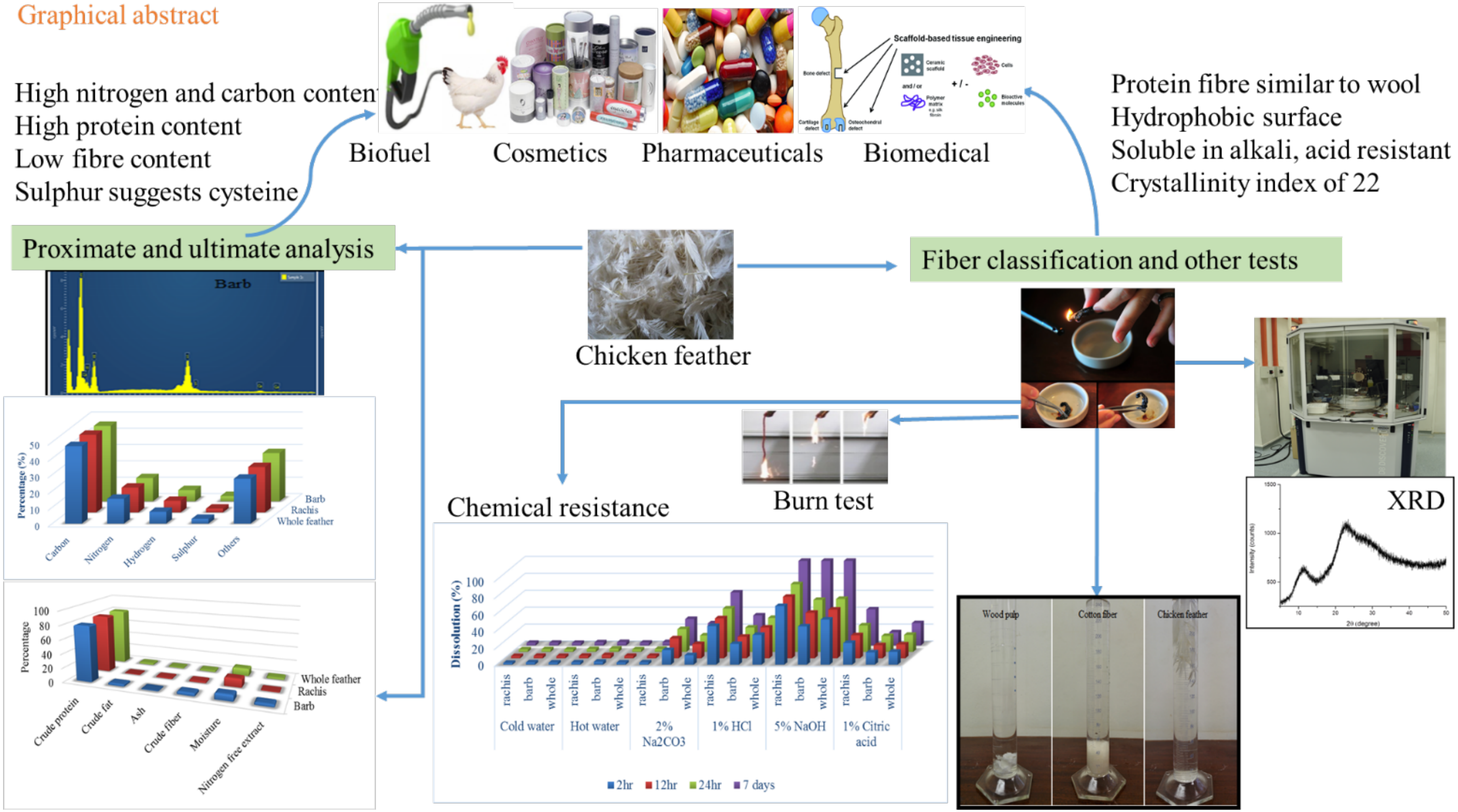
ABSTRACT

The characterisation of the chemical properties of the whole chicken feather and its fractions (barb and rachis), was undertaken to identify opportunities for valorizing this waste product. The authors have described the physical, morphological, mechanical, electrical and thermal properties of the chicken feathers and related them to potential valorisation routes of the waste. However, identification of their chemical properties is necessary to complete a comprehensive description of chicken feather fractions. Hence, the chicken feathers were thoroughly characterised by proximate and ultimate analyses, elemental composition, spectroscopic analyses, durability in different solvents, burning test, and hydrophobicity. The proximate analysis of chicken feathers revealed the following compositions: crude lipid (0.83 %), crude fibre (2.15 %), crude protein (82.36 %), ash (1.49 %), NFE (1.02 %) and moisture content (12.33 %) whereas the ultimate analyses showed: carbon (64.47 %), nitrogen (10.41 %), oxygen (22.34 %), and sulphur (2.64 %). FTIR analysis revealed that the chicken feather fractions contain amide and carboxylic groups indicative of proteinious functional groups; XRD showed a crystallinity index of 22. Durability and burning tests confirmed that feathers behaved similarly to animal fibre. This reveals that chicken feather can be a valuable raw material in textile, plastic, cosmetics, pharmaceuticals, biomedical and bioenergy industries.

Keywords: poultry waste, feathers, chemical properties, burning tests

Graphical abstract



4.2.1. Introduction

The disposal of waste in an economically and environmentally acceptable manner is a critical issue facing most modern industries. This is mainly due to increased difficulties in locating disposal works and complying with stringent environmental quality requirements imposed by waste management and disposal legislations. Worldwide, the poultry–processing industry generates large quantities of feather by-products that amount to $40x10^9$ kg annually (Compassion in world farming, 2013) – in South Africa, more than $258x10^6$ kg of chicken feathers are produced per annum (DAFF, 2014). The feathers are considered wastes to be disposed of although small amounts are often processed into valuable products such as feather meal and fertilisers (Veerabadran et al., 2012; Stingone and Wing, 2011). The remaining waste is disposed of by incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases (Tronina and Bubel, 2008). Traditional methods to degrade feathers for subsequent use as animal feed include alkali hydrolysis and cooking under steam pressure. For example, the feathers may be hydrolysed, dried and ground to a powder to be used as a feed supplement for a variety of livestock, primarily pigs (Park et al., 2000). This is a fairly expensive process, however, and results in a protein product of low quality for which the demand is low (Veerabadran et al., 2012). These methods are problematic in that they not only destroy the amino acids in the feathers but also consume large amounts of energy.

Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. It is important to find ways to beneficiate chicken feathers because this would not only recycle a waste product to provide high-value materials, it would provide extra financial resources to the poultry industry. Physical and morphological properties of chicken feathers have been studied with the objective of ascertaining their valorisation based on the properties (Tesfaye et al., 2017). In the context of this paper, the author could not find studies into the detailed and comprehensive analysis of the chemical properties of the chicken feather. In this research, results of such comprehensive studies are reported: the chemical properties of the whole chicken feather and of the component parts of the feather (barbs and rachis) were used to evaluate the possibilities for beneficiation of waste chicken feathers.

4.2.2. Materials and methods

4.2.2.1. Collection and preparation of chicken feather waste: - Chicken feathers were collected from a slaughterhouse (3 weeks broiler/meat chicken) in Durban, South Africa. On collection from a chicken processing plant, the feathers were a wet mass of blood, faeces, skin, flesh and other slaughterhouse residue. The feathers were washed at 50 ^{o}C to remove easily removable matters and then dried at 105 ^{o}C for 24 hr and conditioned at a relative humidity 65±2 % and a temperature of 20±2 ^{o}C. After drying, barbs were separated by manual stripping from the rachis. A portion of the samples were milled into powder using heavy duty milling machine , and the rest were left intact. The material was then packed and stored at normal room temperature (20–25 ºC) into three groups (whole feather, rachis and barb).

4.2.2.2. Proximate analysis: - This refers to the determination of the major constituents of biomass. For chicken feathers, the following components were determined: water, ash, volatile matter, fixed carbon, crude protein, crude fat, and nitrogen-free extracts. All tests were conducted in triplicate.

Ash Content: - Ash is inorganic residue obtained after combustion of biomass and is an approximate measure of the mineral salts and inorganic matter in feathers. The ash content was calculated in relation to the dry weight of the original sample after overnight ignition of the sample at 575±25 ^{o}C.

Moisture content: - The moisture content was measured according to ASTM D1576-90 standard by drying samples in an oven dryer.

Volatile matter content: - Volatile matter in chicken feathers was determined by heating known weights of samples in capped crucibles in an oven at 800 ºC for 40 minutes under an inert atmosphere. The volatiles liberated were calculated by mass difference before and after heating.

Fixed carbon content: - Fixed carbon is a value obtained by abstracting the sum of ash, moisture and volatile matter from 100 where all values are on the same moisture reference base. Thus:

$$Fixed\ carbon\ = 100 - (ash\ \% + moisture\ \% + volatile\ matter\ \%) \qquad [1]$$

Crude protein content: - This was determined by measuring the nitrogen content of the feathers and multiplying it by a factor (C) of 6.25. This factor is based on the fact that most protein contains 16 % nitrogen. The protein was determined using a Kjeldahl digestion method (AACC, 2000).

$$CP\ \% = \frac{(1.401 * M * (V - V_o))}{W} * K * C \qquad [2]$$

where,

CP= crude protein

M: Amount of substance of H_2SO_4 concentration (mol/L)

C: Conversion coefficient of crude protein

K: Correction factor for the instrument determination

V_0: Blank value (mL)

V: Titration volume of H_2SO_4 (mL)

W = Weight of sample used.

Crude fat content: - Crude fat, also known as the ether extract, is a measure of the free lipid content in a sample and is calculated using hexane as a solvent in a Soxhlet extraction system (AACC, 2000).

Crude fibre content: - “Crude fibre" is considered to be a mixture of largely undigestible substances of vegetable origin obtained as the residue of a precisely defined digestion procedure using acetic, nitric and trichloro-acetic acids (AACC, 2000). It consists chiefly of cellulose and other vegetable cell wall substances.

Nitrogen Free Extract (NFE) content: - NFE consists of carbohydrates, sugars, starches, and hemicellulose in biomass. When crude protein, fat, water, ash, and fibre are added and the sum is subtracted from 100, the difference is NFE. Thus NFE was calculated as (AACC, 2000):

$$NFE = 100 - (Crude\ protein\ (\%) + crude\ fat\ (\%) + crude\ fiber\ (\%) + moisture\ content\ (\%) + ash\ content\ (\%)) \qquad [3]$$

4.2.2.3. Ultimate analysis: - Ultimate analysis is more comprehensive than proximate analysis and provides information on quantitative analysis of various elements present in biomass samples, such as carbon, hydrogen, sulphur, oxygen, and nitrogen.

CHNS analysis: - The amounts of carbon, nitrogen, hydrogen and sulphur in the chicken feathers were ascertained using a CHNS analyser (Leco VTF-900/CHNS-932).

Energy Dispersive X-ray analysis (EDX): - Elemental composition of chicken feather fractions were characterised by EDX using a Field Emission Gun Scanning Electron Microscope with EDX capability (Carl Zeiss, Oberkochen, Germany).

4.2.2.4. Fibre classification: - Since chicken feathers contain fibres that can be beneficiated into fabrics, it is useful to classify the fibre present. This is especially important to know since the fabrics may need to be dyed and many dyes are very specific to the type of fibres treated.

Burning test: - This is one way to ascertain fibre types and also to ascertain their fire resistance properties (Mylsamy and Rajendean, 2010). The samples were burnt by flame using a disposable lighter (temperature of 575±25 ^{o}C). Burning characteristics that can be noted include the way that a fibre burns (or melts); the way it smells when burning; and the type of ash or other residue that is left behind. All these provide clues as to the type of fabric under analysis. Appropriate safety precautions were taken before and during the testing (assurance that the tester does not have sinus problems or a cold and does not use matches or refillable lighters with a strong fuel smell).

Chemical durability in common chemicals: - Durability or degradation is a reduction in one or more physical properties of a polymer material due to contact with a chemical. Certain materials may become hard, stiff, or brittle, or they may grow softer, weaker, and swell to several times their original size (Mylsamy and Rajendean, 2010).

Measurement of the chemical durability of chicken feathers was measured as mass loss, over time, of samples stored in cold water, hot water, strong acid (1 % (HCl, H_2SO_4 and HNO_3), pH 2-3), and weak acid (1 % (citric acid, $C_6H_8O_7$ and oxalic acid, $C_2H_2O_4$) concentration and 5-6 pH), bleaching agent (4 % NaOCl), and strong alkali (5 % NaOH, pH 10-12), and weak alkali (2-5 Na_2CO_3 %, pH 8-9). Known amounts of feather samples (~5 g) were placed in covered Petri dishes and completely covered with the liquids and left to soak at room temperature. For the determination of hot water solubility, 5 g of feather samples were transferred to a 250 mL round bottom flask to which was added 100 mL of hot distilled water and then heated in a boiling water bath. A reflux condenser was attached and the sample was heated for up to 7 days with continual top up of the heating water. Samples were collected for testing after 2 hrs, 12 hrs, 24 hrs, and 7 days of contact time: the samples were dried for 24 hrs at room temperature and weighed to calculate any changes in weight due to soaking. Chemical durability was calculated as:

$$Chemical\ durability, \% = \frac{A - B}{A} * 100 \qquad [4]$$

where,

A = initial weight of the specimen, g oven dry

B = weight of test specimen after soaking, g oven dry

4.2.2.6. Swelling property: - Swelling power is the ratio between the volume occupied by a sample and the original sample weight. The swelling of feathers was determined in a number of solvents, viz., distilled water, ethanol, methanol, n-butanol and dimethylformamide (DMF). 100 mg of feather fractions were dispersed in 10 mL of the solvents in 500 mL graduated cylinders. After soaking for 18 hours at room temperature, the amount of solvent retained by the fraction was determined.

4.2.2.7. Hydrophobicity test: In chemistry, hydrophobicity is the physical property of a molecule (known as a hydrophobe) that is seemingly repelled from a mass of water (Chandler, 2005). Basically, it is the observed tendency of nonpolar substances to aggregate in aqueous solution and excludes water molecules (Chandler, 2005). Currently, research groups around the world use many different kinds of tests to measure hydrophobicity of materials. In this report, the hydrophobic behaviour of chicken feather fractions was determined by contrasting with behaviours of known hydrophilic compounds (i.e., cotton fibre and wood pulp) between an aqueous and organic solvent phase. Dried chicken feathers, cotton fibre and cellulose pulp were immersed separately in an excess of ethyl–ether–water mixture, shaken vigorously and then left to settle overnight at room temperature.

4.2.2.8. Functional group analysis: - Functional groups are the portions of an organic molecule that dictate how the molecule will react. Fourier transform infrared (FTIR) spectroscopy was used to characterise the functional groups present in chicken feathers.

An FTIR spectrometer was used in the attenuated reflectance mode (Frontier Universal, PerkinElmer). Each spectrum contained an average of 4 scans, recorded at a resolution of 4 cm^{-1} in the range of 4000–400 cm^{-1}.

4.2.2.9. X-ray Diffraction (XRD): - Crystallinity refers to the degree of structural order in a solid. In a crystal, the atoms or molecules are arranged in a regular, periodic manner (Xu et al, 2006). Crystallinity makes a material strong, but it also makes it brittle. A completely crystalline polymer would be too brittle to be used as plastic. The amorphous regions give a polymer toughness, that is, the ability to bend without breaking. For the production of fibres, polymers should be as crystalline as possible.

XRD analyses of the chicken feather fractions were ascertained using a Bruker D8 Discover model diffractometer, equipped with a diffracted beam monochromator, and a copper target X-ray tube set to 40 kV and 30 mA (Bruker South Africa, Johannesburg). The feather fractions were milled to about 250 μm particle size and made into pellets that were then analysed. The crystallinity, indicating the relative crystallinity degree, long used to characterise keratin fibres such as wool (Das, and Ramaswamy, 2006) was calculated using the empirical equation:

$$Crystallinity\ index = \frac{Maximum\ crystal\ latice\ diffraction\ with\ 2\theta\ at\ around\ 9°}{Minimum\ diffraction\ intensity\ with\ 2\theta\ at\ around\ 14°} \quad [5]$$

4.2.2.10. Statistical analysis: - The data collected during the course of the project were subjected to statistical analysis. Microsoft Excel and Origin (Origin Laboratory Corporation, Northampton, Massachusetts, USA) were used to determine statistical parameters (mean, standard deviation, and coefficient of variation).

4.2.3. Results and discussions

4.2.3.1. Proximate analysis: - Results for proximate analysis are shown in Figures 4.2.1 and 4.2.2. Basically, the different feather fractions yielded similar data.

Fixed carbon, ash and volatile matter: - Results for proximate analyses of chicken feather fractions are displayed in Figure 4.2.1: they indicate that all the samples contain large amounts of volatile matter (78-82 %), significant amounts of fixed carbon (17-21 %) and small amounts of ash content.

In general, fixed carbon is the solid fuel left in the furnace after the volatile matter is distilled off. It consists mostly of carbon but also contains some hydrogen, oxygen, sulphur and nitrogen not driven off with the gases (Ryu et al., 2006). Fixed carbon gives a rough estimate of the heating value of biomass. Volatile matter consists of the combustible gases like methane, hydrocarbons, hydrogen and carbon monoxide, and incombustible gases like carbon dioxide and nitrogen. Thus, volatile matter is an index of the gaseous fuels present in biomass (Ryu et al., 2006). The typical range of volatile matter is 20 to 35 % in woody biomass. In this study, the average volatile content of feathers is very high (81.56 %): this indicates that feathers have a good ignition point, removing the excess oxygen demand for a complete burning process.

Ash is an impurity that will not burn. The presence of ash reduces handling and burning capacity, increases handling costs, affects combustion efficiency and boiler efficiency and causes clinkering and slugging (Kwiatkowski et al., 2012). The low ash content of chicken feather samples indicates that they could be suitable for use as fuel. Thus the high content of volatiles, together with a low amount of ash (lower than 1.5%), makes feathers a good material for fixed-bed gasification as reported in the literature (Dudyński et al., 2012). Using air as the gasification agent ensures a sufficiently high temperature to start the thermal conversion, and to maintain the conditions for satisfying the environmental requirements for waste disposal (Kwiatkowski et al., 2012).

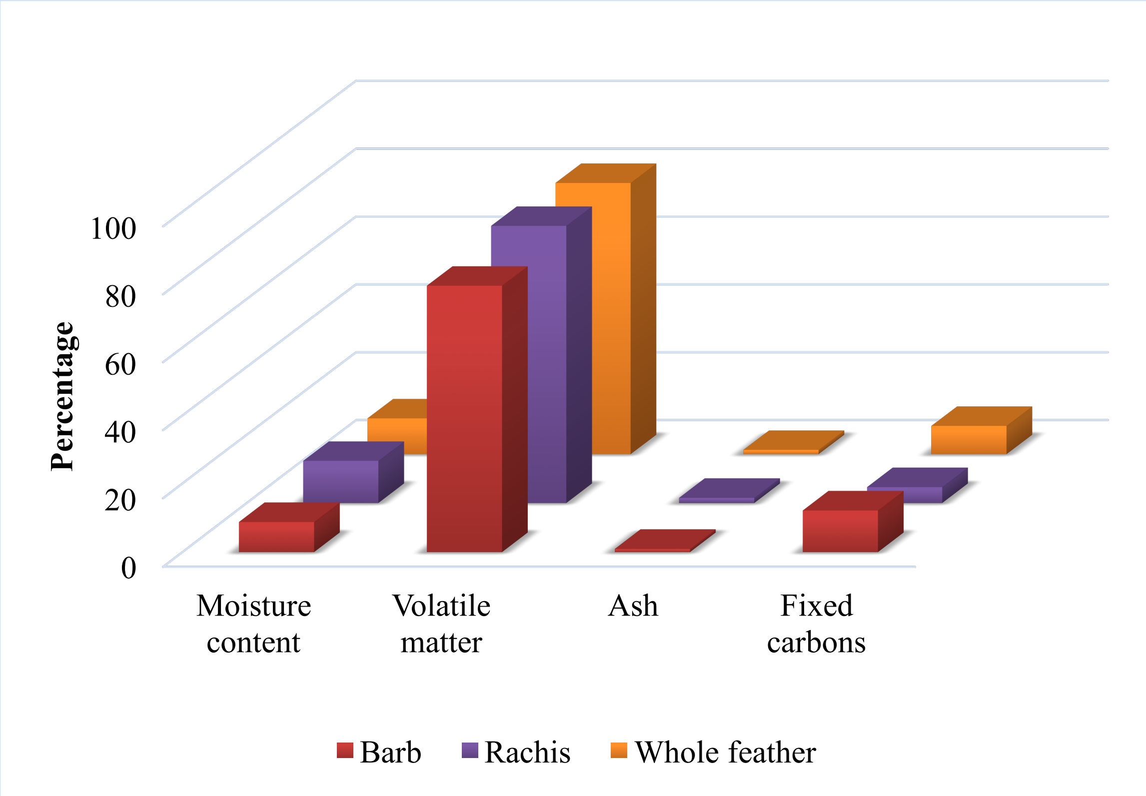


Figure 4.2.1. Proximate analysis of feather fractions

Crude protein: - Crude protein is comprised of true protein and non-protein nitrogen. True protein is sometimes called natural protein and is either degradable or not degradable (Msahli et al., 2006; Zhongfu et al., 2015). The data in Figure 4.2.2 indicates that the crude protein content is similar in all samples at about 80%. It should be noted that higher protein content is usually associated with a higher quality protein source (Msahli et al., 2006). The data confirm that feathers can be beneficiated as a good source of protein material with less amount of NFE.

Crude fibre: - The data in Figure 4.2.2 indicate that chicken feathers contain negligible amounts of crude fibre: this is to be expected considering that feather biomass, unlike cellulosic biomass, does not contain cellulose, hemicelluloses, and lignin.

Crude fat: - Crude fat, an estimate of total fat content, includes true fat (triglycerides) as well as alcohol, waxes, terpenes, steroids, pigments, esters, aldehydes and other lipids (Matthews, 1921). The significant fat content in feathers (about 3%) determined in this study is indicative of a potential route for beneficiation of feathers. For example, studies have been reported on the production of biodiesel from chicken feathers (Kondamudi et al., 2009). Beneficiation of chicken feathers into other products will require processing of fibres to remove the fat so that the residual grease content is below 2% (Bateup, 1986). Thus the fibres need to be pretreated and scoured to remove the fat before further processing.

Moisture content: - The data in Figures 4.2.1 and 4.2.2 indicate that the moisture content of the chicken feather fractions varies between 8.8 and 12.3 %. The ability of chicken feathers and fractions to absorb moisture from the environment has important implications for processing, storage, transportation, and durability of chicken feather-containing composite materials. The increases in moisture content may interfere with processing or bonding in the final products, increase the weight of the products (and hence transportation costs), or lead to rapid deterioration of the product since moisture content will lead to microbial growths (Munawar et al., 2007; Jones et al., 1998). However, in this study the average moisture content of the chicken feathers did not exceed 10.5 %: this implies that the material could be safely stored for long time periods with no concerns of deterioration due to microbial growths. Moisture contents of 8-13 % impliy that chicken feathers can absorb enough water to prevent static build-up – a useful property in applications where static build-up is of importance.

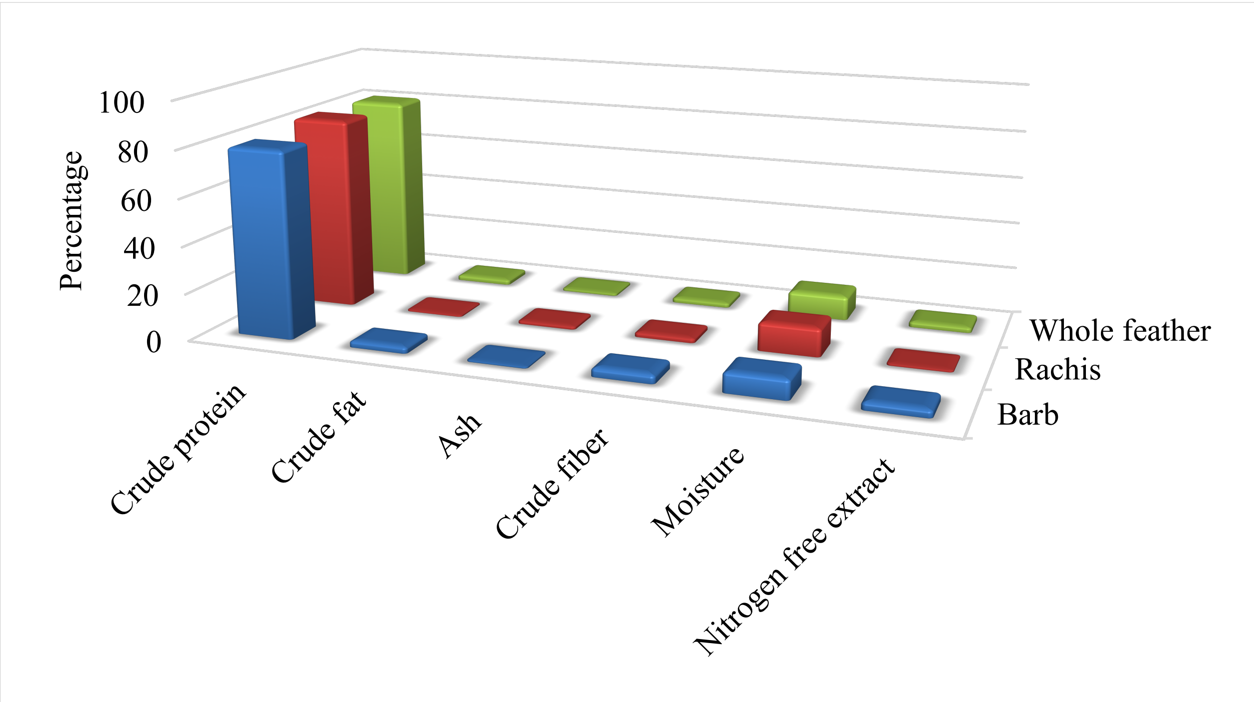


Figure 4.2.2. Ultimate analysis of chicken feather fractions

4.2.3.2.Ultimate analysis

CHNS analysis: - Results for CHNS analysis of the feather fractions are shown in Figure 4.2.3: they reveal no significant differences in the composition of the feather fractions. The average composition was 47.4 % C; 7.2 % H; 15.1 % N; 2.9 % S; and 27.4 % other (oxygen + inorganic matter). The high carbon and hydrogen contents indicate that chicken feathers could be used as a source of energy, while the sulphur content suggests the presence of cysteine protein. Overall, chicken feathers have a nitrogen content of about 15 %: this high nitrogen content indicates that chicken feathers can be used to produce bio-compost or animal feed.

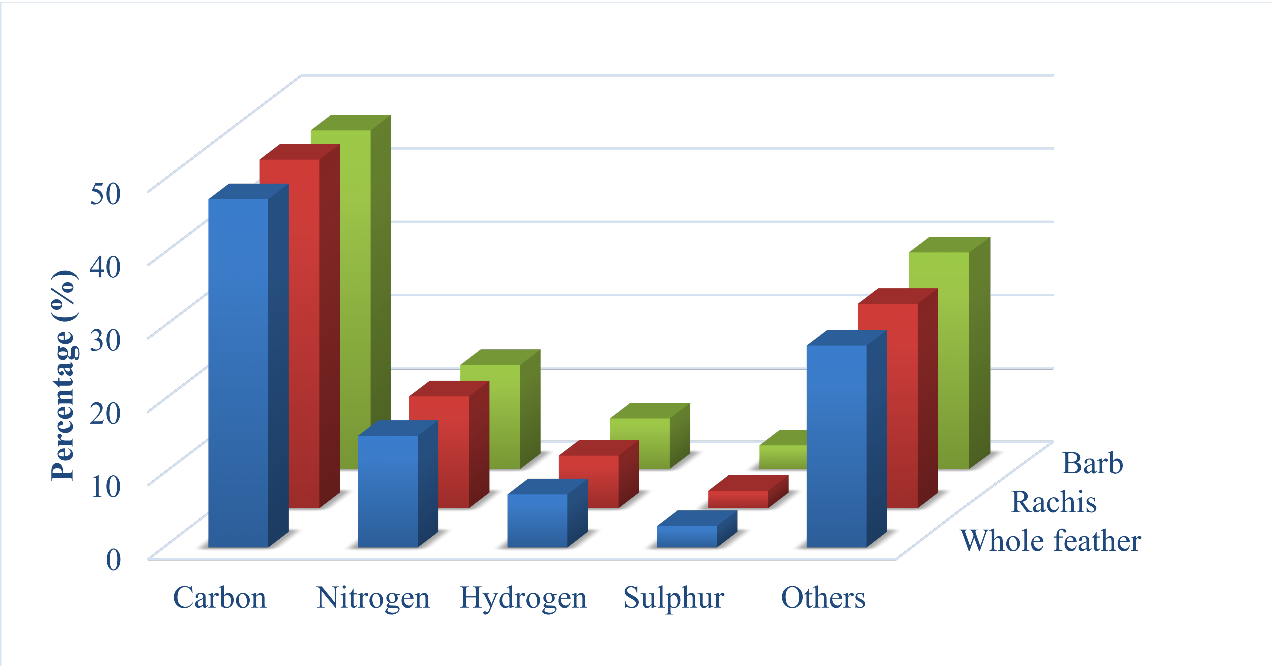


Figure 4.2.3. Elemental analysis of chicken feathers

3.2.2. Energy Dispersive X-ray Spectroscopy analysis: - The EDX results are shown in Figure 4.2.4. Basically, they corroborate the CHNS analysis results with additional evidence for the presence of oxygen (not detectable with the CHNS analyser). The average elemental composition was 59.14 % C; 14.21 % N; 24.34 % O; and 2.17 % S. As with CHNS analysis, the results were identical among the feather fractions.

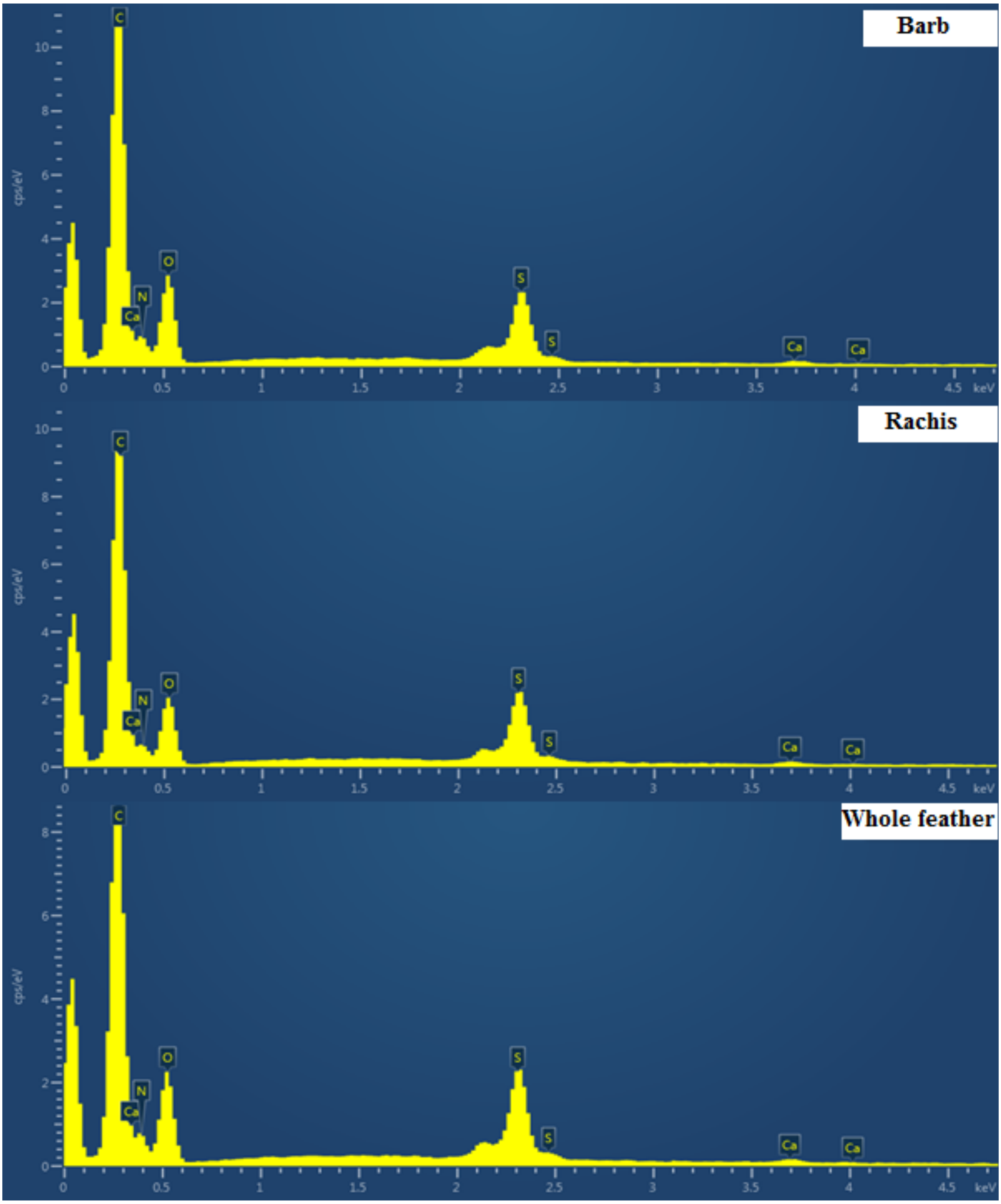


Figure 4.2.4. EDX results of the elemental profile of chicken feather fractions.

4.2.3.3. Fibre identification

Burning Test: - The results are summarised in Table 4.2.1: in summary, it was observed that chicken feathers do not support continuous burning, and emit an odour like that of burning human hair. They burn with an orange sputter colour and do not melt. When the flame died, the feathers supported combustion very slowly for a short period. This indicated that chicken feathers are self-extinguishing, but for them to be used safely near a fire, they need to be fire-proofed by application of appropriate fire-retardant and protective finishes.

Table 4.2.1. Burning characteristics of chicken feather fractions.

Chemical properties	Rachis	Barbs	Whole feather
Approaching flame	Smoulders and curls away from flame; ignites slowly	Smoulders and curls away from flame; ignites slowly	Smoulders and curls away from flame; ignites slowly
In the flame	Burns slowly with small flickering /orange flame; sizzles and curls, no smoke	Burns slowly with small flickering /orange flame; sizzles and curls	Burns slowly with small flickering /orange flame; sizzles and curls
Away from the flame	Supports combustion with difficulty for short time	Supports combustion for a short time melts ahead	Burns slowly/self-extinguishing
Odour	Burning rubber	Burning hair	Burning hair
Residue	Easy crushable black soft ash	Completely fuses	Crisp, dark ash; round, irregular bead; easy to crush

The burning test characteristics indicated in Table 4.2.1 were compared to information in Table 4.2.2 which is a guideline for classification of fibres. The comparison indicated that chicken feathers are similar to wool fibre - thus they are categorised as a protein fibre.

Table 4.2.2. Guideline for classification of fibres using the burn test (adapted from Anonymous, 2016).

Cellulose (Cotton/Linen/Hemp/Rayon/Bamboo): • Ignites and burns quickly may flare, leaves a glowing ember after the flame is extinguished. Smoke is white or light coloured and smells like burnt paper or leaves. Ash is light grey or white and very soft. **Protein (Silk/Wool, Cashmere, Alpaca etc):** • Burns slowly and shrinks or curls away from the flame. Will not stay lit after the flame is removed. Very little smoke is produced but it smells like burnt hair (wool) or feathers (silk). Ash is a gritty powder or a dark brittle, easily crushable bead. **Synthetics (Nylon/Polyester/Acrylic):** • Ignites and burns quickly and can continue to burn after a flame is removed—exercise caution. Fibre may shrink from the flame, melt, and can drip (DANGER) leaving a hard plastic-like bead. Burning these fabrics will produce black smoke and hazardous fumes. Nylon smells like plastic when burnt but can also produce a celery-like smell; Acrylics burn with a strong, acrid, chemical smell. Polyester smells slightly sweet, also with a chemical odour.

Chemical durability in common chemicals: Results were compared with control samples of chicken feather fractions soaked in deionized water. The reactions observed included swelling and dissolution, dissolution without swelling, disintegration, colour reaction and changes, and duration time taken for the changes to occur. This test is very important since chemical reactions are utilised in the manufacturing processes of high-value materials from chicken feathers. The chemicals tested were categorised into five groups: water (hot and cold), acids (strong and weak), alkalis (strong and weak). Moisture sensitivity and chemical degradation are serious problems that can affect natural fibres and materials made from them due to potential swelling and rotting of fibres. Contact time will inevitably result in different degrees of damage to feather fractions (Table 4.2.3 and Figure 4.2.5).

Chemical durability in alkaline solutions**:** Upon soaking in alkali (both strong and weak alkali), the chicken feathers dissolved rapidly and completely. From Figure 4.2.5 and Table 4.2.3 it is clear that rachis lost less weight than barbs, however, the rachis completely dissolved in 5 % NaOH after 24 hrs, whereas barbs lost weight and became brittle. The results imply that in beneficiation processes that require treating fibres with NaOH for enhancement or induction of certain properties, contact with alkali more for than 1 hour is not recommend so as to maintain the stability of feather fibres. After 7 days of soaking, the feather fractions experienced greater than 99 % mass loss, indicating that chicken feathers are unstable in strongly alkaline environments. This property indicates that chicken feather can be categorised as animal fibre.

Chemical durability in acidic solutions: The feathers have good resistance to mild acid but poor resistance to strong acid in which they dissolved completely. In strong acid, the chicken feathers suffered damage and high weight losses. Figure 4.2.5 and Table 4.2.3 show high mass losses relative to results of chicken feather fractions soaked in deionized water. Concentrated sulphuric acid induced more disintegration and severe weight loss than hydrochloric or nitric acids. This indicates that strong acids damage chicken feathers: the bonds connecting the subunits in feathers are destabilised by acidic media, with a corresponding high loss in tensile strength (Munawar et al., 2007).

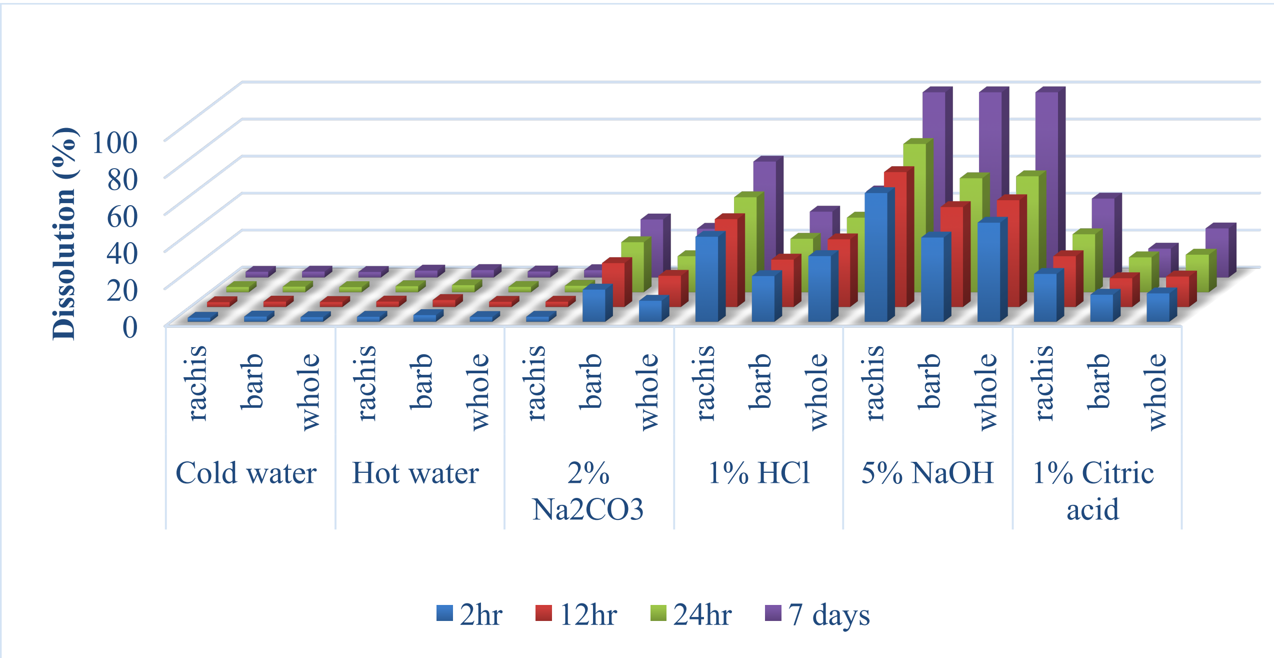


Figure 4.2.5. Chemical resistance of chicken feather fractions in water, acids and base.

Chemical durability in other chemicals: The most common reagents used in textile fibre processing are bleach and detergents. They are not strongly alkaline or acidic, and thus, can be safely used on the chicken feathers, with low effect on the structure and tenacity thereof. When reacted with concentrated sodium hypochlorite, the feather fractions were bleached, but after prolonged exposure, the feather fractions weakened and disintegrated. This indicates that oxidising solutions like sodium hypochlorite should only be used when cold and diluted, and only for short periods. Also, the reagents should be thoroughly washed out of the fibres to avoid damaging the fibres.

Soaking in hot water removes some extraneous components in waste feathers such as inorganic compounds, sand, gums, and colouring matter. The different feather fractions exhibited variations in hot water solubility: feather rachis had significantly higher hot water extractives content than feather barbs.

Table 4.2.3. Chemical resistance of chicken feather fractions

		Observed reaction	
Category	**Chemical**	**Immediate**	**After 2hr**
Water	Hot/cold	No visible change in colour or structure	In cold water, there is no change at all but in cold water folding and curling of feather is observed.
Strong acid	Conc. Sulphuric acid	The fibres disintegrated and dissolved. Fibres changed colour from white to brown	Fibres disintegrated and then completely dissolved.
	Conc. Nitric Acid	No visible change in structure. The fibre colour changed from white to brown and then was bleached to white	A marked weakening and tendering of fibres resulted. The fibre was partially dissolved.
	Conc. hydrochloric acid	The fibre did not change colour or structure	The fibre weakened and partially dissolved
	Acetic acid	The fibre did not change colour or structure	The fibre did not change colour or structure
Weak acids	Citric Acid	The fibre bleached, no change in structure.	Fibre remained strong and bleached.
	Oxalic Acid	The fibre bleached, no change in structure.	Fibre did not change in structure or colour
Strong Alkalis	Sodium hydroxide	Fibres did not change in colour or structure.	Folding and curling of fibre. There was a visible distortion of fibres.
	Sodium hypochlorite	Fibre bleached, no change in structure.	Fibre weakened and disintegrated
Weak alkalis	Ammonium hydroxide	No reaction noted	No reaction noted
	Sodium hydrogen carbonate	No reaction noted	No reaction noted

4.2.3.4. The swelling property: Figure 4.2.6 shows data for the swelling properties of chicken feather fractions in different solvents. The swelling behaviour in different solvents followed the trend: water > ethanol > methanol > DMF > n-Butanol. The feather barbs exhibited the most swelling in water: this may be because they contain larger amounts of hydrophilic hydroxyl groups than the other feather fractions. Water can then penetrate more easily and deeper into feather fractions, resulting in more swelling than in organic solvents. The feather fractions showed more swelling in methanol than in ethanol. This may be due to the presence of the bulkier ethyl ($-C_2H_5$) group in ethanol providing a hindrance to sorption. Also, the presence of alkyl groups in chicken feather fractions makes them hydrophobic in nature; therefore, these hydrophobic chains have a strong affinity toward non-polar solvents like DMF. The stability of chicken feathers in n-butanol was fairly good but there was extensive dissolution in DMF. These results indicate that swelling property of chicken feather could be affected by the presence of polar solvents.

It must be emphasised that chemical compatibility of materials can be affected by various parameters such as concentration, temperature, the presence of other chemicals, and other factors. Hence the results presented in the preceding section only serve as a general guide to the chemical compatibility of chicken feathers.

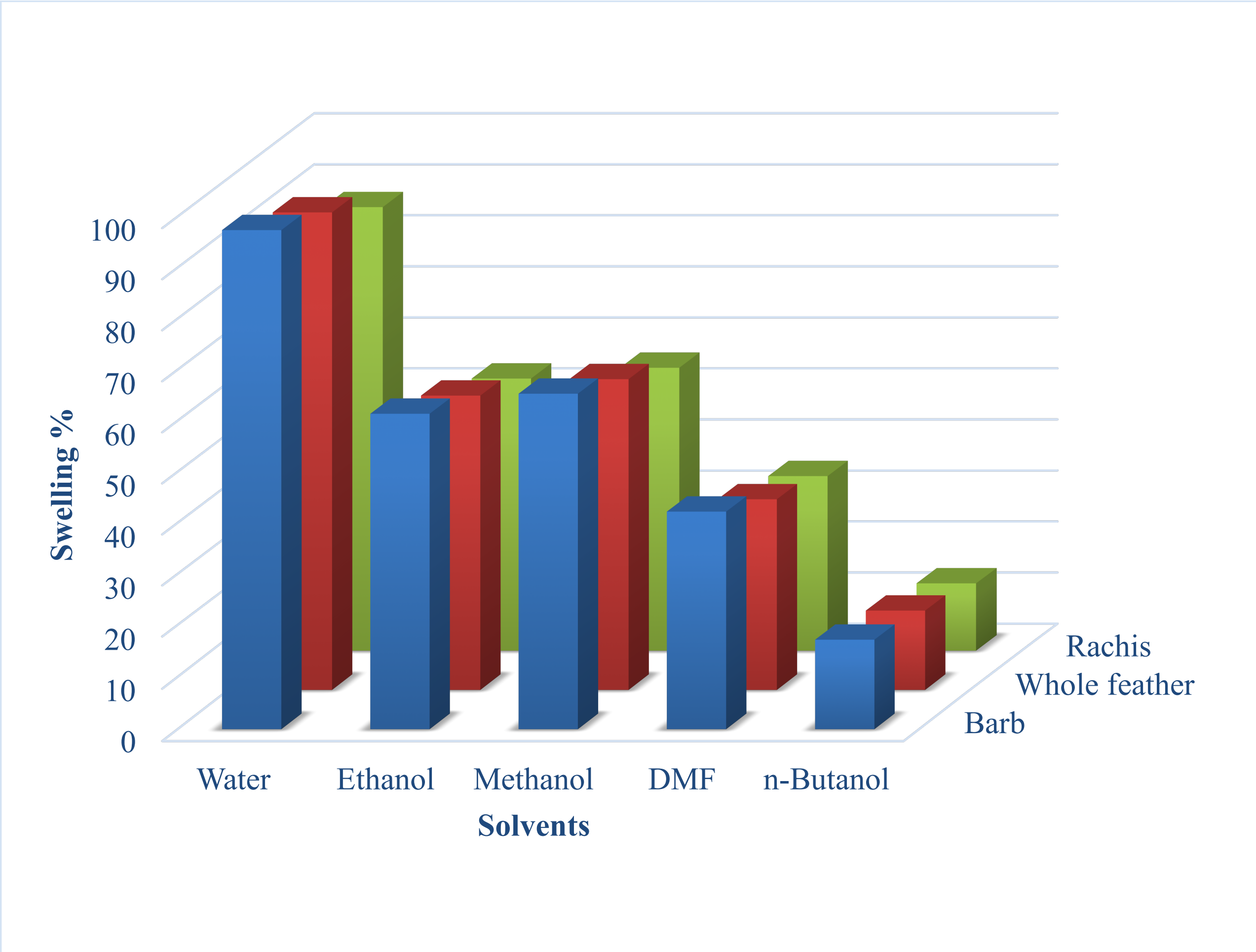


Figure 4.2.6. The swelling properties of chicken feathers.

4.2.3.5. Hydrophobicity test: As shown in Figure 4.2.7, it is evident that cotton and wood pulp were aggregate in the second layer (water layer) showing the complete wettability of the fibres. However, the chicken feather fractions (barb and rachis) aggregated in the interphase between the water and ethyl ether layers. This indicates poor wettability of chicken feather fractions compared with cotton fibre and wood pulp; these observations confirm the hydrophobic properties of chicken feather fractions.

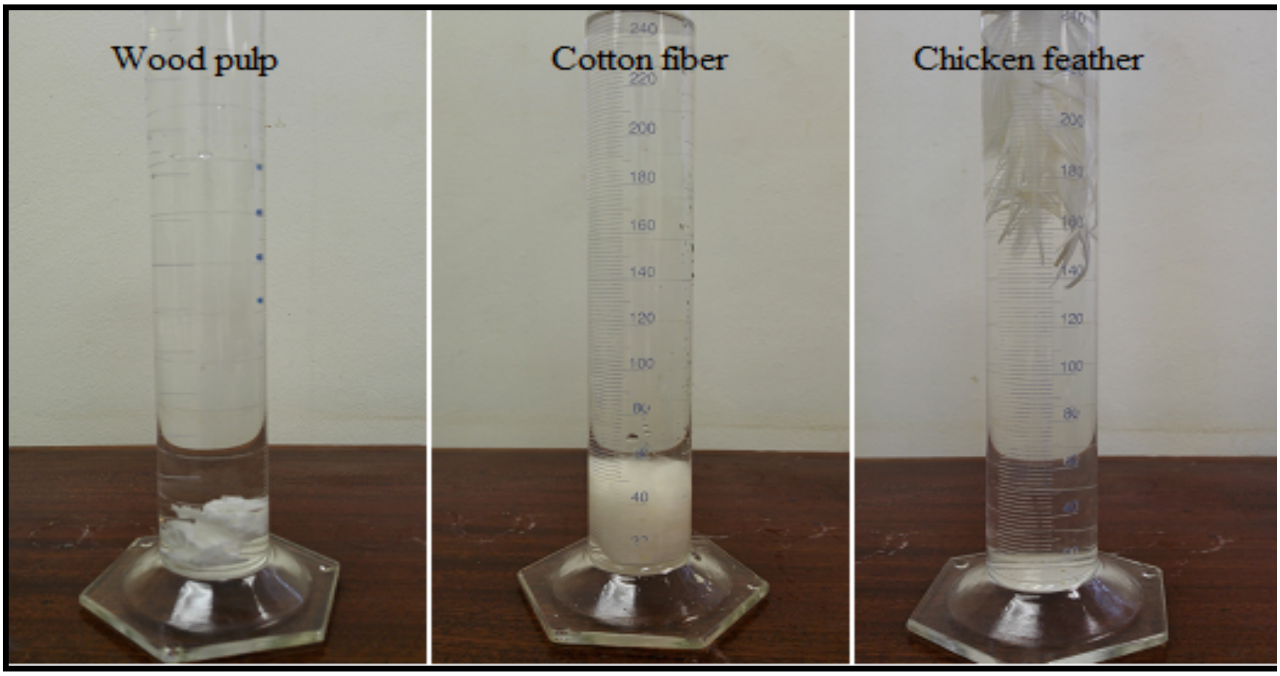


Figure 4.2.7. Hydrophobicity test on wood pulp, cotton fibre and chicken feathers

4.2.3.6. Functional group analysis: A comparison of the FTIR of the feather fractions is shown in Figure 4.2.8. The strong signal at 1650 cm^{-1} caused by the elongated C=O amide band was assigned to the C=O amide I, an α-helix conformation (Senoz, and Wool, 2010). The peak at 1550 cm^{-1} characteristic of amide II conformation, was observed in all samples, but with lesser intensity that the amide I peak. This is caused by the vibrations of the deformation angle of N-H in plane bending for β sheet conformation and the stretching of C-N in the backbone of keratin. The signal at 1455 cm^{-1} corresponds with CH_2 or CH_3 (Silverstein et al., 2014). In this study, the amide III region was easily resolved and clearly-defined (1330–1200 cm^{-1}), due to the in-phase combination of N–H in-plane bending and C–N stretching vibrations and corresponds to the α-helix conformation (Martinez and Velasco-Santos, 2012). The weak peak between 1270 and 1220 cm^{-1}, helps to characterise the presence of a β-sheet structure, from amide III, which corresponds largely to the stretchability of C-N, and the angular deformation in the plane of the N-H group, and weakly to the stretching of the C-C bond and the deformation in the plane C=O. The absorption at 2370 cm^{-1}, attributed to S-H stretch, is believed to cause the sulphide smell from waste feathers (Martinez and Velasco-Santos, 2012). The band close to 1174 cm^{-1} is produced by (C-C link) from side chain amino acids. The region from 1050 to 1150 cm^{-1} also corresponds to skeletal (C-C links). Finally, the (C-S) from alkylthiols is localised approximately at 730-620 cm^{-1}; this group is originated from amino acid cysteine. The signal at 500-730 cm^{-1} is assigned to the (C-S) functional group (Silverstein et al., 2014).

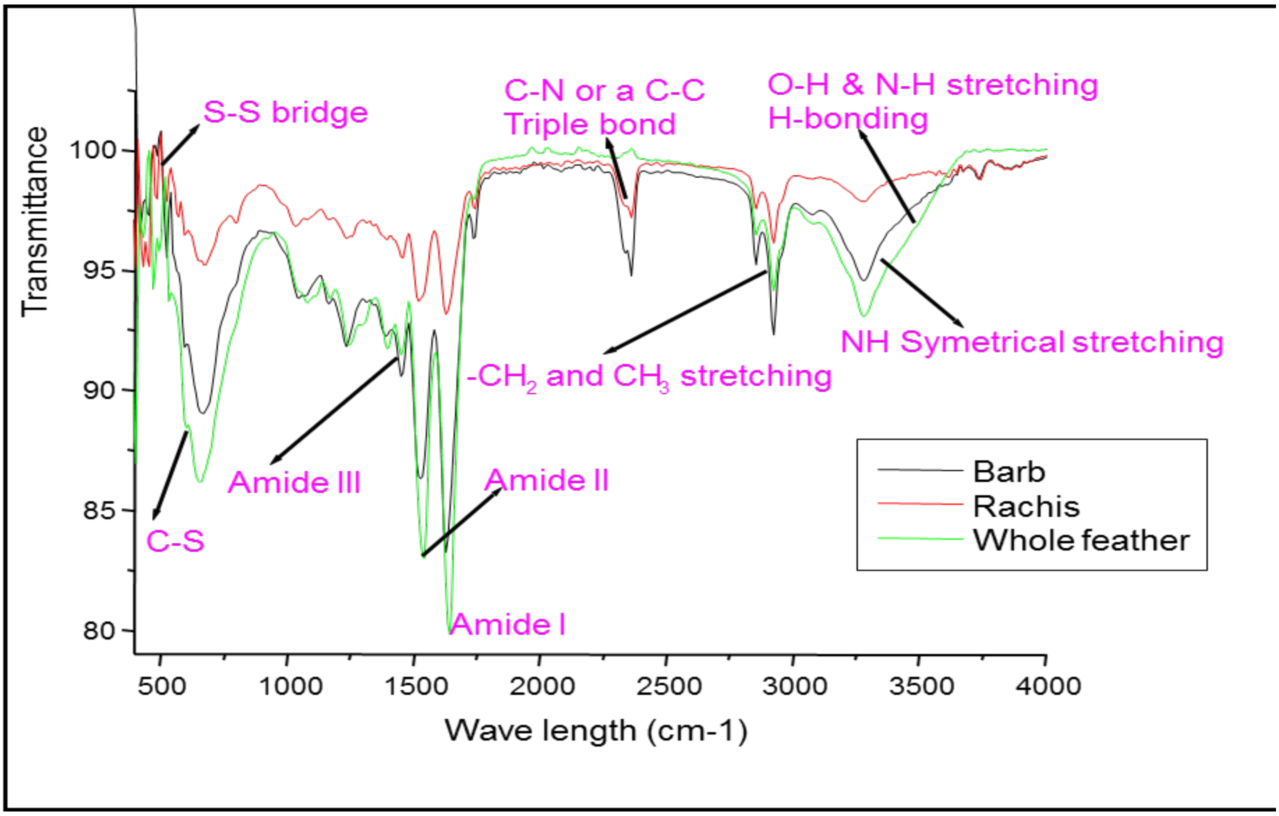


Figure 4.2.8. FTIR spectra of chicken feather fractions

From the FTIR results, it was verified that the chicken feathers reveal a broad band in the range of 3550-3150 cm^{-1}, and a peak at 3075 cm^{-1}, associated with the stretching of the amide group N-H. The bands closer to 3300 cm^{-1} have been associated with the regions that characterise the ordered region, α- helix structure, of secondary proteins (Barth, 2007). This corresponds to the amide groups A and B, i.e., N-H (symmetrical stretching) and O–H modes. The bands in the region 3320-3070 cm^{-1} correspond to the amides A and B resulting from Fermi resonance (Kong, and Yu, 2007). Additionally, the range from 2708-3100 cm^{-1} was viewed as characteristic of dipolar ion amino acids $RCH(NH_3^+)COO^-$. The NH_3^+ group corresponds to a wide band around 3100-2700 cm^{-1} with NH and NH (asymmetrical stretching vibrations). A shoulder around 2960 cm^{-1} can be assigned to CH_3. The bands from 3230-3280 cm^{-1} are equivalent to amide A, and 3075-3130 cm^{-1} are equivalent to amide B. The spectrum showed a double band (2930 and 2965 cm^{-1}) characteristic of symmetric and asymmetric stretching of aliphatic hydrocarbons (primary and secondary carbons), C-H, that are found between 2850 to 2960 cm^{-1} region. This indicates the preservation of CH_2 and CH_3 functional groups in chicken feather fractions (2900-2960 cm^{-1}), (Silverstein et al., 2014; Kim and Hochstrasser, 2009). The presence of proteinious functional group in chicken feather samples indicates that they could be suitable for use as a raw material in cosmetics, regenerated fibre, biomedical materials, bioplastic, textile sizing, enzyme production, pharmaceuticals and animal feed.

4.2.3.7. Crystallinity index Analysis: The crystallinity of chicken feather fractions plays an important role in their physical, chemical, optical and thermal properties. Similarly to other animal fibres, chicken feathers have a kind of macromolecular polymer structure between its crystal and amorphous regions. As can be seen from the crystal diffraction peak (Figure 4.2.9) all feather fractions show a medium diffraction peak around $2\Theta = 9^o$ (for the α-helix structure of peptide chains in chicken feather fractions) and a prominent peak around $2\Theta = 22^o$. Moreover, a diffraction peak-valley was observed at $2\Theta = 14^o$ between the two characteristic diffraction peaks mentioned above, which was assigned to the amorphous region of chicken feather structures. Peak intensity in the diffractograms is indicative of crystal structure content. The results show that rachis possess more β-sheet content than the barb fraction. The peak at $2\Theta = 9^o$ corresponds to the α-helix configuration (Xu et al, 2006; Zhao et al., 2012). The three feather fractions exhibited a sharp peak at this position that is due to the keratin membrane in feathers. The peak intensity of the rachis is stronger than that of the other samples. This suggests that there is a more α-helix structure in the rachis than in the other samples. Based on the above analysis, chicken feather fractions possess two types of crystal structures: i.e., α-helix and β-sheet. The peak intensity around 22^o of the barb fraction was lower than that of the whole feather and rachis fraction. The peak around 17^o corresponds to the diffraction pattern of the α-helix, whereas the peak around 20^o is a typical peak of the β-sheet structure (Zhao et al., 2012). However, the two peaks are usually not clearly assigned due to the overlapping signals; this leads to the broad single peaks at 22^o.

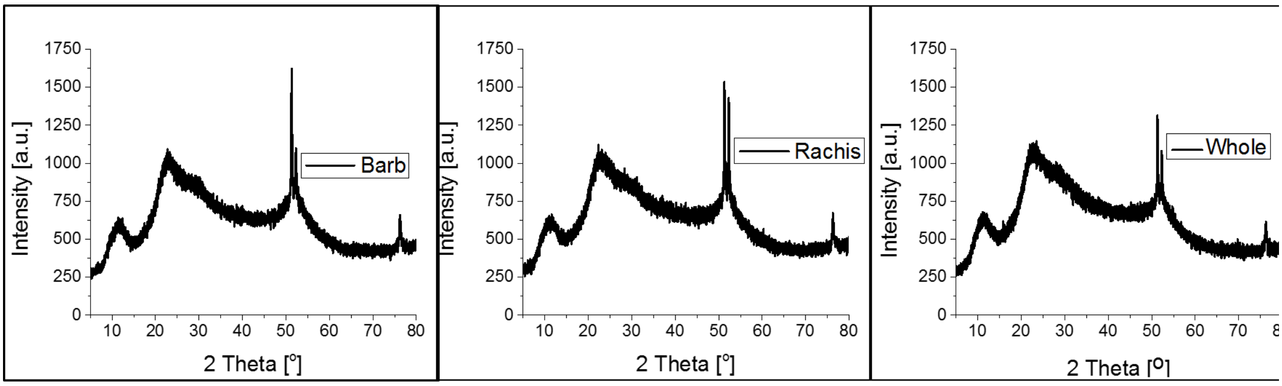


Figure 4.2.9. XRD patterns of chicken feather fractions

It is well known that keratin is semi-crystalline and naturally macromolecular (Xu et al, 2006; Steinert et al., 1976); its XRD profiles have confirmed this. The chicken feathers exhibit two narrow peaks at around 2θ = 52^{o} and 77^{o} (Figure 4.2.9). Besides this being narrow, it is the most intense, at around 52^{o}. These effects are caused by the presence of crystalline regions within the sample. This was also observed for the whole chicken feather fraction, albeit with reduced intensity (Figure 4.2.9). This indicates a reduction in crystallinity. From the results, it is seen that in addition to disulphide bonds, crystallinity also plays an important role in the high strength and stiffness of feather keratins (Xu et al, 2006; Fonollosa et al., 2004; Zhao et al., 2012). From the crystalline peaks, the crystallinity indexes were calculated and the results are summarised in Table 4.2.4. It is known that the feathers' mechanical stability, insolubility, and resistance to proteolytic digestion, are consequences of the tight packing of the protein chain in β-sheets (β-keratin) into a supercoiled polypeptide chain (Fonollosa et al., 2004; Onifade et al., 1998). The decrease of crystallinity and decomposition of the β-sheet structure could improve the extraction, dissolubility, and enzymatic accessibility of the feather keratins.

Table 4.2.4. Crystallinity index of chicken feather fractions

Feather fraction	Barb	Rachis	Whole feather
Crystalinity (%)	22.09	19.36	20.55

4.2.4. Potential valorisation of chicken feather fractions based on chemical properties

The results on the chemical characterisation chicken feathers imply that they could be used in a variety applications such as in the agricultural industry (biofertiliser and animal feed); the textile industry (as a source of regenerated fibre, sizing agents to replace costly starch based sizing agents, as a binder and thickener in textile finishing and printing, as a finish to impart flame retardancy); in the energy industry (biofuel, biogas and energy storage devices), in the cosmetics industry (as a source of keratin), in the health industry (as a source of pharmaceuticals and biomedical materials), and in the packaging industry (as a source of biodegradable plastics) (Figure 4.2.10) (Tesfaye et al., 2017).

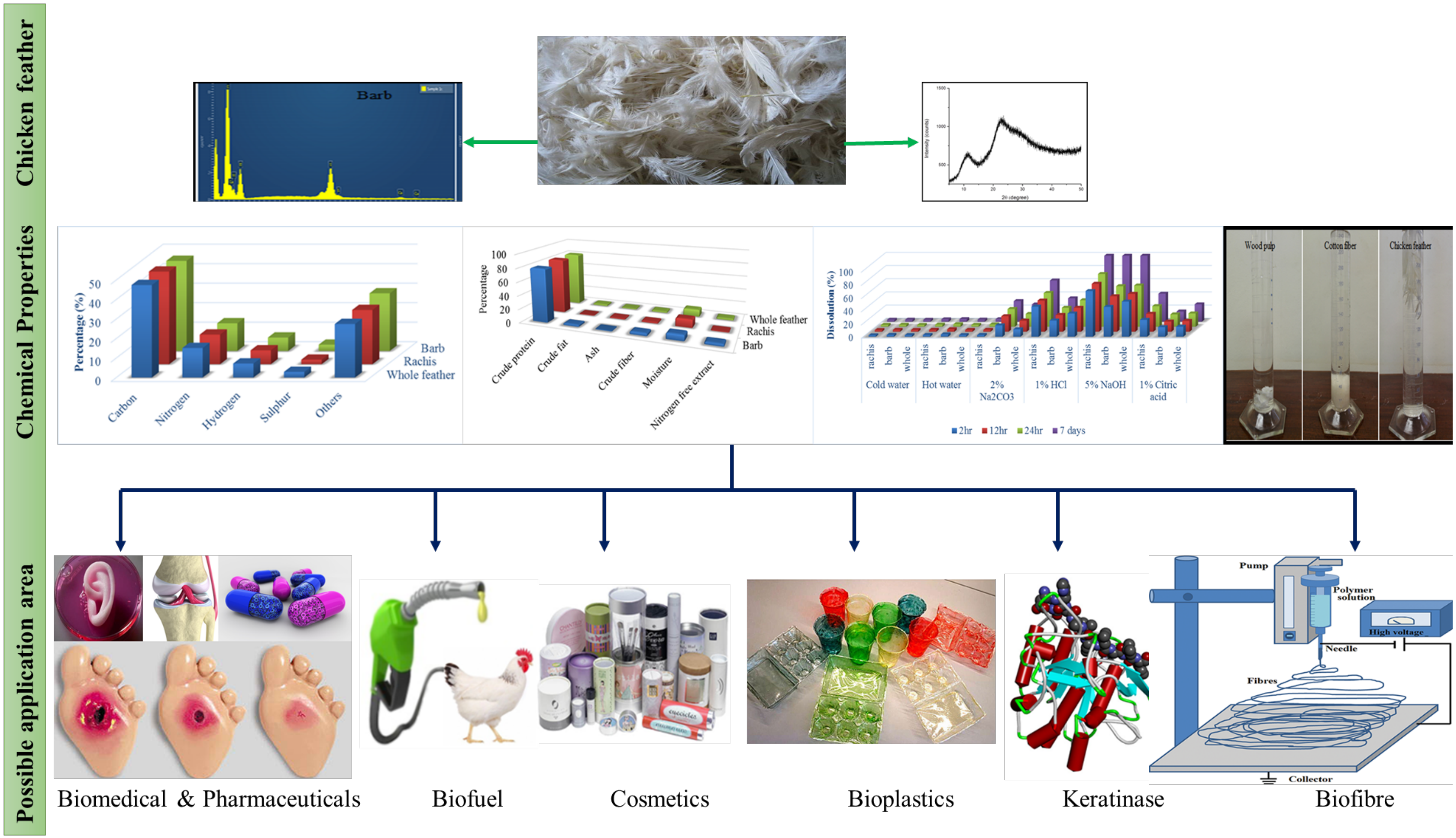


Figure 4.2.10. Possible valorisation route of waste chicken feathers based on chemical properties.

4.2.5. Conclusions

A detailed characterisation of chemical properties of chicken feathers has been conducted with the objective of ascertaining valorisation products that can be made from this waste material. The characterisation included proximate and ultimate analysis, durability tests as well spectroscopic techniques. The proximate analysis of chicken feathers revealed the following nutrients and anti-nutrients: crude lipid (0.83 %), crude fibre (2.15 %), crude protein (82.36 %), ash (1.49 %), NFE (1.02 %) and moisture content (12.33 %) whereas the ultimate analyses showed: carbon (64.47 %), nitrogen (10.41%), oxygen (22.34 %), and sulphur (2.64 %). FTIR analysis revealed that the chicken feather fractions contain amide and carboxylic groups indicative of proteinaceous functional groups; XRD showed a crystallinity index of 22. Durability and burning tests confirmed that feathers behaved similarly to animal proteins. The results confirm that chicken feathers contain animal fibres. Future studies will entail extraction of valuable materials from chicken feathers for conversion into relevant high-value products. They include proteins for conversion into, e.g., cosmetic products, and fibres for conversion into biomaterials or superabsorbent fabric materials. The proper utilisation of this waste would open up new industries and job opportunities, and make the poultry industry more competitive.

ACKNOWLEDGMENTS

The authors would like to acknowledge the DST/NRF South African Research Chairs Initiative (SARChI), the Biorefinery Industry Development Facility at the CSIR, and the Department of Science and Technology for the support of this research, Mr Pradeep Suthan for carrying out the XRD test and Ms Fiona for editing the manuscript.

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4.3. VALORISATION OF CHICKEN FEATHERS: CHARACTERISATION OF THERMAL, MECHANICAL AND ELECTRICAL PROPERTIES

(BASED ON PAPER FIVE)

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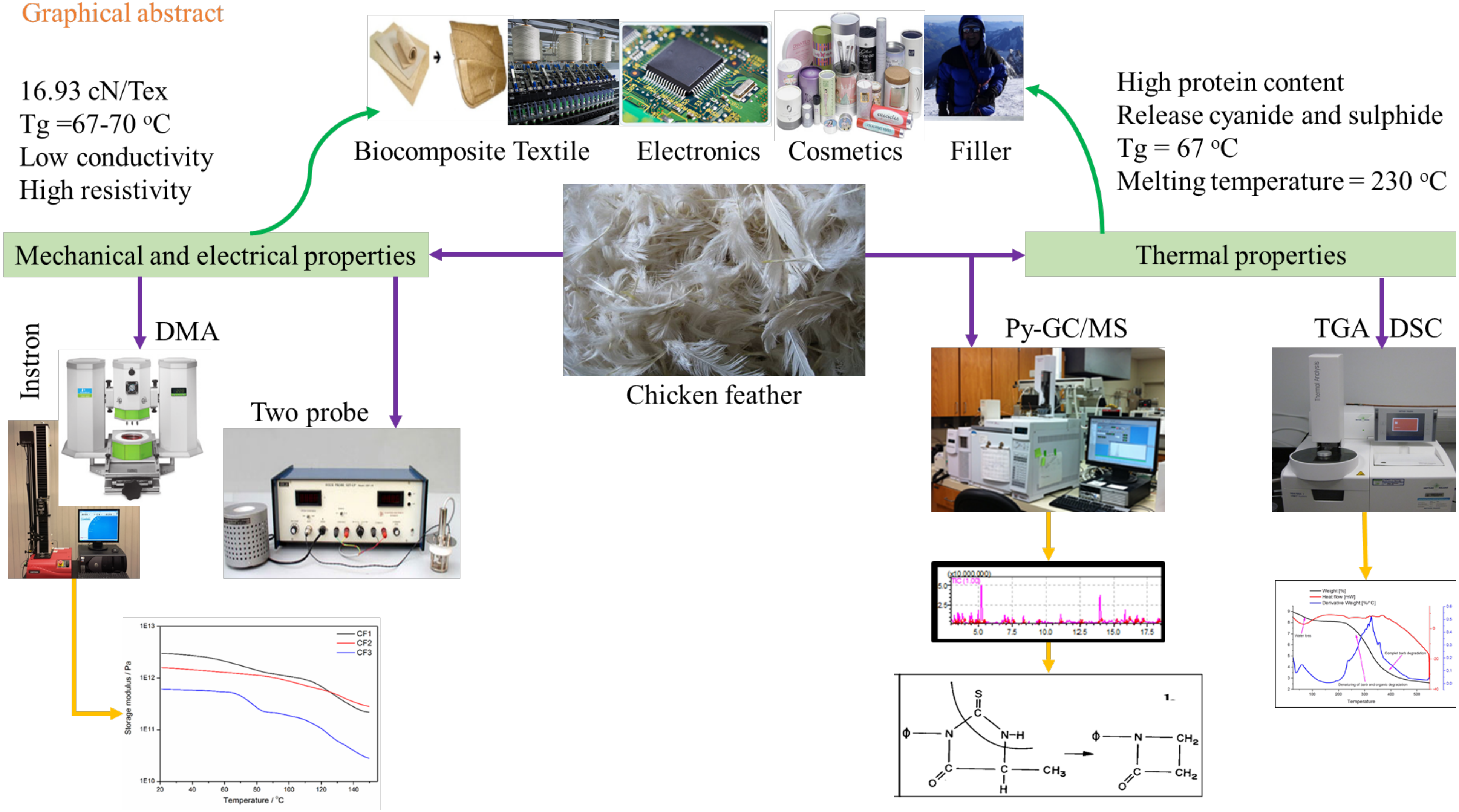
ABSTRACT

Increasing consumption of chicken results in generation of large amounts of wastes that need to be disposed of properly. Chicken feathers constitute about 5-10 % of the weight of the chicken and thus they comprise a significant portion of the poultry wastes. Disposal of waste chicken feathers is problematic in that they do not readily degrade after landfilling, there is increasing shortage of landfill space, and they are contaminated with microbial biomass that makes them hazardous waste. Feathers contain ~91% keratin protein and thus, potentially, feathers can be beneficiated into high-value compounds or products comprised of keratin proteins or keratin fibres. Thus, valorisation of feathers could be a viable option for sustainable disposal of the waste. **C**haracterisation of physicochemical properties of the chicken feather is an essential step to identifying possible avenues for valorisation of this waste biomass. While chemical, physical and morphological properties of chicken feathers and related potential valorisation routes have been described by the authors, identification of their mechanical, thermal and electrical properties have not been reported and this information is necessary to have a complete and comprehensive characterisation of waste chicken feathers. Hence, in this research, the mechanical, thermal and electrical properties of feathers were determined and evaluated to ascertain suitability of the feathers for production of high-value materials. The feathers and fractions thereof were characterised by TGA/DSC, Instron (material and structural testing), Dynamic Mechanical Analyser, and a two-probe measurement of resistivity instrument. Under heated conditions, the TGA of chicken feathers confirmed the occurrence of three zones of weight loss. The TGA/DSC results revealed a glass transition temperature around 67 ^{o}C and a melting temperature ~ 230 ^{o}C in the crystalline phase. The tenacity of chicken feather barbs at maximum load was ~ 16.93 cN/tex. The results from electrical properties indicated that chicken feather fractions have low conductivity. Overall, the results indicate that chicken feathers have potential to be used in a variety of applications such as electrical insulator materials, yarn production for use in textiles, nonwoven fabric production, filler for winter clothing, geotextile and construction materials.

Keywords: chicken feathers, mechanical properties, thermal properties, electrical properties, characterisation, valorisation, beneficiation

Graphical abstract



4.3.1. Introduction

Increasing consumption of chicken results in generation of large amounts of wastes that need to be disposed of properly. Chicken feathers constitute about 5-10 % of the weight of the chicken and thus they comprise a significant portion of the poultry wastes. USA, Brazil and China are the largest producer in the world with South Africa, Egypt and Nigeria being the largest in Africa (Compassion in World Farming, 2013). On a world scale, it is estimated that $40x10^9$ kg of chicken feathers are produced from the slaughter of more than $58x10^9$ chickens (Compassion in World Farming, 2013). In South Africa, Statistics 2013, indicates the availability of more than 322 large scale chicken meat processing abattoirs. These poultry farming activities generated more than $258x10^6$ kg of feathers (DAFF, 2014). Disposal of waste chicken feathers is problematic in that they do not readily degrade after landfilling, there is increasing shortage of landfill space, and they are contaminated with microbial biomass that makes them hazardous waste (El-Boushy et al., 2000; Zhan and Wool, 2011). Feathers contain ~91% keratin protein (El-Boushy et al., 2000; Zhan et al., 2011) and thus, potentially, feathers can be beneficiated into high-value compounds or products comprised of keratin proteins or keratin fibres. Thus, valorisation of feathers could be a viable option to sustainable disposal of the waste.

Characterisation of physicochemical properties of chicken feather is an essential step to identifying possible avenues for valorisation of this waste biomass. While chemical, physical and morphological properties of chicken feathers and related potential valorisation routes have described by the authors (Tesfaye, et al., 2017), identification of their mechanical, thermal and electrical properties have not been reported and this information is necessary to have a complete and comprehensive characterisation of waste chicken feathers. In this research, results of such comprehensive studies are reported with a focus on understanding the mechanical, thermal and electrical properties of waste chicken feather fractions (barb and rachis) with the ultimate aim of developing valorisation routes for the waste feathers depending on their characteristics.

4.3.2. Materials and methods

4.3.2.1. Materials

Sample collection: Chicken feathers were collected from 3-week old broiler/meat chickens at a slaughterhouse in Durban, South Africa.

Preparation and decontamination of waste chicken feathers: - On collection, the feathers were a wet mass of blood, faeces, skin, flesh and other slaughterhouse residues. They were washed with water at 50 ^oC to remove easily removable matters and then dried at 105 ^oC for 24 hr and conditioned at a relative humidity of 65±2 % and a temperature of 20±2 ^oC. After drying, barbs were separated by manual stripping from the rachis. A portion of the sample was milled into powder, and the rest left intact. The material was then packed and stored at normal room temperature (20–25 ºC) in three groups (whole feather, rachis and barb). Chicken feathers treated with 0.5 % w/v SDS (CF3) and H_2O_2 0.5 % v/v (CF2) samples were compared with raw chicken feather (CF1), to see the effect of pretreatment on mechanical properties.

4.2.2.2. Methods

Thermogravimetric analysis (TGA): - TGA profiles of feathers and fractions were determined using a TA Instruments Q500 unit. The rate of heating, sample weight, mode of heating and temperature range used for this study were 5 ^oC/min, 10 mg, under nitrogen with a purge flow rate of 50 ml/min, and 30-550 ^oC respectively.

Differential scanning calorimetry (DSC): - DSC profiles of feathers and fractions were determined using a TA Instruments Q500 unit. The rate of heating, sample weight, mode of heating and temperature range used for this study are 5 ^oC/min, 10 mg, Nitrogen with a purge flow rate and temperature range of 50 ml/min and 30-550 ^oC respectively. The melting temperature (Tm) of a sample can be deduced from a peak in the endothermic direction.

Mechanical properties: Chicken feathers fractions were dried and conditioned at a relative humidity 65 ± 2 % and a temperature 20 ± 2 ºC. The conditioned samples were tested for bundle strength tenacity and liner density according to the bundle tensile strength (Flat bundle method) – ASTM D1445 (ASTM D1445, 2005). This test method covers the determination of (1) the tensile strength or breaking tenacity of fibres as a flat bundle using a nominal zero-gauge length, or (2) the tensile strength or breaking tenacity and the elongation at the breaking load of cotton fibres as a flat bundle with 1/8-in. [3.2-mm] clamp spacing. The samples were prepared by carefully removing single barbs from the rachis of waste chicken feathers and combed, and then 11.8 mm long feathers were prepared. The bundle tensile test was carried out on an Instron Tensile Tester (Model 3345) at 0 mm gauge length using Pressley clamps with leather facing.

Dynamic Mechanical Analysis: - The dynamic mechanical analysis (DMA) of the chicken feather barbs was done using a Perkin Elmer DMA 8000 DMA dynamic mechanical analyser. Feather barbs were tested in the tensile mode, while heating from 20 °C to 200 °C at a heating rate of 2 °C min^{-1}, and at a frequency of 1 Hz.

Electrical properties: - The electrical properties of the chicken feather fractions were carried out using the Two Probe Method. This is a standard and most commonly used method for the measurement of resistivity of very high resistivity samples - near insulators. Samples were air-conditioned and measurement was carried out at relative humidity 65±2 % and a temperature of 22±2 ºC. The instrument used was a Keithley 4200 semiconductor characterisation system from Cascade Microtech Inc. USA.

4.3.3. Results and discussions

4.3.3.1. Thermal properties

Thermogravimetric analysis (TGA)

The thermal stabilities of the chicken feather and its fractions were investigated by TGA and the results are shown in Figure 4.3.1 where it can be seen that the weight loss profiles of all three feather fractions were similar. Thus, the thermal behaviour of chicken feathers can be described in three main steps:

The first step is due to loss of moisture (12.9-13.4%) in the 25-230 ^{o}C temperature range. It is recognised that there are three different types of water within chicken feathers, namely, free water, loosely bonded water, and chemically bonded water which contribute to the conformational stability of keratin protein (Ehen et al., 2004; Wortmann et al., 2006). Consequently, the loss of water, as recorded by the thermogravimetric curve, is the result of the overlapping of three different processes by which the three types of water are lost (Wortmann et al., 2006).

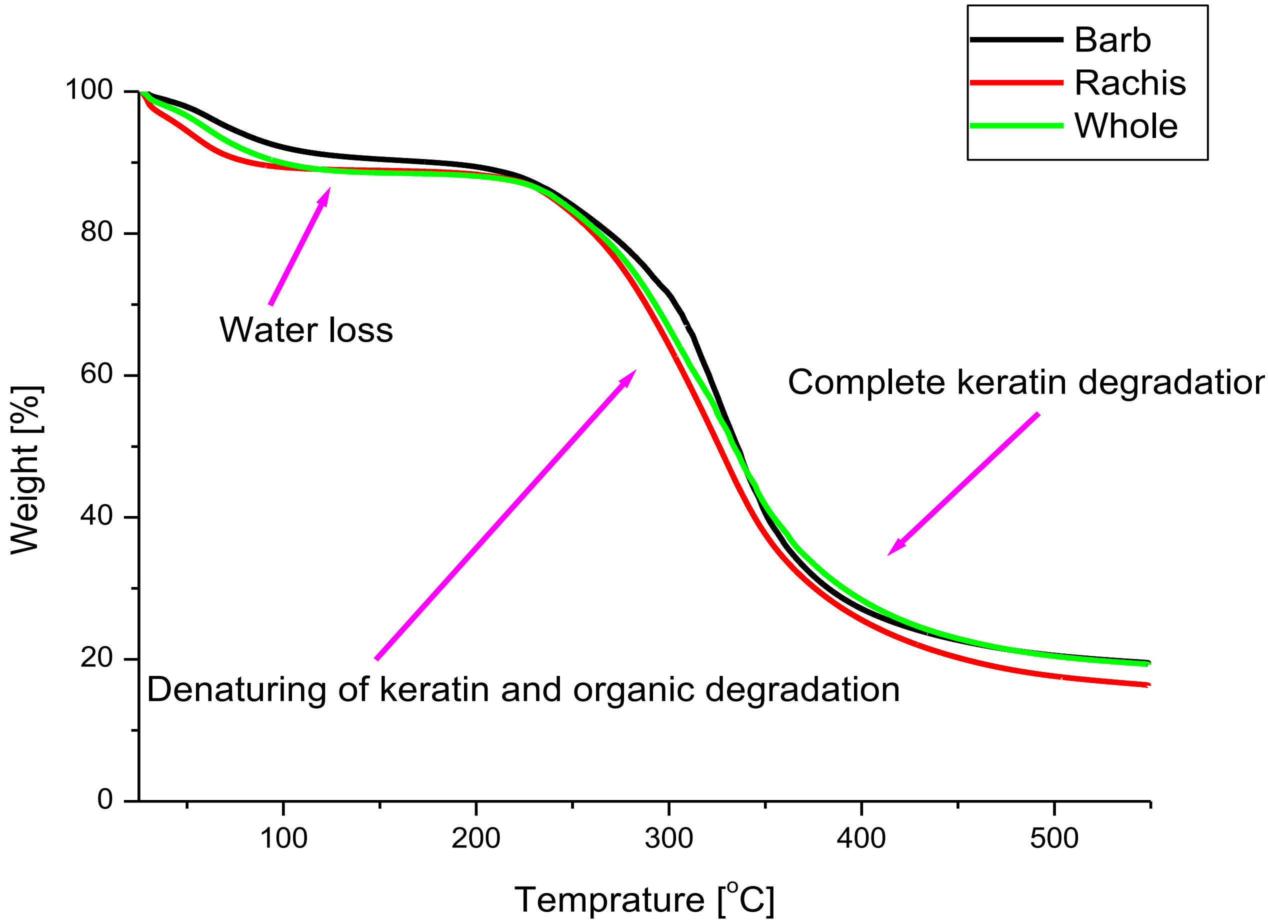
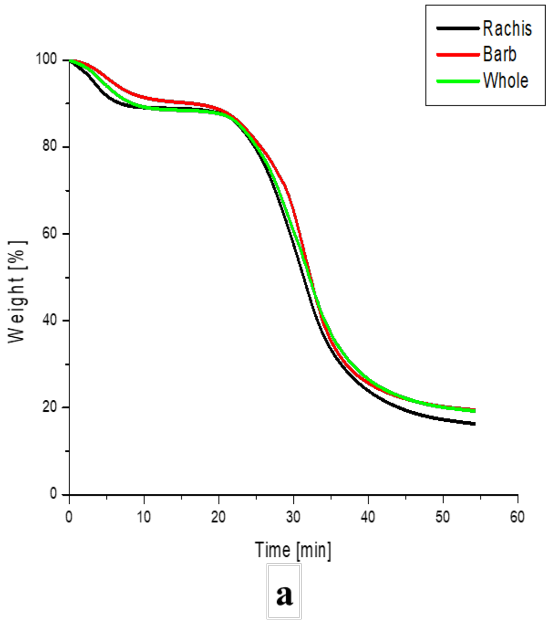


Figure 4.3.1. TGA curve for chicken feather fractions

The second step is due to partial decomposition of the feather fractions in the 230-380 °C temperature range with mass losses of ~46%. This loss is due to thermal denaturation of peptide bridge and protein chain linkages: a complex process that includes thermal pyrolysis of peptide chain linkages, depolymerisation of peptide bridges, dehydration of the protein structure, and skeletal degradation and decomposition of the protein units (Menefee and Yee, 1965; Milczerek et al., 1992; Wortmann et al., 2006). Also, this stage corresponds with the destruction of hydrogen bonds, disulphide bonds between spiral peptide chain of the feather structure, denaturation of the predominantly β-sheet structure, elimination of H_2S originating from the amino acid cysteine in keratin, and the oxidation of carbon (Haly and Snaith, 1970; Monteiro et al., 2005). The curves for the whole feather and rachis indicates nearly identical behaviour of decomposition, compared to the barb of chicken feathers, indicating that esterification of the protein has taken place and induced thermal stability. Nevertheless, the distinctively different TGA behaviour of the barb, in terms of decomposition and weight loss, is useful for sorption phenomenon. During this process, the helix structure is melted, followed by the thermal pyrolysis of the chain linkages, peptide bridges, and some other lateral chains, which finally leads to skeletal degradation (Haly and Snaith, 1970; Wortmann, and Deutz, 1998). The greater packing efficiency of the α-helical structure results in a lower thermal stability of the rachis compared to the fibre, i.e., at 222 °C.

In the third step, the feather fractions were fully decomposed from 380–550 °C with the greatest weight loss corresponding to complete degradation (81.75-83.70 %); this is in agreement with reports (Ehen et al., 2004; Wortmann, and Deutz, 1998). It can be seen that the rachis has the highest weight loss (81.53 %) and in contrast, the whole chicken feather and barb show the highest weight loss (81.75 and 83.70 % respectively); this effect is related to the inherent variations. The feather fraction completely decomposed to its elements at around 550 °C (gaseous state). This region includes several chemical reactions and skeletal degradation by which keratins are decomposed to lighter products and volatile compounds such as H_2S, CO_2, H_2O, HCN (Haly and Snaith, 1970; Wortmann et al., 2006). At nearly 550 °C, the weight loss rate became steady and a carbonised residue remained 16.30 %, 19.25 %, and 19.47 % of the original mass for rachis, whole feather, and barb, respectively. The feather fraction withstands up to 380 °C which was supported from the peak. These results suggest that the drying temperature for whole chicken feather should be above 100 °C and below 125 °C whereas the processing temperature for chicken feather and its fractions for different valuable materials like composite manufacturing should be controlled below 230 °C.

Figure 4.3.2a and b show the impact of time on weight loss and the impact of time on the derivative weight of the chicken feather fraction, respectively. The percentage weight loss increases with increase in time as shown in Figure 4.3.2. The first loss is due to the loss in the moisture contents below 150 °C and 15 minutes of residence time. Another sharp weight loss of chicken feather fraction starts after 150 °C and above 15 minutes. This could be due to the rapid devolatilisation of peptide bonds of the feathers. A derivative of weight loss shows the rate of change of weight loss is much faster during devolatilisation of the feathers.



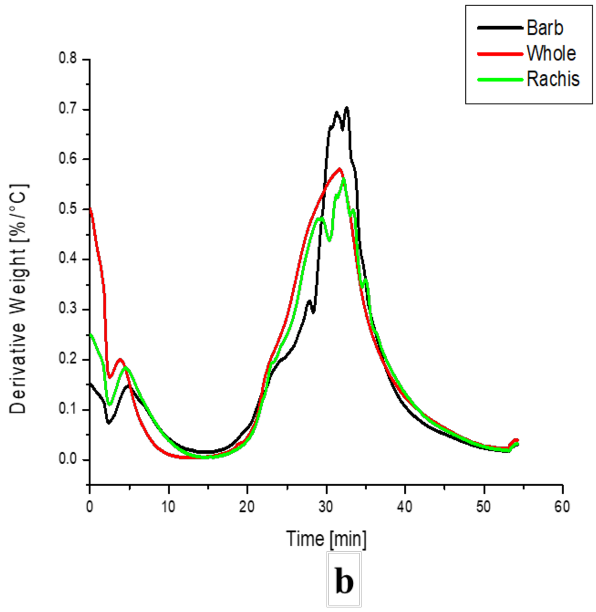


Figure 4.3.2. TGA: Impact of time on weight [%] for chicken feather fractions (a); on derivative weight [%/^{o}C] for chicken feather fractions (b)

Differential scanning calorimetry (DSC)

The phase behaviour of flow chicken feather fractions was studied by DSC to ascertain possible effects of thermal transition on mechanical and sorption properties of the feathers. DSC tests were performed on the bulk samples to determine the appropriate melting points (T_m). DSC curves of the chicken feather fractions and their T_m values are shown in Figure 4.3.3. The data revealed that the chicken feather fractions underwent two transitions when heated from 30-550 ^{o}C: a broader transition at approximately 45^{o}C -140 ^{o}C, and a much sharper transition at approximately 230-250 ^{o}C.

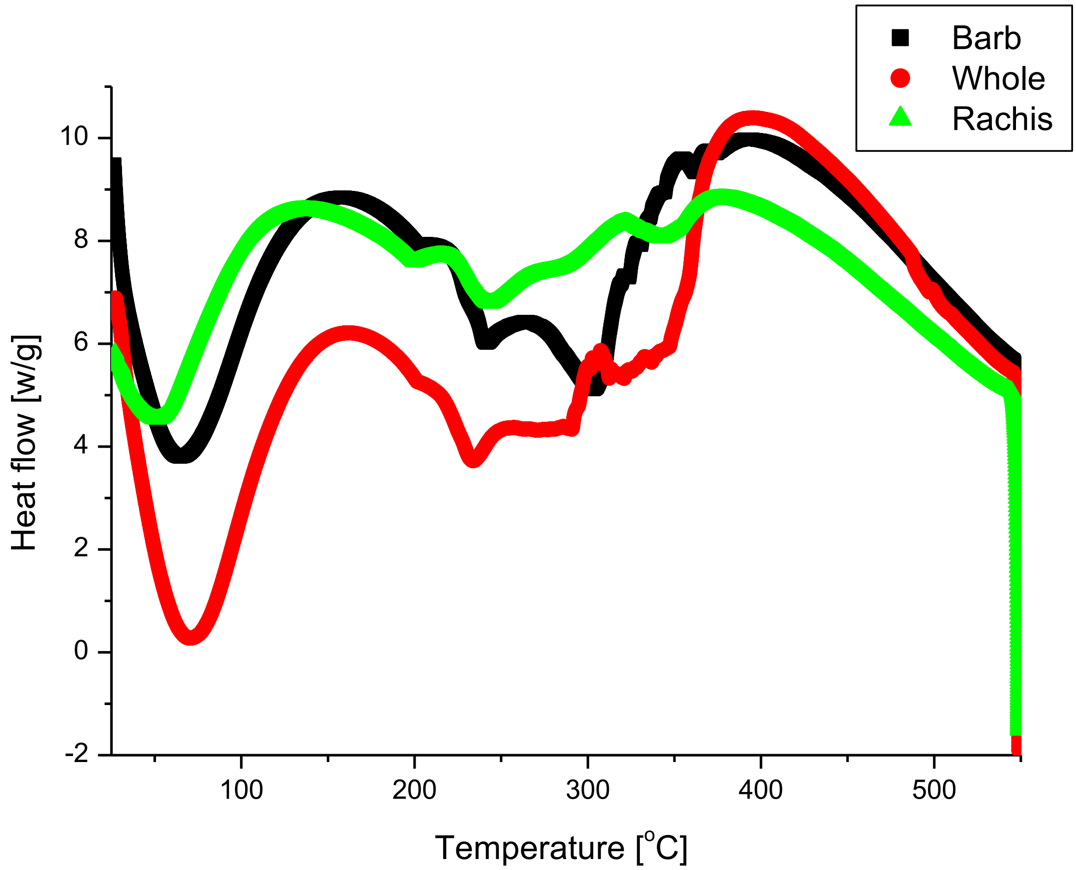


Figure 4.3.3. DSC curves for chicken feather fraction

Three peaks were observed as follows:

Peak 1: A broad, low-temperature peak was observed at 43-145 °C. This peak shows the amount of bound water in the keratin structure. Water is thought to bind to keratin in three forms and because of hydrogen bonding between water molecules and the keratin structure in chicken feather fractions, some of the water requires the temperature to exceed 100 °C for it to evaporate (Wortmann et al, 2006; Abu Baker et al., 2004). The activation energy of water undergoing hydrogen bonding to keratin has been estimated at 25.1 kJ mol^{-1} (Haly and Snaith, 1970; Menefee and Yee, 1965). Thus, the steady release of water from the chicken feather fractions are a result of activation energy limitations, and not thermal lag. This peak is on occasion referred to as the ‘‘denaturation’’ temperature. A significant change in denaturation curves can be seen particularly for rachis, which shows a distinctively different behaviour with broader denaturation, suggesting a wide range of structural changes. DSC results indicate that temperatures below 110 °C may not allow for the progress of moisture through feathers (Jeffery, 2006;

Milczarek et al., 1992).

The DSC of the whole chicken feather fraction demonstrates an exothermic peak at < 230 °C, which is generally assigned to α-helix decomposition and disordering (some literature also describes this transition as a "melt"). However, in rachis, this peak was broadened and shifted to comparatively lower temperatures and this indicates the gain of amorphous behaviour and loss of α-helix structures, marked with a broadened melting curve trend.

Peak 2: The partial degradation of chicken feather fractions occurs in the next narrow endothermic peak around 230-275 °C. This can be assigned to the crystalline melting temperature found in keratin that shows a tighter keratin structure to which water is more strongly bonded (Monteiro et al., 2005; Wortmann et al., 2006). The colour change from white to black was observed during degradation. The sharpness of this change shows a very ordered phase with low polydispersity (Haly and Snaith, 1970; Schmidt and Jayasundera, 2004; Wortmann et al., 2006). This peak reveals either melting (Haly and Snaith, 1970; Menefee and Yee, 1965; Wortmann et al., 2006) or denaturation (Haly and Snaith, 1970; Wortmann et al., 2006) of crystalline phases.

Peak 3: The third peak at 280-340 °C is related to thermal changes in keratin, specifically to thermal degradation of disulphide bonds, and denaturation of helical structures in the feathers (Monteiro et al., 2005). The peak could be also attributed to total decomposition chicken feather keratin (Haly and Snaith, 1970; Schmidt and Jayasundera, 2004). Hence the decomposition temperature for chicken feather fractions is around 280–340 °C, and this temperature range agrees with the highest weight loss observed during TGA. This is due to the different reactions caused by the thermal treatment of amino acids present in the chicken feather keratin.

The peak at approximately 67 ^{o}C (Figure 4.3.3) appears to be the glass transition temperature (Tg) of chicken feather fractions. The last endothermic peak at 418 ^{o}C was assigned to a decomposition process which is also reflected in TGA, from 230 ^{o}C to 380 ^{o}C (Figure 4.3.1), as a 12 to 67 % decrease in mass of the feather fractions. This decomposition is associated with destruction of disulphide bonds and elimination of H_2S. It also involves the destruction of the helix structure and thermal pyrolysis of peptide bridges, degradation of skeletal and chain linkages as several chemical reactions occur in this region where protein compounds are pyrolysed to volatile compounds and lighter products such as H_2S, CO_2, H_2O and HCN. In all the feather fractions (Figure 4.3.3), no sharp peak was observed; this is consistent with loss of crystallinity observed by XRD analysis (Tesfaye et al., 2017). The result from DSC endothermic peaks is related to TGA degradation steps as described earlier (Figure 4.3.1).

4.2.3.2. Mechanical properties

Mechanical properties characterise the mechanical behaviour of the materials in various fabrication processes. Maximum load (cN), tenacity @ maximum load (cN/tex), tensile extension @ maximum load (mm), tensile stress @ maximum load (MPa), tensile strain @ maximum load (%) and dynamic mechanical analysis were the most important parameters studied to ascertain mechanical properties of feathers.

Tensile properties of chicken feather fractions

The data in Table 4.3.1 is a comparison of mechanical properties of untreated and treated chicken feather fractions. The tensile properties of waste chicken feather fractions were not uniform. Since the diameters of chicken feather barb and rachis are not uniform and are not cylindrical along their longitudinal dimensions, their mechanical properties also vary. This can be explained by the fact that feather is a natural fibre and natural fibres are subject to growth irregularities to the extent that fibres from the same source are not uniform in size and properties (Ullah et al., 2011). The outer part of the chicken body produces the strongest fibres whereas the inner part produces the shortest and weakest fibres. The outermost fibres have more elongation before breaking than inner fibres. The wet strength of all proteinous fibre is lower than dry fibre strength but, elongation at break is higher when the fibre is in a wet state (Hearle and William, 2008; Matthews, 1921). From the data in Table 4.3.1 it can be concluded that both chicken feather barb and rachis can be beneficiated for use in end products where there is the application of instantaneous force. The mean tenacity of chicken feather barbs were found to be 16.93 cN/tex, for raw chicken feather and shows a reduction for treated chicken feathers (8.87 cN/tex for SDS and 9.37 cN/tex for H_2O_2) with a mean elongation at maximum load 0.48 mm, 0.40 mm and 0.46 mm of respectively. The higher strength value could be explained by the S-S linkage and the keratin composition of chicken feather – this implies that this material could be used as textile fibre.

Table 4.3.1. Bundle strength result of treated and untreated chicken feather barbs

Sample	**Maximum Load (cN)**	**Tenacity at maximum Load (cN/tex)**		**Tensile extension at maximum load (mm)**		**Linear density (Tex)**	
		Mean	**CV%**	**Mean**	**CV%**	**Mean**	**CV%**
CF1	820.81	16.93	18.44	0.48	15.67	8.09	16.86
CF2	332.68	8.87	19.00	0.40	9.88	37.60	15.42
CF3	447.83	9.37	19.15	0.46	8.06	47.80	17.84
Rachis	93.16×10^2			3.302	36.21		

CV, Coefficient of variation

This tensile strength of chicken feather barb implies that all parts of the chicken feather can function well for yarn production, upholstery fabrics, furnishing fabrics, floor mats, carpets, rugs, as well as in geotextile, fibre reinforced composites and nonwovens (Hearle, 2000; Hearle and William, 2008). Barbs of chicken feathers are coarser than wool fibre, however, the strength, elongation and modulus of the chicken feather barbs are similar to those of wool (Table 4.3.2). The strength of chicken feather rachis is higher than that of barbs, however, that of the barb of the chicken feather is similar to that of wool and higher than that of cotton fibre with lower elongation at break. The low density and unique morphological structure of barbs makes them suitable for beneficiation into a variety of applications such as textiles, lightweight composite, geotextiles and diaper production.

Table 4.3.2. Tensile properties of fibres (Hearle and William, 2008)

	Maximum load [cN]	**Tenacity at maximum load [cN/tex]**	**Tensile extension [%]**	**Tensile strain at maximum load [%]**	**Tensile stress at maximum load [MPa]**
Wool	485.06	10.25	2.54	2797.33	0.49
Silk	1000.77	12.40	6.09	6744.38	1.00
Cotton	662.75	12.58	3.36	3703.99	0.66

Dynamic Mechanical Analysis (DMA):

The viscoelastic properties of chicken feather fractions were analysed by DMA. The storage modulus corresponds to the solid-like (elastic) component of the material, whereas the loss modulus signifies the liquid like (viscous) nature of the material. The ratio between the loss and storage moduli gives a useful quantity known as the mechanical damping factor (tan δ) which is a measure of the amount of deformational energy that is dissipated as heat during each cycle (Feughelman 1997). Figures 4.3.4, 4.3.5 and 4.3.6 show the DMA results of untreated chicken feather barbs (CF1), sodium dodecyl sulphate (SDS) treated feather barbs and hydrogen peroxide (H_2O_2) treated feather barbs (CF3), heated from 20 to 150 °C at a heating rate of 2 °C min^{-1}, and at a frequency of 1 Hz. Chicken feather barbs are composed of beta-keratin (β-keratin) which is extremely insoluble in water and organic solvents. The β-keratin is made up of protein strands hydrogen-bonded into β-sheets, which are twisted and crosslinked by disulphide bridges that give strength and stiffness to the protein structure (Ullah et al., 2011; Zhan and Wool, 2011).

Storage modulus: The variation in the storage modulus as a function of temperature for raw and treated chicken feather single barb is depicted in Figure 4.3.4. As can be seen in the Figure, the storage modulus decreased steadily as the temperature increased and this can be ascribed to the molecular mobility increment of the chicken feather polymer chains. Due to the heterogeneity of the chicken feather structure, type of treatment and the geometrical irregularity of the chicken feather barb, the measured storage modulus had significant deviation (Figure 4.3.4). From Figure 4.3.4, the storage modulus for all chicken feather fractions gradually decreased with increasing temperature, but the modulus did not drastically decrease within the measured temperatures. The drop-in modulus around the glass transition region (65–90 °C) is much smaller for raw and SDS treated chicken feather barb than that for H_2O_2 treated chicken feather barbs that was much more drastic. The untreated feathers show higher storage modulus than treated feathers barbs (Figure 4.3.4). This suggests that the chemical treatments (SDS and H_2O_2) applied on the chicken feathers may have dissolved or denatured some of the cross-linked networks of the protein structure, especially for bleached (H_2O_2) feather barbs. This implies that the stiffness of the fibres, owing to the crosslinked network of disulphide bridges within the fibre structure, was not significantly reduced within the measured temperatures. The decrease in stiffness observed at high temperatures may be attributed to degradation of the fibres as a result of the increased temperatures.

The storage modulus of chicken feather barb decreased with the treatment of chicken feather in glassy as well as the rubbery region. This observation is most likely related to the interaction between the hydroxyl groups that are present on keratinous materials. Although the absolute values of storage and tensile moduli cannot often be compared directly, both moduli results indicate that the mechanical properties of chicken feather barbs are heterogeneous. The higher storage modulus seen in Figure 4.3.4 is due to low brittleness in chicken feather barbs. This indicates that the softness and flexibility of a chicken feather barb and the lower the modulus, the flexible and softer the material is. Therefore, chicken feather fractions could be used in the production of composites where toughness and softness are desirable properties.

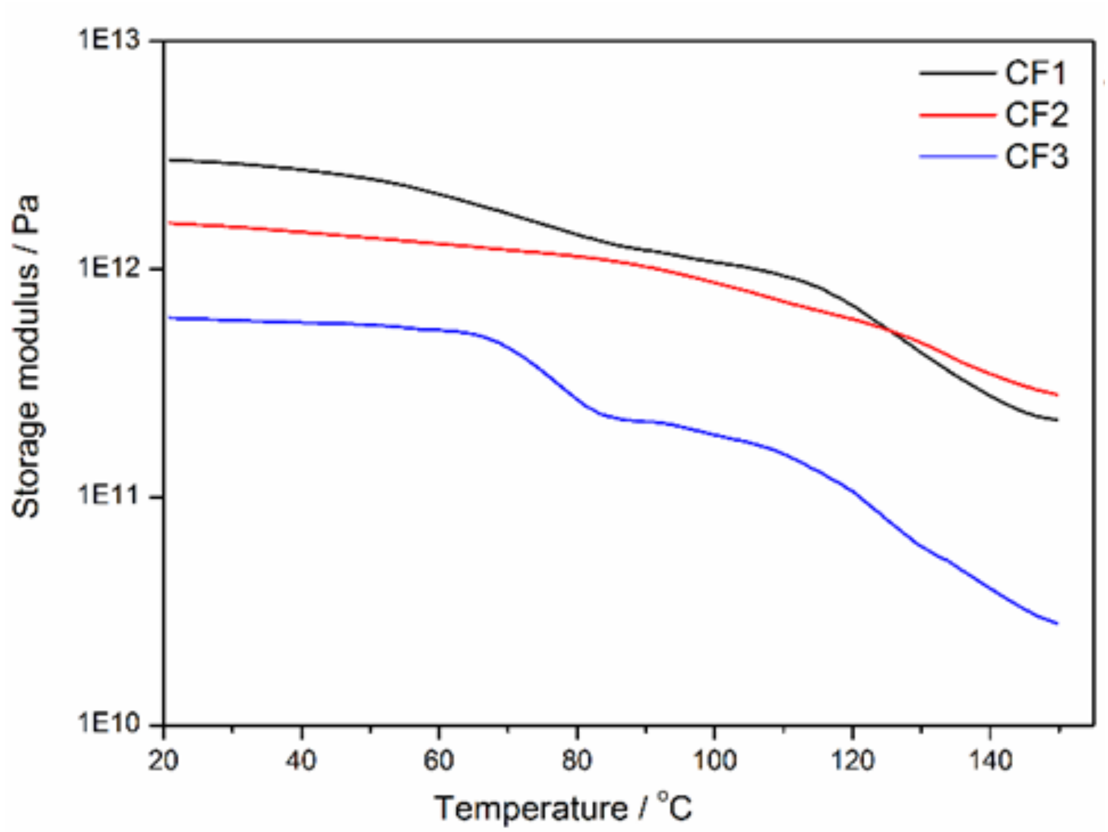


Figure 4.3.4. DMA storage modulus analysis of chicken feather barbs

Loss modulus: Figure 4.3.5 depicts the variation of loss in modulus with the different temperature range. The loss modulus is a measure of the energy dissipated as heat per cycle under deformation and defined as the stress 90^o out-of-phase with the strain divided by the strain (Feughelman, 2002; Hearle and William, 2008; Ornaghi et al., 2010; Ullah et al., 2011; Zhan and Wool, 2011). Figure 4.3.5 shows the loss modulus vs. temperature plots of the treated and untreated chicken feather barbs. This may be attributed to the inhibition of the relaxation process within the chicken feather barbs as a consequence of a higher number of chain segments. As loss modulus is sensitive to molecular motions it could mean that the mobility of the polymer molecular chains decreases as the chains were hindered by the treatment of chicken feather barbs leading to a shift of Tg. The loss modulus decreases after treatment of chicken feathers. This may be due to energy losses caused by molecular rearrangement of the polymeric chains in the chicken feathers. The loss modulus in the transition region is higher for untreated chicken feather barbs, which may be due to an increase in internal friction, promoting energy dissipation (Ullah et al., 2011; Zhan et al., 2011; Zhan and Wool, 2011).

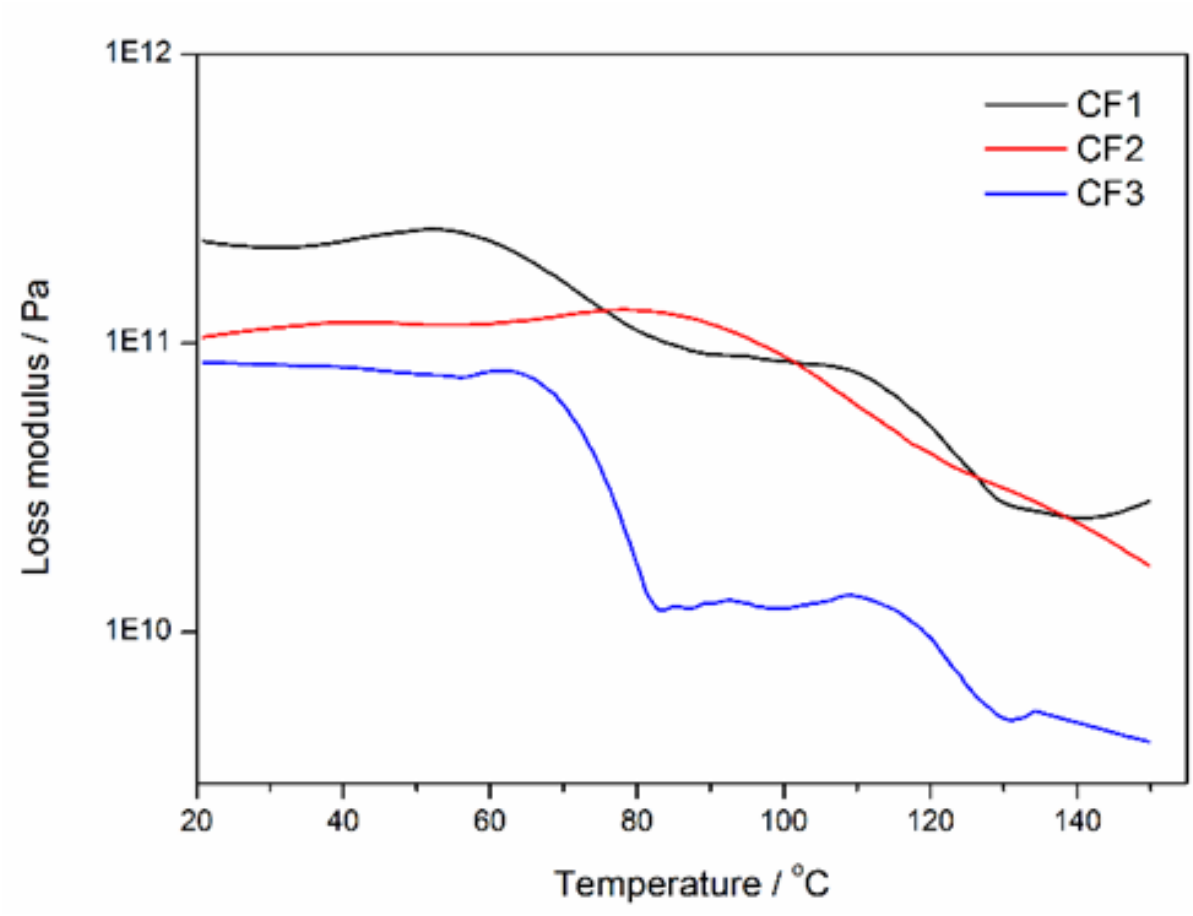


Figure 4.3.5. DMA loss modulus analysis of chicken feather barbs

Damping parameters

Damping parameter/ mechanical loss factor/tan δ is the ratio of loss modulus and the storage modulus (Feughelman, 2002; Ornaghi et al., 2010). Figure 4.3.6 indicates the damping properties of the chicken feather barbs between the viscous and elastic phases in the chicken feather polymeric structure. As the temperature increases, the mechanical loss factor shows an increase in transition region then decrement in the rubbery region (Figure 4.3.6). Below Tg, since the chain segments are in the frozen state, damping is low the molecular slips resulting in the viscous flow are low and the deformations are primarily elastic. In the rubbery region, there is no resistance to flow, because of low damping that is due to molecular segments that are quite free to move. In a region where most of the chain segments take part in cooperative motion under a given deformation, maximum damping will occur (Ornaghi et al., 2010).

The homogeneity of the mechanical properties are checked by the width of the tan δ peak (Ornaghi et al., 2010). The amplitude of tan δ peak is directly related to a material's ability to dissipate energy through segmental motion (Ornaghi et al., 2010). From Figure 4.3.6, it can be observed that raw chicken feathers have a high Tg value of around 60-70 ^{o}C, whereas H_2O_2-treated chicken feather barbs have a higher Tg value of 60-100 ^{o}C.

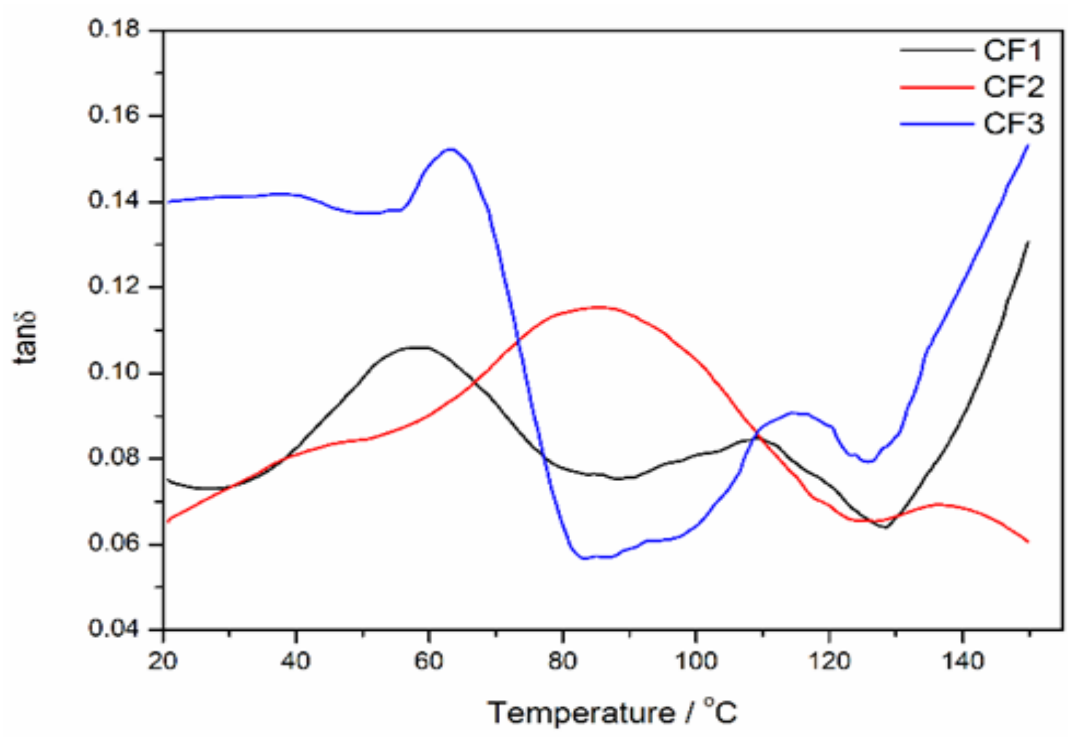


Figure 4.3.6. DMA tan δ analysis of chicken feather barbs

3.3.3.4. Electrical properties

Electrical conductivity, resistivity and dielectric constant are major parameters that describe the electrical properties of chicken feathers (Varesano and Tonin, 2008). Like other physical, chemical, mechanical and thermal properties, the electrical properties of chicken feathers can be varied due to the feather orientation. Depending on the morphological structure chicken feather contain high amounts of air pockets in the structure (honeycomb structure) (Figure 4.3.7). Porosity is the property of an insulating material that is able to absorb moisture (Varesano et al., 2005). An insulating material having high porosity will absorb more moisture thereby affecting its other electrical properties. The SEM micrographs in Figure 4.3.7 revealed that chicken feathers are light and hollow in structure. The nodes and hooks in the feathers bear a hollow structure. This hollow structure contains a significant volume of air and can impart low density (about 0.86 g/cm^3) (Tesfaye et al., 2017) as well as good dielectric behaviour. Thus, any dielectric materials produced from chicken feathers will have low density which would decrease with increase of chicken feather content the products that can be made to density less than 1 g/cm^3.

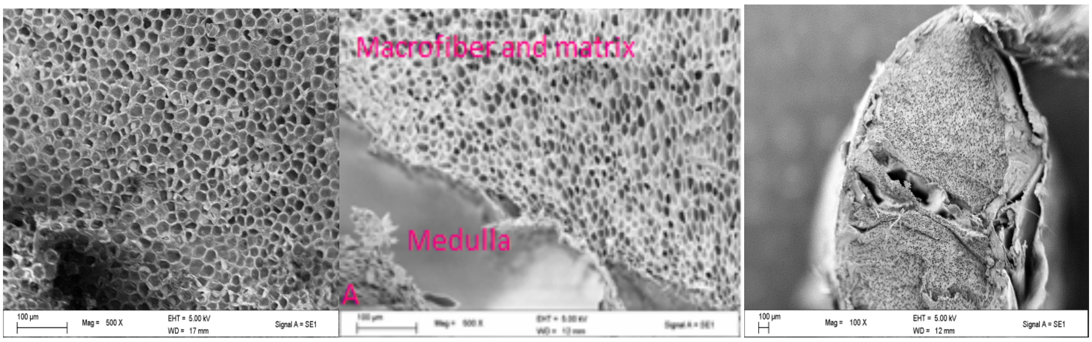


Figure 4.3.7. Hollow structure of chicken feather fraction (Tesfaye et al., 2017)

Electrical resistance and conductivity tests were carried out at different voltage levels (-5V to 5V). The results revealed that the electrical resistance of chicken feathers decreased with increase in input voltage, i.e., the chicken feather fractions have electrical resistances of 6.74x10^{11} Ohms (Ω) for barbs and 8.13x10^{11} Ohms (Ω) for rachis whereas the conductivities were 2.84x10^{-12} Siemens per metre (S/m) for the barbs and 3.62x10^{-12} Siemens per metre (S/m) for the rachis. Since resistivity is a measure of how strongly feathers resist electrical current, the high resistivity values indicate that feathers cannot be used as conductors for electricity. Composites made from the chicken feathers can be used as electrical insulators since both the barb and rachis have high resistivity and low electrical conductivity. Generally, for ohmic materials, resistance remains constant with an increase of voltage and current. However, with chicken feathers, the current does not increase with an increase in voltage, hence the resistance decreases. This also implies that if the input voltage increases, caution must be taken regarding the use of chicken feathers as insulating materials.

Table 4.3.3. Resistance and conductance values of chicken feather barbs

Time	AI	AV	Resistance (Ω)	Conductance (S/m)
2.24E+00	-1.78E-11	-5.00E+00	2.81E+11	3.56E-12
3.98E+00	-1.40E-11	-4.50E+00	3.22E+11	3.10E-12
5.53E+00	-3.35E-12	-4.00E+00	1.19E+12	8.38E-13
8.32E+00	-8.26E-12	-3.50E+00	4.24E+11	2.36E-12
9.87E+00	1.07E-12	-3.00E+00	-2.80E+12	-3.57E-13
1.24E+01	-2.01E-13	-2.50E+00	1.25E+13	8.02E-14
1.37E+01	1.50E-12	-2.00E+00	-1.33E+12	-7.50E-13
1.51E+01	6.88E-12	-1.50E+00	-2.18E+11	-4.58E-12
1.66E+01	5.46E-12	-1.00E+00	-1.83E+11	-5.46E-12
1.92E+01	5.11E-12	-5.00E-01	-9.79E+10	-1.02E-11
2.18E+01	9.49E-12	5.00E-01	5.27E+10	1.90E-11
2.30E+01	1.91E-11	1.00E+00	5.24E+10	1.91E-11
2.44E+01	7.51E-12	1.50E+00	2.00E+11	5.01E-12
2.62E+01	1.12E-11	2.00E+00	1.78E+11	5.60E-12
2.81E+01	6.39E-12	2.50E+00	3.91E+11	2.55E-12
2.93E+01	2.32E-11	3.00E+00	1.29E+11	7.75E-12
3.07E+01	2.59E-12	3.50E+00	1.35E+12	7.40E-13
3.25E+01	1.34E-11	4.00E+00	2.97E+11	3.36E-12
3.50E+01	1.36E-11	4.50E+00	3.31E+11	3.02E-12
3.66E+01	1.12E-11	5.00E+00	4.47E+11	2.24E-12
		Mean	6.74E+11	2.84E-12
		SD	2.83003E+12	6.69059E-12
		Cv	419.9454804	235.1735749

The dielectric constant of a material describes its general behaviour in an electrical field. The ideal minimum dielectric constant value is 1.0, as represented by air. A chicken feather has a measured dielectric constant of 1.7, probably due to void spaces that can contain a significant amount of air (Zhan et al 2011). Therefore, chicken feather fractions have lower dielectric values than conventional semiconductor insulators, e.g., polyimides, epoxies, and other dielectric materials. Thus, composites made from chicken feathers can be used for electronic applications such as printed circuit boards in mobile phones, computers, keyboards, laptops, televisions etc., which require relatively high electric resistance and low dielectric constant.

Table 4.3.4. Resistance and conductance of chicken feather rachis

Time	AI	AV	Resistance (Ω)	Conductance (S/m)
1.74E+00	-1.90E-11	-5.00E+00	2.63E+11	3.80E-12
3.13E+00	-1.28E-11	-4.50E+00	3.52E+11	2.84E-12
4.68E+00	-6.69E-12	-4.00E+00	5.97E+11	1.67E-12
7.46E+00	-9.17E-12	-3.50E+00	3.82E+11	2.62E-12
9.02E+00	-6.32E-13	-3.00E+00	4.74E+12	2.11E-13
1.10E+01	-6.54E-12	-2.50E+00	3.83E+11	2.61E-12
1.25E+01	2.86E-12	-2.00E+00	6.98E+11	1.43E-12
1.47E+01	-2.89E-13	-1.50E+00	5.19E+12	1.93E-13
1.62E+01	4.37E-12	-1.00E+00	2.29E+11	4.37E-12
1.82E+01	5.35E-12	-5.00E-01	9.34E+10	1.07E-11
2.17E+01	1.62E-12	5.00E-01	3.08E+11	3.25E-12
2.32E+01	9.45E-12	1.00E+00	1.06E+11	9.45E-12
2.52E+01	7.18E-12	1.50E+00	2.09E+11	4.79E-12
2.67E+01	8.71E-12	2.00E+00	2.30E+11	4.35E-12
2.87E+01	1.49E-11	2.50E+00	1.68E+11	5.97E-12
3.02E+01	9.81E-12	3.00E+00	3.06E+11	3.27E-12
3.26E+01	1.18E-11	3.50E+00	2.97E+11	3.36E-12
3.41E+01	1.06E-11	4.00E+00	3.77E+11	2.65E-12
3.65E+01	1.25E-11	4.50E+00	3.59E+11	2.78E-12
3.81E+01	1.16E-11	5.00E+00	4.30E+11	2.33E-12
		Mean	8.13E+11	3.62E-12
		SD	1.43331E+12	2.61893E-12
		Cv	176.2131232	72.26066688

4.3.4. Potential valorisation of chicken feather fractions based on thermal, mechanical and electrical properties

The whole chicken feather, due to its complex structure, cannot be processed into protein fibre; however, its unique properties provide the potential for many applications. The results of the thermal, mechanical and electrical characterisation of chicken feathers imply that feathers could be used in a variety of applications such as:

- in the textile industry (as a cost-effective alternative source of raw material to the commonly used natural protein fibres, namely, wool and silk);
- as a source of fibre to be used as a filler in thermal insulation applications;
- use in geotextile and road construction applications;
- in the energy industry as insulation materials;
- in the electronics industry (as a source of electrical insulator material);
- in the packaging industry (as a source of biodegradable plastics) (Figure 4.3.8) (Tesfaye et al., 2017).

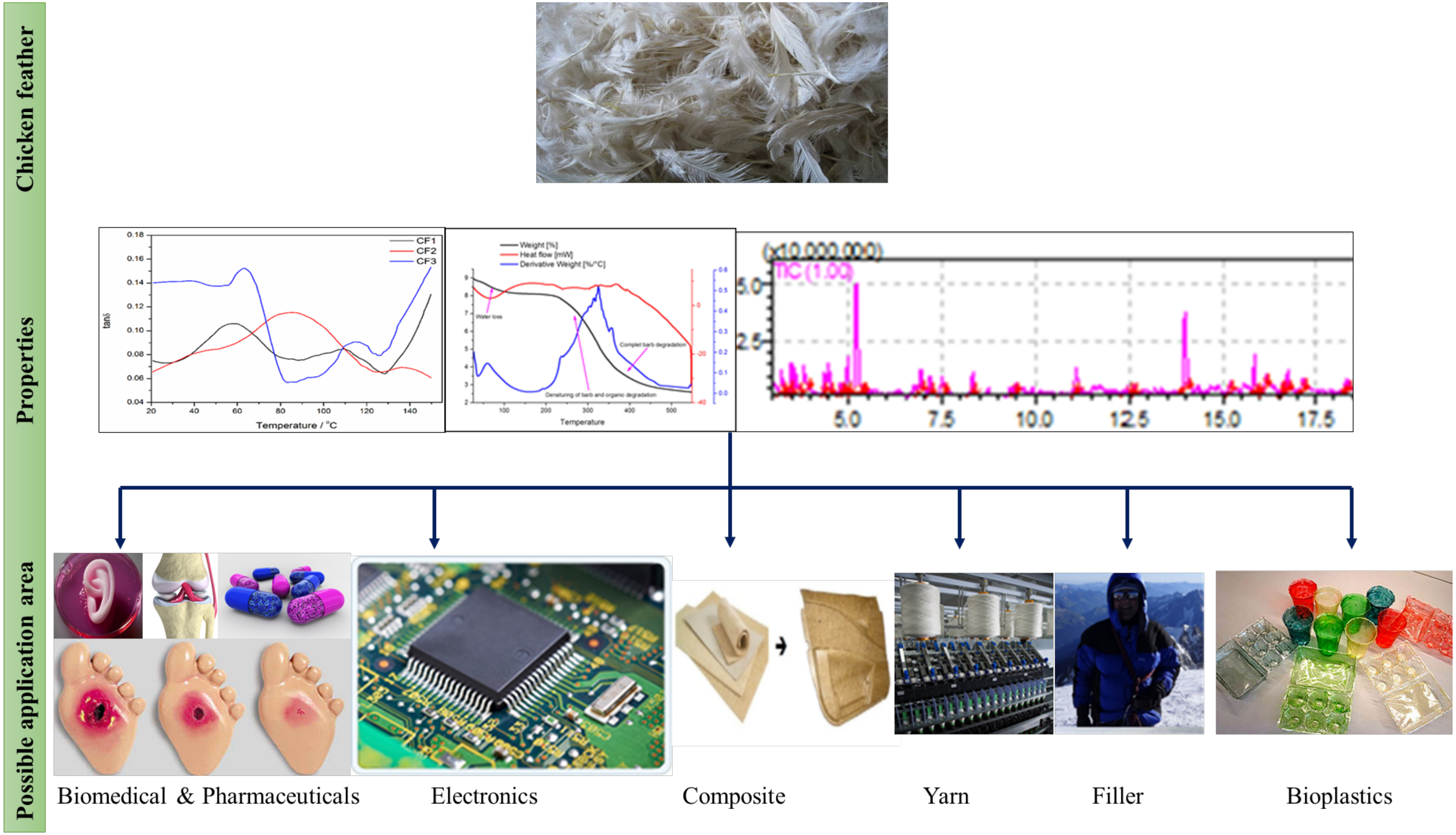


Figure 4.3.8. Possible valorisation route of waste chicken feathers based on characterised properties.

4.3.5. Conclusions

The substantial growth of the poultry industry has led to the generation of large amounts of waste. Due to environmental and sustainability concerns, this waste should be properly managed beneficiated. Mechanical, thermal and electrical properties of feathers were determined and evaluated to ascertain suitability of the feathers for production of high-value materials. The feathers and fractions thereof were characterised by TGA/DSC, Instron (material and structural testing), Dynamic Mechanical Analyser, and a two-probe measurement of resistivity instrument. Results suggest that the drying temperature for whole chicken feather should be above 100 ^{o}C and below 125 ^{o}C whereas the processing temperature for chicken feather and its fractions for different valuable materials like composite manufacturing should be controlled below 230 ^{o}C. Overall, the results indicate that chicken feathers have potential to be used as electrical insulator materials, fibres for packaging applications, fillers for construction materials, yarns for use in textile applications. Such beneficiation of waste chicken feathers would open up new industries and job opportunities, and make the poultry industry more competitive.

ACKNOWLEDGMENTS

The authors are highly grateful for the financial and technical support received from the Institute of Technology for Textile and Fashion Design/EiTEX at Bahir Dar University, Thermodynamics Research Unit at Chemical Engineering of University of KwaZulu-Natal, the Biorefinery Industry Development Facility, CSIR, Department of Science and Technology, Waste Research Development and Innovation Roadmap, and Rainbow Chicken Limited Foods.

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CHAPTER 5

PRODUCTION OF HIGH VALUE MATERIALS

Chapter overview

A detailed characterisation of properties of chicken feathers has been conducted with the objective of ascertaining valorisation products that can be made from this waste material. The results of the characterisation of chicken feathers imply that they could be used in a variety applications such as in the agricultural industry (biofertiliser and animal feed); the textile industry (as a source of regenerated fibre, sizing agents to replace costly starch based sizing agents, as a binder and thickener in textile finishing and printing, as a finish to impart flame retardancy); in the energy industry (biofuel, biogas and energy storage devices), in the cosmetics industry (as a source of keratin), in the health industry (as a source of pharmaceuticals and biomedical materials), in composite manufacturing and in the packaging industry (as a source of biodegradable plastics). Examples of how and where chicken feather waste can be a useful resource are described in this chapter as a review paper (valorisation of chicken feathers: a review on recycling and recovery route-current status and future prospects).

To further clarify the potential utilisation of waste chicken feathers in the production of high-value materials, this chapter illustrates the possibilities of beneficiation of waste chicken feathers into various high value products. The research result in the publication of five peer-reviewed research articles:

- Valorisation of chicken feathers: a review on recycling and recovery route-current status and future prospects
- Valorisation of chicken feathers: utilisation in yarn production and technical textile application;
- Valorisation of chicken feathers: application in paper production;
- Valorisation of waste chicken feathers and avocado seeds: preparation and characterisation of green biofilms and
- Valorisation of chicken feathers: application as a green oil sorbent.

The proper utilisation of this waste would open up new industries and job opportunities, and make the poultry industry more competitive.

5.1. VALORISATION OF CHICKEN FEATHERS: A REVIEW ON RECYCLING AND RECOVERY ROUTE-CURRENT STATUS AND FUTURE PROSPECTS

(BASED ON PAPER SIX)

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ABSTRACT

Worldwide, the poultry meat processing industry generates large quantities of feather by-products that amount to 40×10^9 kilogrammes annually. The feathers are considered wastes although small amounts are often processed into valuable products such as feather meal and fertilisers. The remaining waste is disposed of by incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases. Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. A closer look at the structure and composition of feathers shows that the whole part of a chicken feather (rachis and barb) can be used as a source of a pure structural protein called keratin which can be exploited for conversion into a number of high-value bioproducts. Additionally, several technologies can be used to convert other biological components of feathers into high value-added products. Thus, conversion of the waste into valuable products can make feathers an attractive raw material for the production of bioproducts. In this review, possible applications of chicken feathers in a variety of technologies and products are discussed. Thus, using waste feathers as a valuable resource can help the poultry industry to dispose of the waste feathers in an environmentally sustainable manner that also generates extra income for the industry. Their valorisation can result in their sustainable

conversion into high-value materials and products on the proviso of existence or development of cost-effective technologies for converting this waste into the useful products.

Keywords: *poultry waste, feathers, biodegradable product, value-added product, keratin*

5.1.1. Introduction

There is a critical need and increasing interest across the world to decrease the consumption of petroleum-based products and to develop bioproducts using renewable and sustainable sources (Robertson, 2012). Many such efforts have already been made and practised in both developing and developed countries. Such efforts are necessary to satisfy the food, clothing, pharmaceutical, automobile, cosmetic, plastic and other basic needs of the future generation. Due to limited fossil resources, the recent focus is to utilise agricultural by-products and co-products as a replacement in industrial application. These products are inexpensive and environmentally sustainable renewable resources for use in the development of bioproducts. Nourishment squanders are produced by a mixture of sources, extending from rural operations to household consumption. Excluding food and agricultural waste generated during agricultural processing, households produce up to 42 % of the waste, 38 % of the of the food waste occurs during food preparation, and 20 % is disseminated along the food processing chain (Baiano, 2014). Currently, legislations around the world encourage valorisation of waste and by-products of manufacturing processes (Baiano, 2014). This valorisation of waste can be accomplished through the extraction of essential segments, for example, filaments, polysaccharides, flavour mixes, proteins and phytochemicals, which can be re-utilized in the nutrition, textile, cosmetic, composite materials and pharmacological functional industries (Ambrose and Clanton, 2004).

The chicken meat processing industry is developing at a rapid growth rate all over the world. Reasons for the great pace include efficient feed to weight gain ratio, the fast growth rate of chickens, poultry being a rich source of nutrients for human consumption, fast production time, and low economic value of poultry per unit (Rahayu and Bata, 2015). Almost all sections of the society, encompassing all customs and religions, consume chicken meat. According to the USA Foreign Agricultural Service, the total domestic per capita consumption of chickens is 59 kg in the United States; 48.0 kg in Saudi Arabia, 67.1 kg in Hong Kong, 69.7 kg in Israel, and 35.4 kg in Canada (USDA Foreign Agricultural Service, 2014). In South Africa the consumption rate in 2011 was 36.27 kg (DAFF, 2014). This large consumption of chicken results in the generation of huge amounts of chicken feathers each year worldwide. Unfortunately, the demand for feathers is low, and most of them are disposed of by burning, landfilling, or conversion into feather meal and fed to livestock or used as fertiliser (Gurav and Jadhav, 2013).

In this report, we review the possibilities of beneficiation of chicken feathers into high-value products. Since poultry feathers are rich sources of keratin proteins and amino acids, we believe that they are a valuable resource – their valorisation can result in their sustainable conversion into high-value materials and products on the proviso of existence or development of cost-effective technologies for converting this waste into useful products.

5.1.1.1. The poultry industry

Chickens can be classified into broilers, used for chicken meat supply, and layers, used for egg laying. Broilers are selected for competent feed to weight gain ratio and rapid growth rate. Chickens are slaughtered and processedfrom chicks that grow from a hatch weight of 45 g to 2.5 kg after 42 to 45 d (Rahayu and Bata, 2015). The poultry processing procedure is summarised in Figure 5.1.1, starting with live chickens up to meat packaging and storage. The process leads to the production of both inedible and edible by-products. Feathers are major components of the inedible by-products.

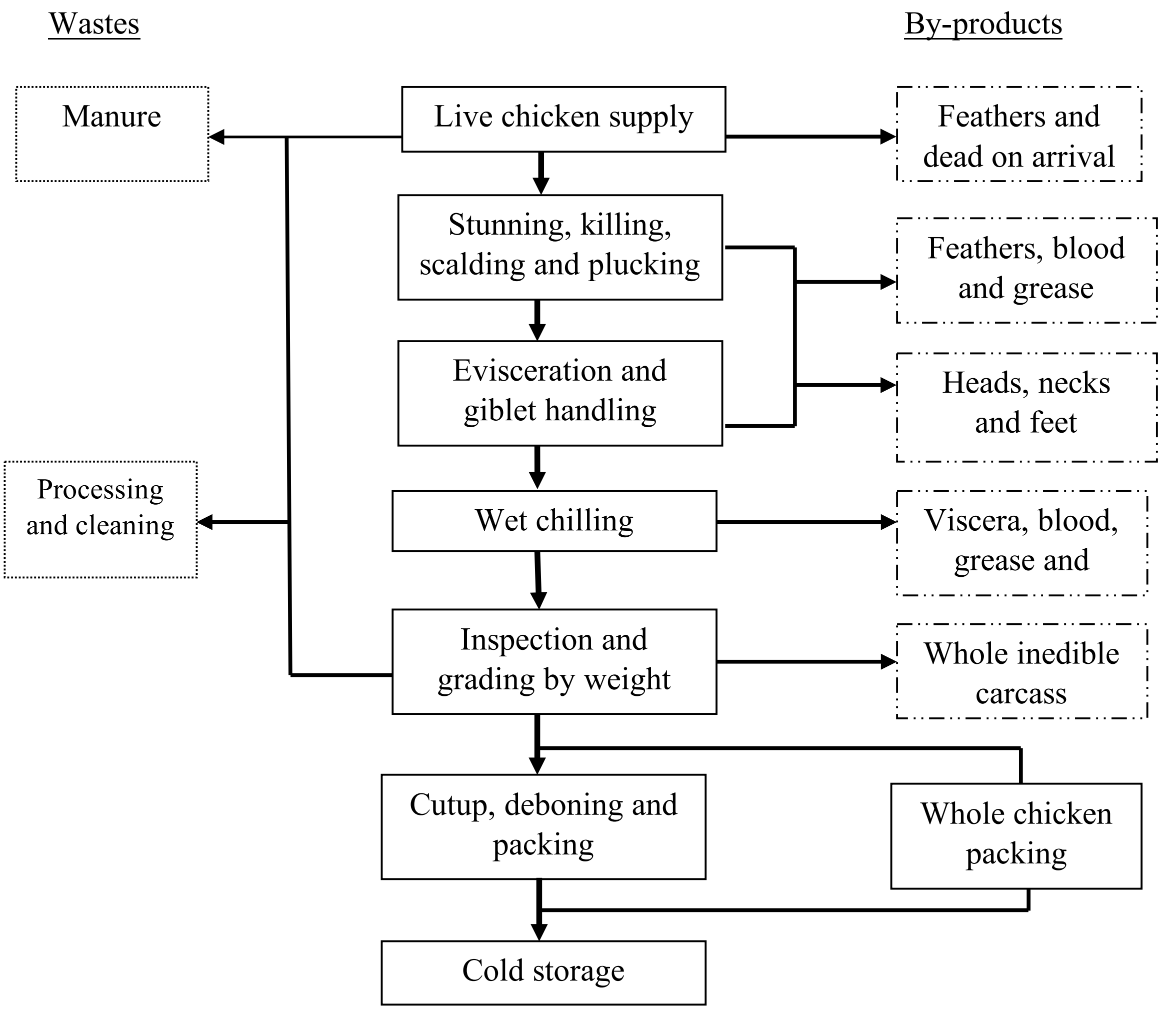

Figure 5.1.1. Typical poultry processing procedure (Molapo, 2009).

5.1.1.2. Collection and disposal of chicken feathers

During poultry processing, many inedible by-products unfit for consumption are produced. After the chickens have been slaughtered, the feathers are plucked by mechanical pluckers fitted with rubber fingers on rotating discs and followed by manually finish plucking the feathers by operators called pinners. The feathers, together with dilute blood, grease and cleaning water are then pumped into a container followed by screening (Saravanan and Dhurai, 2012). Then the feathers are conveyed into temporary storage area before disposal. The amount of poultry by-products produced at a single location is increasing because of centralisation and escalation of poultry slaughtering and chicken meat processing.

The gathering, stockpiling, disposal, and processing of slaughterhouse by-products is an important veterinary occupation in locations with concentrated animal husbandry and meat production establishments. Environmental pollution and transmission of diseases through improper and/or off-base treatment of slaughterhouse by-products must be anticipated (Franke and Insam, 2013). The use of slaughterhouse by-products for value-added products could be of economic benefit to slaughterhouses and could reduce the environmental pollution and transmission of diseases due to processing.

The microbial quality of poultry by-products is a major concern, and the presence of microbial toxins cannot be excluded. Most poultry by-products are sullied with high quantities of microorganisms, e.g., microbes, infections, parasites and yeasts (Franke and Insam, 2013). Slaughterhouse by-products constitute a potential danger to human and creature wellbeing and may additionally pollute the environment. Until recently, not much efforts have been invested to gathering and disposal of these by-products. There are, however, socio-economic reasons to increase scientific knowledge about handling and disposal of slaughter by-products:

A. Storage of by-products at slaughterhouses for long periods (6-30 h) under non-chilled conditions, can results in large amounts of metabolites of degradation procedures in the products, making them unsuitable as raw material for animal feed. High-quality raw materials are the first requirement for production of high-quality animal feed. Furthermore, the degradation products pollute the environment due to the formation of off-odours (Kraham, 2017);
B. Disposal of poultry wastes, often contaminated and with bad-smelling by-products, is mainly by road transportation to disposal sites. This poses a high risk of the spread of microorganisms and environmental pollution (Kraham, 2017).

5.1.2. Utilisation of feathers: present scenario

According to statistics on broiler chickens provided by Compassion in World Farming, around $58*10^9$ chickens are slaughtered for meat in the world every year (Compassion in

World Farming, 2013). The United States of Department of Agriculture estimates that $46.6*10^9$ kg of chicken meat was processed in the USA poultry processing industry in 2014 (USDA Foreign Agricultural Service, 2014). Processing of this chicken generates more than $40*10^9$ kg of feathers per annum worldwide (Compassion in World Farming, 2013). In the competitive poultry industry, the challenge is to transform chicken feathers into significant new products that add to the organisation's bottom line.

Currently, feathers are a waste product for which disposal is difficult. For example, the feathers may be hydrolysed, dried and ground to a powder to be used as a feed supplement for a variety of livestock, primarily pigs (Park et al., 2000). This is a fairly expensive process, however, and results in a protein product of low quality for which the demand is low. Other disposal means such as burning or burying are also occasionally utilised, but these methods are considered environmentally unsound and are therefore largely prohibited. The world poultry industry has struggled with this question: what to do with more than $40x10^9$ of poultry feather waste their business generates each year? The next section reviews current recuperation and disposal practices and prerequisites for chicken feathers.

5.1.2.1. Disposal technique

Incineration

Incineration is a thermal destruction technology that is one of the most effective methods for destroying conceivably infectious agents. In this procedure, air discharges, process conditions, and the disposal of solid and liquid deposits should be entirely controlled. Smouldering poultry squanders might create as much or more toxic air emissions than coal plants. Analysis led by the North Carolina Department of Environment and Natural Resources found that a 57 MW poultry waste burning plant emitted levels of carbon dioxide (CO_2), nitrogen oxides (NO_2), particulate matter (PM), and carbon monoxide (CO) per unit of power generated, that were higher than those for new coal plants (Stingone and Wing, 2011).

Burial and controlled landfilling

Burial and controlled landfilling of chicken feathers on farms should be strictly monitored to keep away from groundwater contamination. As the operation, monitoring, and control of land filling likewise turn out to be more tightly regulated, landfilling must be prevented as much as could reasonably be expected because of its unfriendly consequences for the nearby environment, especially the contamination of surface water, groundwater, soil and air. Every one of these measures may increase the expenses of landfilling (Veerabadran et al., 2012).

5.1.2.2. Current uses

Feathers for decorative purposes

Artificial flowers have been made from feathers of large birds. The critical criteria for determination of feathers for decorative intentions are their shading, shape, size, and plumage designs. Since feathers from cock pheasants are splendidly shaded, they are in extraordinary interest for decorative purposes (Levine, 1991).

Feathers in medical applications

Chicken feathers are utilised as a part of traditional medications. For instance, in South America blends produced using the feathers of condors are utilised as a part of conventional pharmaceutical and in India, feathers of Indian peacocks have been utilised as a part of traditional medication for barrenness, hacks and snakebites (Murari et al., 2005).

Feathers in religion and culture

Different flying creatures and their plumages serve as cultural symbols all throughout the world, from the hawk in ancient Egypt to the bald eagle and the turkey (bird) in the United States. Numerous sorts of feathers have cultural and religious significance, e.g., eagle feathers have extraordinary spiritual and social worth to local American societies. In the USA the religious utilisation of eagle and hawk feathers is governed by the eagle feather law (Levine, 1991). Different birds and their plumage serve as cultural symbols all through the world, e.g., birds of prey, bald eagles, and so on (Murari et al., 2005).

Feathers as sporting equipment

Feathers are utilised as sporting equipment. For this reason, feathers are deliberately chosen from particular parts of the body of the birds, e.g., hardened wing feathers are utilised to make shuttlecocks, turkey feathers are utilised on fletching arrows, and other chose feathers are utilised to produce artificial lures for fishing (Levine, 1991).

Feathers as fertiliser

Feathers contain more than 13 % nitrogen content (Tesfaye et al., 2017 (b)); this is higher than the best quality blood meal also utilised for such purposes, so they are astounding for compost purposes (Figure 5.1.2) (Choi and Nelson, 1996). Thus, feathers are used in plants growing operations that require rich nitrogen dressings. However, feathers are highly cross-linked with cysteine linkages and difficult to degrade (Park et al., 2000). Therefore, the availability of nitrogen from the feathers as fertiliser is considerably low. Feathers can also be used as mulching material. This is on account of; they deteriorate gradually and continuously discharge their nitrogen. Their tough, fibrous structure is ineffectively processed by most protein-degrading compounds, however, when blended with compost they degrade well (Gurav and Jahav, 2013). At the point when the feathers are composted, their produced by-products do a reversal as organic matter into the land which further adds to the soil fruitfulness. They form an important poultry composite blend in light of the fact that they add nitrogen, a critical fertiliser component (Veerabadran et al., 2012).

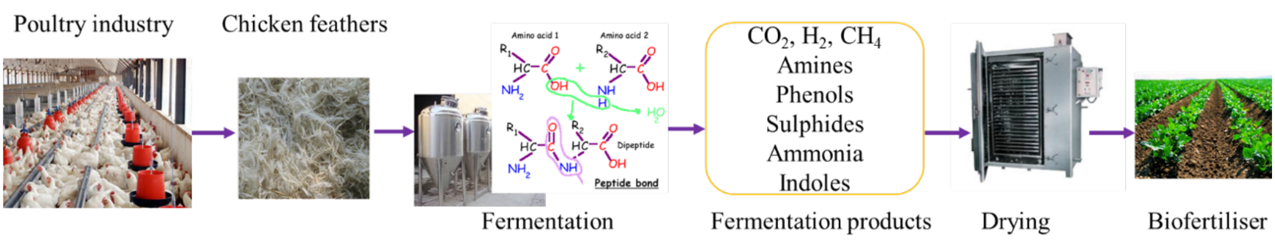

Figure 5.1.2. Schematic diagram of biofertiliser production from chicken feathers

Feathers as dusters

A feather duster is a cleaning gadget in which feathers are utilised to expel the dust from the objects, since when rubbed they build up friction based electricity, which catches and hold dust particles until shaken out. The high-quality feathers from the external layers of ostrich plumes are exceptionally attractive for this reason because their fine delicate points won't scratch furniture surfaces. This is a scientific property of feathers that makes them trap dust furthermore the structural characteristics for the feathers gives them tiny fingers to catch dust (Poopathi and Abidha, 2007).

Feathers as bedding material

Since they fulfil all the necessities of good bedding, such as cleanliness, warmth, fluff ability, low absorption, softness, drapability, fire resistance, launderability and durability; feathers are also used as bedding material. Additionally, feathers have superior lofting performance and insulating capability. These attributes make goose down the favoured fill material for cushions and extravagance comforters. Also, feathers are warm, soft, have the ability to expand from compression and light-weight (Bonser and Dawson, 1999).

Feather meal as a feedstock

Most feathers are not suitable for the aforementioned applications due to their hazardous nature (presence of microbiological pathogens) and their poor digestibility if land filled. Therefore, the fundamental strategy for feather waste administration is the conversion into feather meal to be utilised as stock food (Figure 5.1.3). For the generation of feather meal, the rachis must be broken down by hydrolysis to make it digestible. A typical process is as follows:

- Feathers are washed with water, after collection from processing plants.
- Followed by de-watering by mechanical pressure rather than heat.
- They would have steamed and wet-cooked for hydrolysis under pressure for 1-2 hours, after removing of water.
- The feathers are then cooled, dried and ground.

- To remove coarse metal particles, the ground meal is then passed through metal detectors (El Boushy et al., 1990).

Table 5.1.1. Compositions of feather meal (McCasland and Richardson, 1966).

Composition	Percentage
Protein	92.3 % (ranges 70-80 %) as digestible protein.
Moisture	5.9 %
Fat	1.3 %.

Cooking time and pressure (amount of hydrolysis) directly affects the digestibility of feather meal (McCasland and Richardson, 1966). Feather meal contains about 92 % crude protein (ranges 70-80 % as digestible protein) (Table 5.1.1), be that as it may, the protein edibility is extremely poor on account of the vicinity of disulphide bonds which are refractory to digestive enzyme present in chickens. Feather meal is inadequate in four fundamental amino acids, methionine, histidine, lysine, and tryptophan; however, it is rich in arginine, threonine and cysteine (El Boushy et al., 1990). A reasonable level of utilisation of feather meal as a feedstock is about 0.5-1.5 %. (Park et al., 2000).

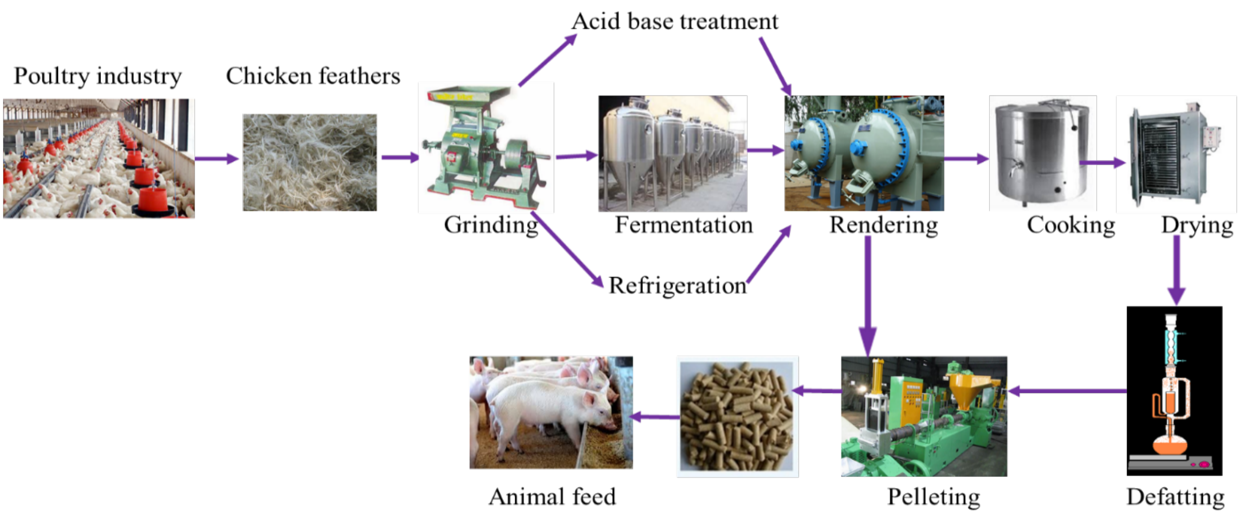

Figure 5.1.3. Schematic diagram of animal feed production from chicken feathers

The applications mentioned in the preceding paragraphs utilise only a small portion of waste feathers generated by the poultry processing industry. More uses of the waste are needed and may be possible to achieve.

5.1.3. Physicochemical properties of chicken feathers

Characterisation of physicochemical properties of the chicken feather is an essential step to identifying possible avenues for valorisation of this waste biomass. A comprehensive characterisation of waste chicken feathers for their chemical, physical, thermal, mechanical and electrical properties and morphological and fine detail structures have described by the authors.

5.1.3.1. Physical properties of chicken feathers

Chicken feathers have low density than any other natural or engineered filaments commercially available today. Their low density, low thickness, warmth retention, astounding compressibility and strength, capacity to hose sound and particular morphological structure of their barbs make them remarkable fibre (Tesfaye et al., 2017 (a); Saravanan and Dhurai, 2012). Besides the special structure and properties, feathers are cheap, richly accessible and a renewable hotspot for protein fibre. A feather is essentially made out of three particular units; rachis, barbs and barbules as shown in Figure 5.1.4. Rachis is the solid and focal shaft of the feather to which the auxiliary structures, the barbs are joined. In the tertiary structures of the feathers, the barbules are joined to the barbs in a way like the barbs being attached to the rachis. The rachis runs the whole length of the rachis up to 15 cm long. The barbs have lengths anywhere in the range of 1 to 4.5 cm, contingent upon their area along the length of the rachis. Individual strands at the base of the rachis are longer than those at the tip (Tesfaye et al., 2017 (a)).

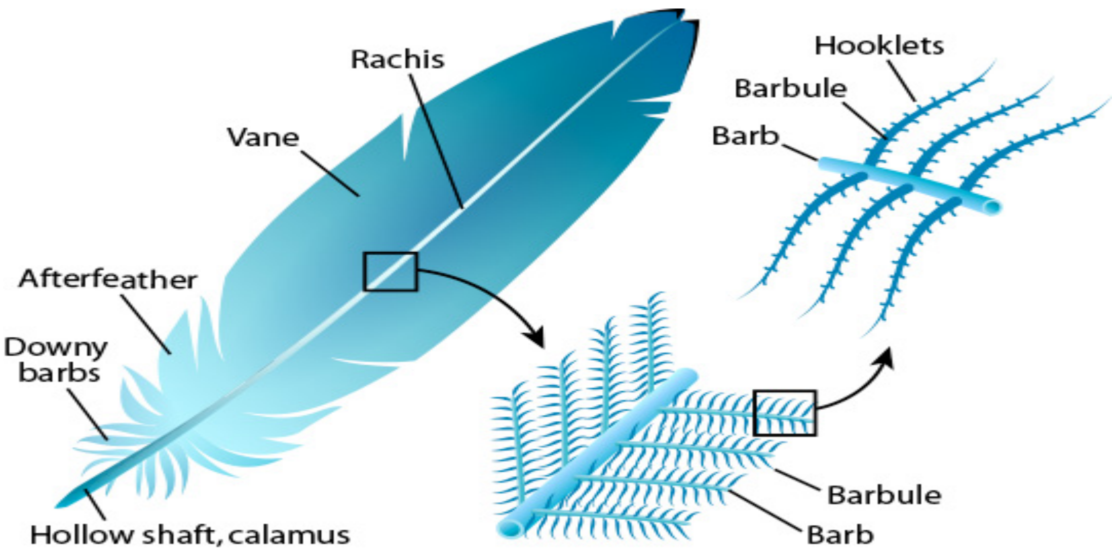

Figure 5.1.4. Morphological structure of chicken feathers (adapted from Stettenheim, 2000).

5.1.3.2. Chemical properties of chicken feathers

Chicken feathers contain approximately 91 % protein (keratin), 1 % lipids, and 8 % water. The amino acid succession of a chicken feather is precisely the same as, furthermore has an incredible arrangement just the same as, reptilian keratins from claws (Saravanan and Dhurai, 2012). The amino acid sequence is mainly composed of cysteine, glutamine, proline and serine as shown in Table 5.1.2. However, histidine, lysine, tryptophan, glutamic acid and glycine are absent. Serine (16 %) is the most abundant amino acid in chicken feathers (Saravanan and Dhurai, 2012). Keratins are insoluble proteins present in rachis, fleece, hooves, scales, hair, nails (hard keratins) furthermore in the stratum corneum (delicate keratins) (Misra and Kar, 2004). These particular proteins, which belongs to the scleroprotein groups, intensify that are exceedingly impervious to physical, chemical and biological activities. Mechanical stability and high resistance to proteolytic degradation of keratin is because of the presence of disulphide bonds, hydrogen bonds, salt linkages and cross linkages (Misra and Kar, 2004).

Table 5.1.2. Amino acid content in keratin fibre from chicken feathers (adapted from Saravanan and Dhurai, 2012).

Functional group	**Amino acid**	**Percent content**
Positively charged	Arginine	4.30
Negatively charged	Aspartic acid	6.00
	Glutamine	7.62
Hydrophobic	Tyrosine	1.00
	Leucine	2.62
	Isoleucine	3.32
	Valine	1.61
	Cysteine	8.85
	Alanine	3.44
	Phenylalanine	0.86
	Methionine	1.02
Hygroscopic	Threonine	4.00
	Serine	16.00
Special	Proline	12.00
	Asparagine	4.00

Basically, a chicken feather consists of α- helical and some β- sheet conformations. Its outer rachis is almost entirely made up of β- sheet conformations and few α- helical conformations (Tesfaye et al., 2017 (b)). Hard β- sheet keratins have higher cysteine content than soft α- helix keratins and thus a much greater presence of disulphide (S-S) bonds that link adjacent keratin proteins. The presence of strong covalent bonds stabilises the three-dimensional protein structure and are very difficult to break (Saravanan and Dhurai, 2012). Feathers contain ~91 % keratin protein and thus, potentially, feathers can be beneficiated into high-value compounds or products comprised of keratin proteins or keratin fibres. Thus, valorisation of feathers could be a viable option for sustainable disposal of the waste.

5.1.4. Utilisation of feathers: future prospects

Of the $58*10^9$ chickens killed each year, poultry processors around the world throw away almost all their feathers: more than $40*10^9$ into landfills (DAFF, 2014). Conventional waste disposal methods, namely incineration, burial and controlled landfilling or recycling the feathers for fertiliser and animal feeds are problematic as they have high water and energy demands and there are also health concerns such as bird flu (Edwards and Daniel, 1992; Urlings et al., 1992). Because of the keratin protein that retards degradation of feathers, the feathers take up a lot of space in landfills and take a long time to decay and incineration releases greenhouse gases.

The costs to the poultry processing industry to dispose their feather waste are increasingly high due to reduced availability of landfill space. It is very likely that poultry industries in the future will not be permitted to dispose their waste to landfill. For example, the South African government has promulgated legislation for proper disposal and waste minimisation. The National Environmental Management bill enforces the generators of waste to deal with their waste according to the hierarchy of waste management in a sustainable way. That is, every industry will need to re-utilise, recycle, minimise, avoid, treat and dispose of waste as a last a last alternative (Molapo, 2009). The sustainability of the poultry processing plants is threatened and the challenge is to design technologies that convert waste on site into valuable products which can be used on site or sold. There is still a lot of research to be explored in the utilisation of chicken feathers for beneficial use. The valorisation of waste feathers can take advantage of their chemical constituents, their cheapness (free availability), ease of availability, and potential to offer sustainable procedures for their disposal. Examples of how and where chicken feather waste can be a useful resource are described below.

5.1.4.1. Feathers in automobile and aeroplane industries

Modern day material science industries are looking for light weight, low cost and biodegradable raw materials for manufacturing of different parts of automobiles and aeroplanes using environmentally sustainable materials. Currently, most automobile and aeroplane parts are made from petroleum-based raw materials. Owing to remarkable strength (due to the high cysteine content of the keratin protein, and low-priced properties), lightweight nature, and better quality (Tesfaye et al., 2017 (a)), feathers could be used to produce composites for use in automobile and aeroplane industries such as in dashboards, car parts, seats and cushioning, interior linings etc. to reduce their weight while strengthening them.

5.1.4.2. Textile industry

Feathers in fibre, yarn and fabrics: Scientists are investigating ways to process agricultural and food industry waste product into significant consumer products, replacing natural fibres, man-made fibres and saving trees in textile processing. High surface area, toughness, flexibility, fine diameter, durability property of the chicken feather makes feather valuable resources to replace expensive natural fibres, wood pulp, and synthetic fibres. Because of the structural property of the chicken feather, the feathers cannot be rehabilitated directly into new products. The malleable interconnectedness strands for materials that develop from the rachis (the barbs) must be stripped off from the hardened focal centre of the feather (the rachis) because this delicate barb material satisfies the property of textile fibre. Even though the whole feather contains keratin, the soft but durable barbs protein is different from that in the crystal structure of the rachis (Tesfaye et al., 2017 (a); Bonser and Dawson, 1999). Only the barbs have the desirable properties to be used as textile fibre. There are two options to use chicken feathers as a fibre source:

The first one is blending chicken feather barb fibres with other fibres for spinning into yarns. This is because chicken feather barbs have fibres that can be processed into yarns (after stripping the barbs from the rachis). The air flow technique could be an efficient method for separating the rachis from barbs because of density difference. Stripped rachis and barb parts have different shapes and lengths. Since individual fibres from feather are too short to be spun into yarns, they can be blended with wool, cotton and man-made fibres and then spun into yarns.

The second option could be producing regenerated fibres from the whole chicken feather (Figure 5.1.5). Chicken feathers contain more than 91 % fibrous structural keratin protein, the monomers inside the keratin composition assemble into bundle to form intermediate filament. Keratin proteins, like all intermediate filaments, form filamentous polymers in a series of assembly steps starting with dimerization; dimers collect into tetramers and tetramers into octamers and after that into unit-length filaments capable of annealing end-to-end into long fibres (Tesfaye et al., 2017 (b); Stuurman et al., 1996). Alternatively, after extracting the keratin protein from chicken feathers, the protein could be spun into filamentous regenerated fibres using electrospinning techniques. The resultant fibres could be used in manufacturing plastics, fabrics, technical materials and other products.

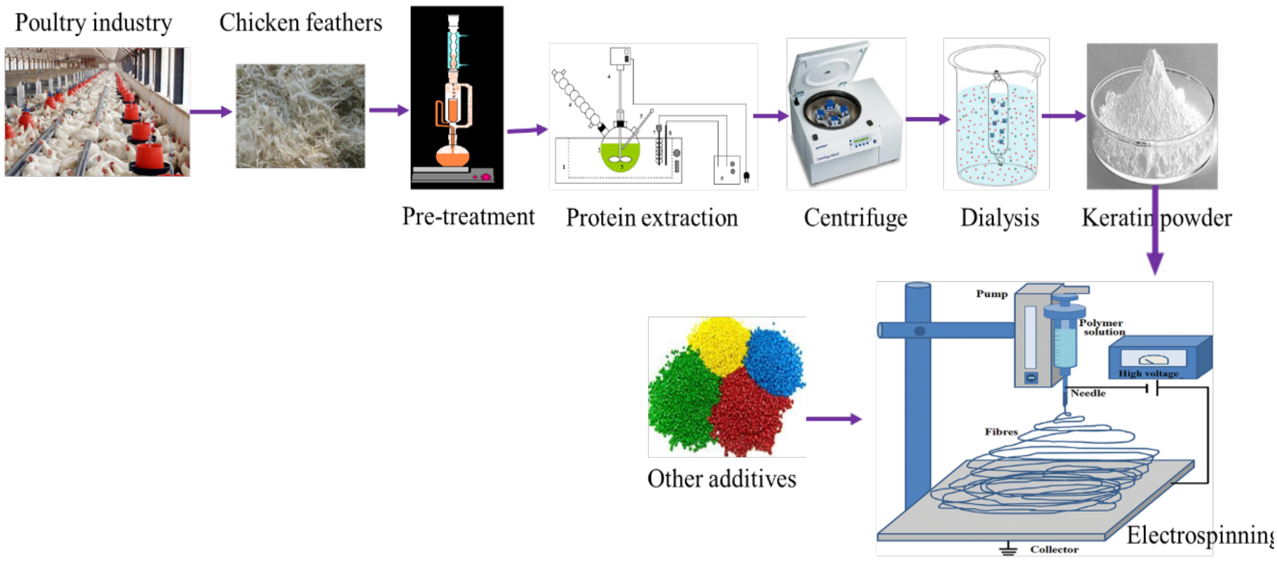

Figure 5.1.5. Schematic diagram of regenerated fibre production from chicken feathers (adapted from Tesfaye et al., 2017)

50 years ago, scientists produced the first regenerated fabrics made from unusual materials, like milk proteins, peanuts, and corn (Poole et al., 2008). Although they performed poorly when wet, the fabrics from the regenerated fibres had the feel and look of wool and silk; which are conventional protein-based fabrics. This issue, consolidated with the presentation of petroleum-based engineered filaments, created the generation of these abnormal fabrics to stop. In any case, worries about skin well-being issues, high costs, environmental problems and consumer’s interest for eco-friendly products and

renewable fabrics produced using unusual waste materials are presently now poised to make a return. Agricultural and food wastes like cellulose and proteins could be valuable resources for the manufacture of fabrics. Advances in nanotechnology and chemical cross-linking technology could enable commercial production of eco-friendly clothing by improving the strength and biodegradability of the final product. The filament fibre from the electro-spinning machine could be woven into warm and cosy fabric made from chicken feathers.

Feathers in warp yarn sizing and fabric finishing: Warp yarn sizing agent is a protective layer added on to the surface of yarns to improve weaving performance. The warp of textile yarns has traditionally been sized using starch, modified starch derivatives, polyvinyl alcohol, or a combination thereof, along with other fibre binding ingredients. Starch and starch derivatives have been the predominant sizing agents. However, starch is extracted from food-based raw materials, and this creates socio-economic problems. The protein in feathers has film forming and binding ability (Reddy et al., 2014), thus, it could be a good source as a textile sizing and binding agent, and in textile printing.

Feathers in flame retardant finishes of fabrics: The presence of high amount of nitrogen (Tesfaye et al., 2017 (b)) in feathers made it a useful material as flame retardants. Hydrolysed feathers were used to prepare flame retardant finish (Guan and Chen, 2006). High flame retardancy was imparted to the cotton fabrics after treating with the flame retardant which was based on feathers.

Feathers to create leather composites: Various treatment processes utilised in leather tanning can bring about cancer, additionally skin and respiratory ailments, so there is a need to replace them with environmentally friendly materials. In this regard, Wool and colleagues have developed bio-composites, using techniques developed by aerospace engineers to process scraped, downy fibres from chicken feathers into the synthetic leather (Figure 5.1.6). Wool consolidates natural fibres and plant oil resins under heat and pressure to produce a composite material that is similar to leather (Sydney, 2015).

Figure 5.1.6. Shoe prototype made from feathers composite (adapted from Sydney, 2015).

Feathers in other textile application: Because of their thermal property, warmth, fluff ability, softness, drapability, fire resistance, launderability and durability chicken feather can be used for filling materials in winter clothing and nonwoven fabric manufacturing and keratin hydrolysate from waste chicken feather could be used in cationisation of fabric and subsequent treatment in textile dyeing process.

5.1.4.3. Plastic and packaging industry

Feathers in biodegradable plastics: There are two types of plastics: thermoplastics and thermosetting plastics. Thermoplastics include polystyrene, polyvinyl chloride, nylon, polyethylene, etc. and dozens of other kinds. A thermoplastic is a material which becomes soft when heated and hard when cooled, while thermosetting plastics harden and melted once and cannot be remelted again: examples include epoxy resin, melamine formaldehyde, urea formaldehyde etc. Both thermosetting and thermoplastic plastics are made for the most part from ingredients obtained from crude oil or natural gas. Researchers are working to discover non-fossil based ingredients as an option, on account of worries about petroleum maintainability, supplies, and costs (Jin et al., 2011; Moore, 2008). One possible route is to utilise waste materials and other renewable resources to make bioplastics that have an extra favourable position of being biodegradable once disposed of into the earth. Since they are reasonably cheap and inexhaustible, chicken feathers are a fabulous prospect. Feathers are inherently non-thermoplastic and do not melt, but simple alkaline hydrolysis makes them thermoplastic and suitable to develop films after cross-linking using citric acid (Tesfaye et al., 2017 (b); Misra, 2004). The other route could be graft polymerization using acrylic monomers. Grafting could impart thermoplasticity which could allow the feathers to be made into films (Figure 5.1.7).

What makes chicken feathers ideal is that they are rich in keratin, a tough natural protein polymer composed of natural monomers. In contrast to other biological sources like plant proteins and modified starch, keratin based plastics could offer greater strength and tear resistance because of the tough keratin proteins (Khosa and Ullah, 2013).

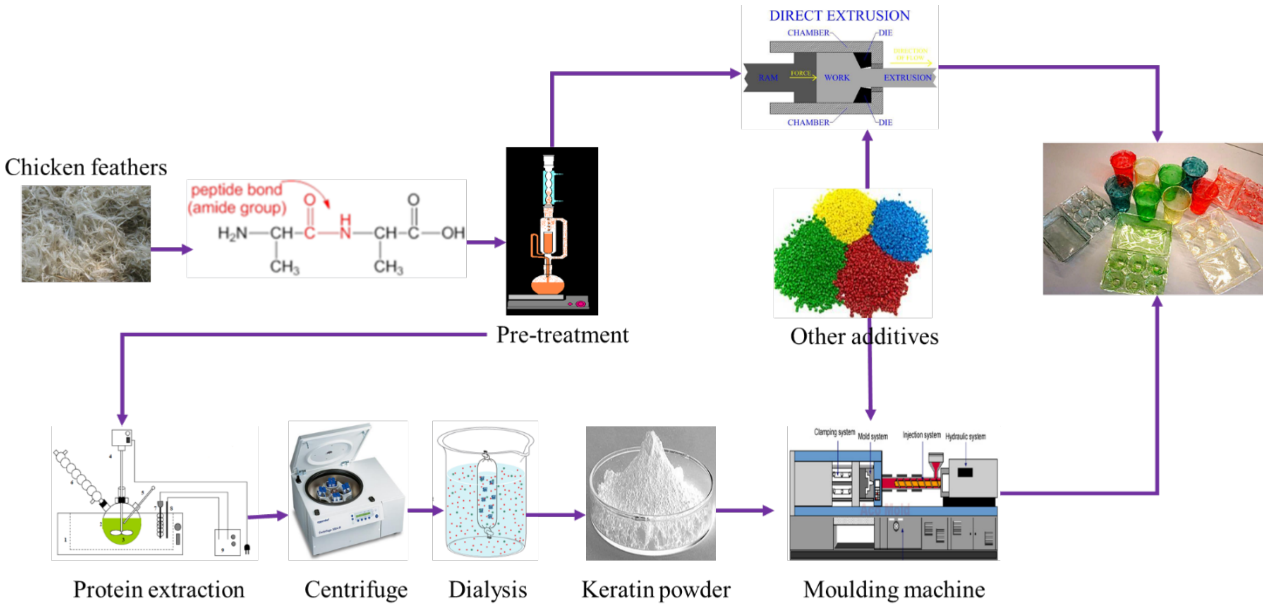

Figure 5.1.7. Schematic diagram of bioplastic production from chicken feathers (adapted from Tesfaye et al., 2017)

Feathers in packaging materials: Petroleum based products in packaging has long been a cause for concern regarding the health of the environment and the country's economy. Not only petroleum is an expensive, non-renewable resource, but the manufacturing, usage and disposal of crude oil based packaging can have a harmful impact on the environment. Chicken feathers could be a good source of raw materials to replace petroleum-based products. Keratin could be used to replace fossil fuel in some products since the main component required to make plastics with chicken feathers is keratin. The utilisation of chicken feathers as a raw material for the manufacturing of packaging material may never be a complete replacement for petroleum. However, any cutback in petroleum use is still a major step forward for the environment. When transporting delicate materials from place to place without damage, cartons lined with chicken feathers nonwovens could be put inside as the interlining to guarantee that the materials are firmly stuffed. This would replace the use of environmentally unfriendly polystyrene films. Nonwovens are made of any kind of fibrous material via three techniques; chemical bonding, thermal bonding and needle punching techniques. After stripping the fibres, the chicken fibres should be laid using hand or machine laying techniques, after which bonding will be performed.

5.1.4.4. Feathers in filtration and paper applications: The super fine size and shape of feather fibres imply that they may be used in filtration applications. Nonwovens made out of chicken feathers will exhibit very good porosity, good resistance to mild acids and alkaline media, and light weight characteristics- a promising future in chemical industries. Feather fibres could replace wood pulp based paper products such as filter papers and decorative papers. Wood pulps are the raw material for most paper-based products, but feather fibres have an advantage in full or partial replacement of wood pulp, as they are finer in diameter than wood pulp (Figure 5.1.8). Feather fibres have a width of 5 µm, whereas that of wood pulp fibres is 10-20 microns (Tesfaye et al., 2017 (a); Jin et al., 2011). Therefore, filters produced from feather fibres are likely to have smaller holes with good ability to entrap spores, dust and dander from the air.

Figure 5.1.8. Process flow diagram for chicken feathers/wood pulp handsheet preparation (adapted from Tesfaye et al., 2017 (c)).

5.1.4.5. Construction industry

Feathers in lightweight construction composites: In recent years, researchers have focused their efforts in the manufacture of composite materials from thermoplastics and natural fibres for different applications. These natural fibres offer good strength, low cost, low density, good thermal property, high toughness and biodegradability to the composites. In addition, natural fibres reduce consumption of synthetic polymers and, therefore, decrease the consumption of petroleum products. However natural fibres are cellulosic and are incompatible with the hydrophobic nature of polymer materials. Chicken feathers can be used instead. The feathers could be used as reinforcement material after prior separation of the feathers into long fibres, short fibres and powdered rachis. Since feathers contain more than 91 % keratin protein (Tesfaye et al., 2017 (b); Reddy et al., 2014), it could be possible to melt and use them as a matrix material. The thermoplastic properties of the feathers could be modified or enhanced by using acrylic polymers (Misra, 2004). The keratin in feathers makes them (and their composites) resistant to insect infestation as the keratin is indigestible and inedible to termites and insects. Additionally, the use of feathers would result in composites that are not combustible, unlike conventional composite boards. Although more research needs to be done, composites made of chicken feather can be used in panelling or ceiling applications, and for thermal and sound insulation, but not for walls or pillars. Using chicken feathers composite building board in construction industry could be a major breakthrough to replace wood and plastic-based construction materials.

Feathers in geotextile materials: Geotextile materials are often used on road construction sites, building sites, agricultural areas and other areas that have uncovered land, where the stabilisation of soil is required. This material is necessary to conserve the landscape to avoid the removal of sediment during rainfall and to keep the nutrients in place. There is a need for low-cost, biodegradable geotextile materials due to the high cost and environmental impact of synthetic erosion control. One possibility is development of yarns, knitted, and non-woven fabrics from feather fibres. Chicken feathers geotextile materials could be strong, and very stiff because of the tough keratin property of the feathers, thus when placed on soil, the geotextile material preserves the soil. Because of the water holding capacity of the feather fibre, the materials could increase the moisture content of the soil and also decrease compaction of soil due to feathers occupying more space. For successful ecological restoration of habitats, all these are critical properties.

5.1.4.6. Bioenergy production

Feathers in biogas production: Chicken feathers contains high amounts of crude protein, carbon, nitrogen and hydrogen elements (Tesfaye et al., 2017 (b)). Proteins are composed of amino acids linked by peptide bonds, which are hydrolysed by proteases upon decomposition. The degradation products include short or branched chain organic acids, NH_3, CO_2 and H_2. Figure 5.1.9 shows the process flow for the production of biogas from chicken feather waste.

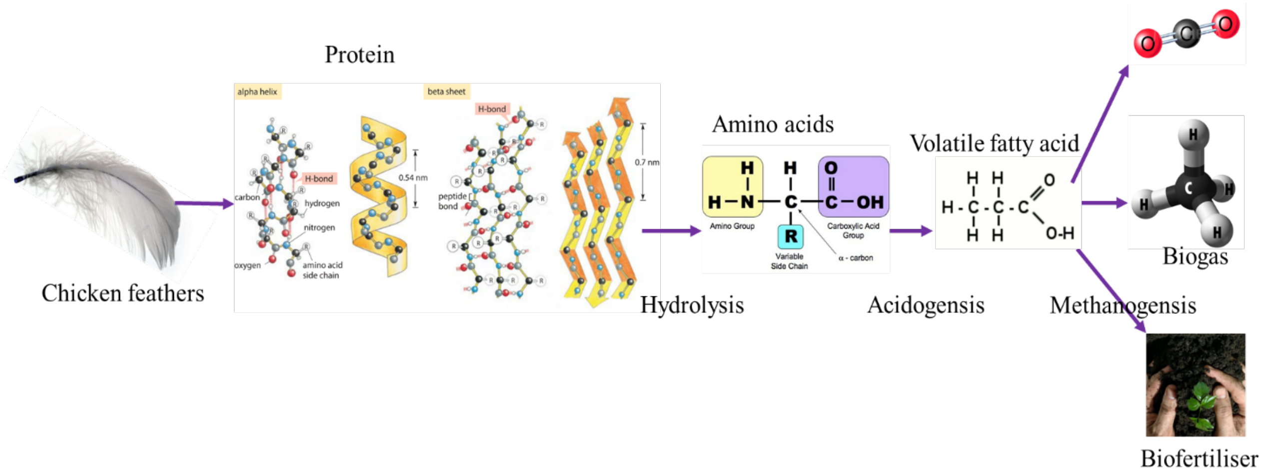

Figure 5.1.9. Schematic process flow of biogas production from chicken feathers (adapted from Tesfaye et al., 2017)

Feathers in biofuel production: In the world, man is facing two major challenges, waste disposal and the need for an abundant source of clean energy. The perfect solution to both of these problems is to turn the waste into energy which could significantly cut carbon emissions while replacing the need for fossil fuels. Soybean, corn, sunflower and cottonseed are the primary sources of renewable energy via biodiesel production. The use of these raw materials faces social problems, availability and cost effectiveness (Demirbas, 2008). Thus, finding alternative non-food, raw materials is a priority. Chicken feathers contain substantial amounts of fat that could be processed for the production of biodiesel from feather meal (Figure 5.1.10). The biodiesel production, the fats could be extracted from feather meal by solvent extraction and subsequently transesterified into biodiesel using catalysts, nitrogen and methanol. From the huge amounts of waste chicken feathers that are generated worldwide, it can be estimated that hundreds of millions of litres of biodiesel can be generated from the waste. This energy from waste could cut carbon emissions by a large percent while replacing the need for large amounts of petroleum.

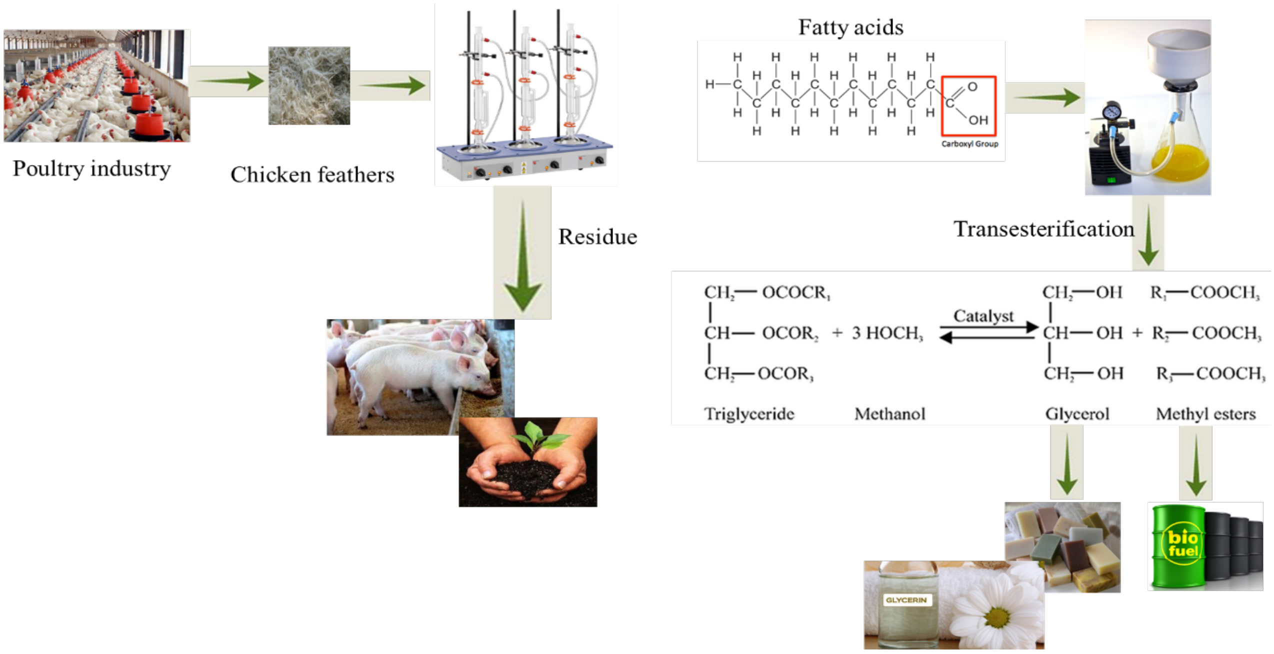

Figure 5.1.10. The schematic process flow of production of biofuel from chicken feathers

Feathers in biohydrogen production: Energy sustainability and alarming increase in pollution of the fossil fuels are the main challenges facing the energy industry in the world. Bioenergy is a sustainable, promising and eco-friendly alternative to fossil fuel energy (Zhu et al., 2011). Hydrogen has been projected as the most promising renewable energy carriers, emitting only water vapour as a by-product (Chandrasekhar et al., 2015). However, the current industrial processes for hydrogen production use fossil fuel through steam reforming, pyrolysis, autothermal reforming, thermal decomposition, catalytic oxidation, and steam gasification (Kapdan and Kargi, 2006). Since the current production increases the emissions of greenhouse gases, the production hydrogen gas from biomass through biological pathways will be an emerging technology. The presence of hydrogen in chicken feather can be used as a raw material for hydrogen gas production to replace fossil fuel.

Feathers in fuel storage applications: Hydrogen, the simplest and most plenteous component in the universe, has long been touted as a clean and ample energy option to fossil fuels (Cheng et al., 2001). When hydrogen reacts with different components it forms numerous compounds, a portion of the basic ones are: methane (CH_4), ammonia (NH_3), water (H_2O), hydrochloric acid (HCl), hydrogen peroxide (H_2O_2) and table sugar ($C_{12}H_{22}O_{11}$). Unfortunately, due to its physical property (lightest element and very low volumetric energy density), it is difficult to store and transport hydrogen. Researchers have been endeavouring to engineer ways to store hydrogen gas on board vehicles at reasonable weights, pressure and temperatures, to significantly reduce the expenses of a hydrogen infrastructure. On the other hand, the alternatives used to store hydrogen, such as metal hydrides and carbon nanotubes, are often very costly (Cheng et al., 2001). Therefore, the world needs a light weighted and economic material which can bind and release hydrogen to assist autos to use hydrogen fuel in the future; one of these materials can be chicken feathers. The feathers might not have a chance to be the fuel, but they might help to store it. Chicken feathers are composed of mainly keratin protein (Tesfaye et al., 2017 (b); Reddy et al., 2014) the same protein found in claws, beaks, nails and scales, a natural protein that forms lightweight, strong, hollow tubes. When heated, keratin turns out to be more permeable, expanding its surface territory, forms hollow tubes between the fibres, and creates crosslink which strengthens its structure; these features increase its ability to bind and store hydrogen. Thus to store and release the gas, one can pump hydrogen gas into the feather at high pressure, and one just de-pressurizes it or raises the temperature respectively.

4.1.4.7. Pharmaceuticals and biomedical engineering

Feathers in pharmaceuticals: Feathers contain fats (Tesfaye et al., 2017 (b)) that are a good source of cholesterol (Moore, 1989). Cholesterol is a steroid found mainly in the spinal cord and it makes up 10 % of the dry matter in the brain, and it plays an important role in metabolism. Cholesterol is necessary for proper body functioning, and to make hormones (Asano, 2003). Chicken feather cholesterol could be used as a building block for the synthesis of different pharmaceuticals. For example:

1. The cholesterol can be a pioneer in the production of vitamin D3. Vitamin D3 is necessary for teeth and bone formation (Holick, 2004).
2. The cholesterol can be utilised as a supplement for male sex hormones since they are used in the synthesis of steroid pharmaceuticals (Moore, 1989).
3. The cholesterol can be a precursor of bile salts that are vital in the blend of steroid hormones. Steroids are used for proper digestion of foods and absorption of fats in the intestine, menopausal syndromes, and they also prevent breast swelling (Asano, 2003).
4. Since bile salts can break down and emulsify fats, the cholesterol could also be used as a bio-emulsifier/bio-surfactant in the cosmetics industry (Asano, 2003).

Feathers in biomedical engineering: Acceptability by the human body is the first essential requirement of materials to be used in biomedical applications (Rouse and Van, 2010). 91 % of chicken fibres are keratin protein (Tesfaye et al., 2017 (b); Reddy et al., 2014) and this protein is the foundation for different biomedical applications starting from the drug delivery carriers, to tissue engineering and to self-assembled nanofibrous scaffolds (Figure 5.1.11). Chemical, biological behaviour and physical properties of these biomaterials contribute to the use of chicken feather for biomedical application. These properties include biodegradability, bioresorbability, biocompatibility, sterilisability, functionality, self-assembly, and manufacturability as well as mechanical and thermal properties (Ambrose and Clanton, 2004). The acceptability, biocompatibility and self-assembly phenomenon are evident in the highly preserved superstructure of the protein keratin (Reddy and Yang, 2011; Rouse and Van, 2010) and, are responsible for the reproducible dimensionality porosity, and architecture of feathers, when processed correctly. In addition, keratin biomaterials derived from chicken feathers are capable of supporting cellular attachment since they could own cell binding motifs, such as glutamic acid-aspartic acid-serine and leucine-aspartic acid-valine binding residues.

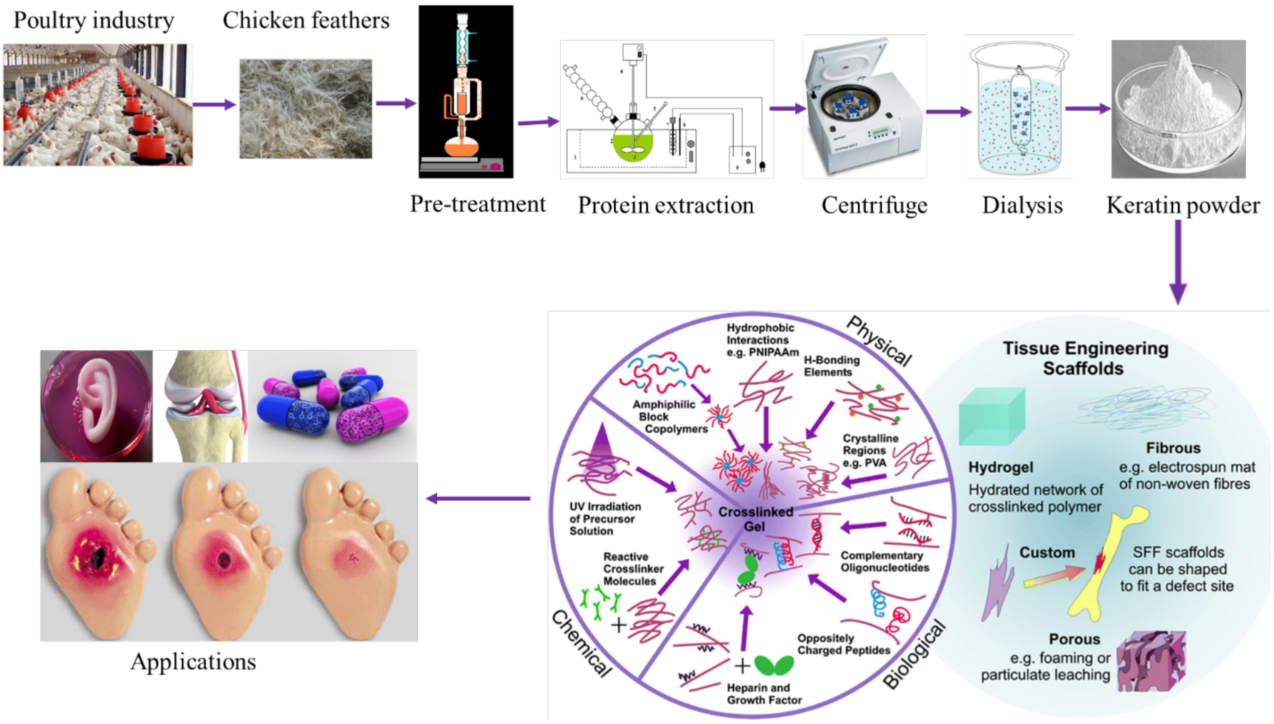

Figure 5.1.11. Schematic diagram of biomedical products production from chicken feathers

5.1.4.8. Feathers in cosmetic applications: The beauty industry has a long history of using unusual ingredients one of them being human hair that is ground to make the keratin available for use in beauty products. Hydrolysed keratin has turned into a typical cosmetic ingredient (Barba, 2008). The fundamental capacity of keratin is to protect the cortex of the human cell from injuries brought on by factors, for example, heat, daily maintenance and chemicals. Topical application of hydrolysed keratin gives noteworthy increment in skin flexibility and hydration. Because of its moisturising properties, the keratin can be fused into shampoos and conditioners, hair loss concealing products, and hair thickening accessories (Villa et al., 2013). Protein hydrolysates are proficient restorers in hair care processing (Niinimaki et al., 1998). These dynamic peptides are reparative and conditioning agents and give advantages to the hair, for example, fortifying hair filaments, strengthening and decreasing fibre breakages. The addition of protein hydrolysates to hair shading splashes and toners empowers hair to retain colours more uniformly. Numerous sorts of plants and animal protein hydrolysates have been utilised as a part of hair repair products furthermore in skin beautifying agents; they include wheat protein (Villa et al., 2013) and wool, nails, and horns keratin (Barba, 2008). Since chicken feathers contain keratin and amino acids, their hydrolysates can be used in hair treatment and skin treatment procedures.

5.1.4.9. Feathers in enzyme production: Keratins are the most abundant structural protein and are components of the epidermal and skeletal tissues. Keratinase is a proteolytic enzyme that attacks disulphide bridges to convert keratin from complex to simplified forms (Figure 5.1.12) (Villa et al., 2013; Paul et al., 2014). Keratinases are used in a wide variety of applications such as for de-hairing of skins in leather manufacturing, fertilisers, or animal nutrients in the agricultural industry, food supplements in the food industry, textile processing, detergents, and in the biomedical and pharmaceutical industries. Thus, chicken feathers could be used as a raw material to produce cheap keratinase enzymes since they contain high protein content, and keratin is the raw material for keratinase.

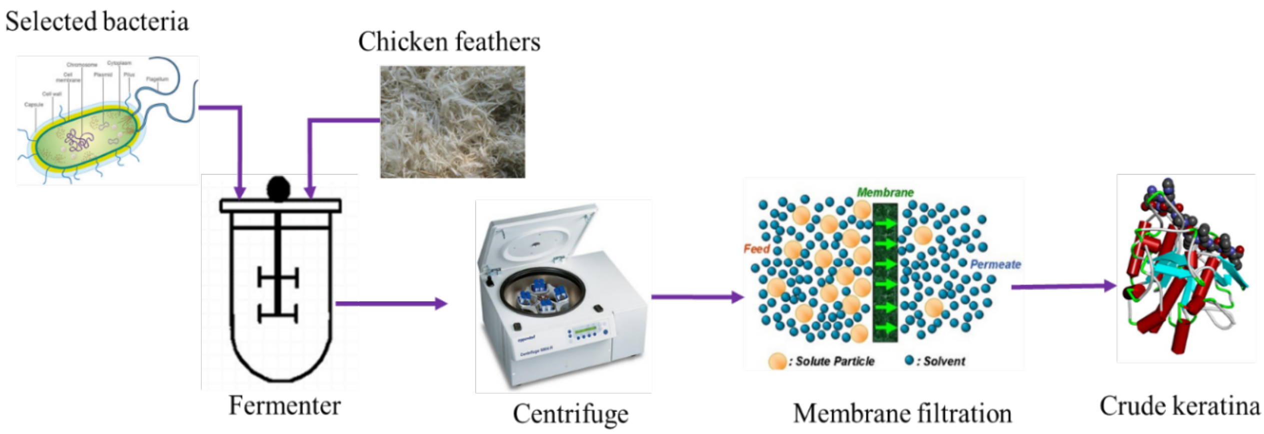

Figure 5.1.12. Schematic diagram of keratinase production from chicken feathers

5.1.4.10. Feathers in waste water purification: Chicken feathers could be used for water purification due to their inherent properties: structural toughness, stability over a wide range of pH, water insolubility, and high tensile strength. Their sorption purposes will be satisfactory for the removal of heavy metals (e.g. copper, selenium, and zinc), toxic organic compounds and colourants in water, because of the hygroscopic nature of keratin protein (Kar and Misra, 2004; Misra et al., 2001). After extraction of keratin from chicken feathers, sponges could be prepared using dilution of the extracted keratin followed by lyophilization. The sponge can be useful for example, in cleaning up of oil spills in water.

5.1.4.11. Feathers in electrical components: The current goal of material engineering and science is to find low cost, light weight and bio-degradable materials. To conduct any kind of electricity one must have a presence of electrons that are free to move within a substance (like metals), ions (like in water) in an electrolyte fluid, or both (Ku, and Liepins, 1993). But chicken feathers lack moisture content; hence they have very good electrical resistance properties, which make them good candidates for use as insulating materials. Feathers are made of keratin protein, which is in fibre form, is extremely light, they are hollow and tough enough to withstand mechanical and thermal stresses due to keratin compound and helix structured coupled with their low cost (Tesfaye et al., 2017 (b)) could considered to be an ideal raw material to develop uniform microporous materials with high surface area as electrode materials that are also environmentally friendly. Dielectric materials are used in a variety of applications including insulation, encapsulation, printed circuit boards, capacitors and other devices. For the material to be dielectric it should have hollow structure or porosity. Since it offers no resistance, air is considered to be a perfect dielectric material with a minimum dielectric constant of 1(Ku, and Liepins, 1993). There are very few dielectric materials in current use that have a dielectric constant close to 1, e.g., porcelain, glass and most plastics. Since feathers contain hollow structures, they could be useful as dielectric materials.

5.1.5. Conclusions

Chicken feathers are produced in large quantities as a by-product at poultry processing plants. Their disposal by incineration or landfilling is fraught with problems, e.g., environmental pollution and transmission of diseases due to microbial contamination. However, chicken feathers are composed of materials and components that can be valorised into valuable products and materials. Thus they should be regarded as a valuable resource for extraction of fibres for conversion into fabrics and composite materials; for extraction of composites that can be converted into high-value products that are normally sourced from petroleum based products. Thus using waste chicken feathers for such purposes will minimise environmental pollution as well as reduce reliance on use of petroleum based products. Extensive research and development work is required to develop appropriate technologies for their full utilisation as a source of some of the proposed applications mentioned in this review.

ACKNOWLEDGMENTS

The authors are highly grateful for the financial and technical support received from the Institute of Technology for Textile and Fashion Design/EiTEX at Bahir Dar University, Thermodynamics Research Unit at Chemical Engineering of University of KwaZulu-Natal, the Biorefinery Industry Development Facility, CSIR, Department of Science and Technology, Waste Research Development and Innovation Roadmap, and Rainbow Chicken Limited Foods.

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5.2. VALORISATION OF CHICKEN FEATHER BARBS: UTILISATION IN YARN PRODUCTION AND TECHNICAL TEXTILE APPLICATIONS

(BASED ON PAPER SEVEN)

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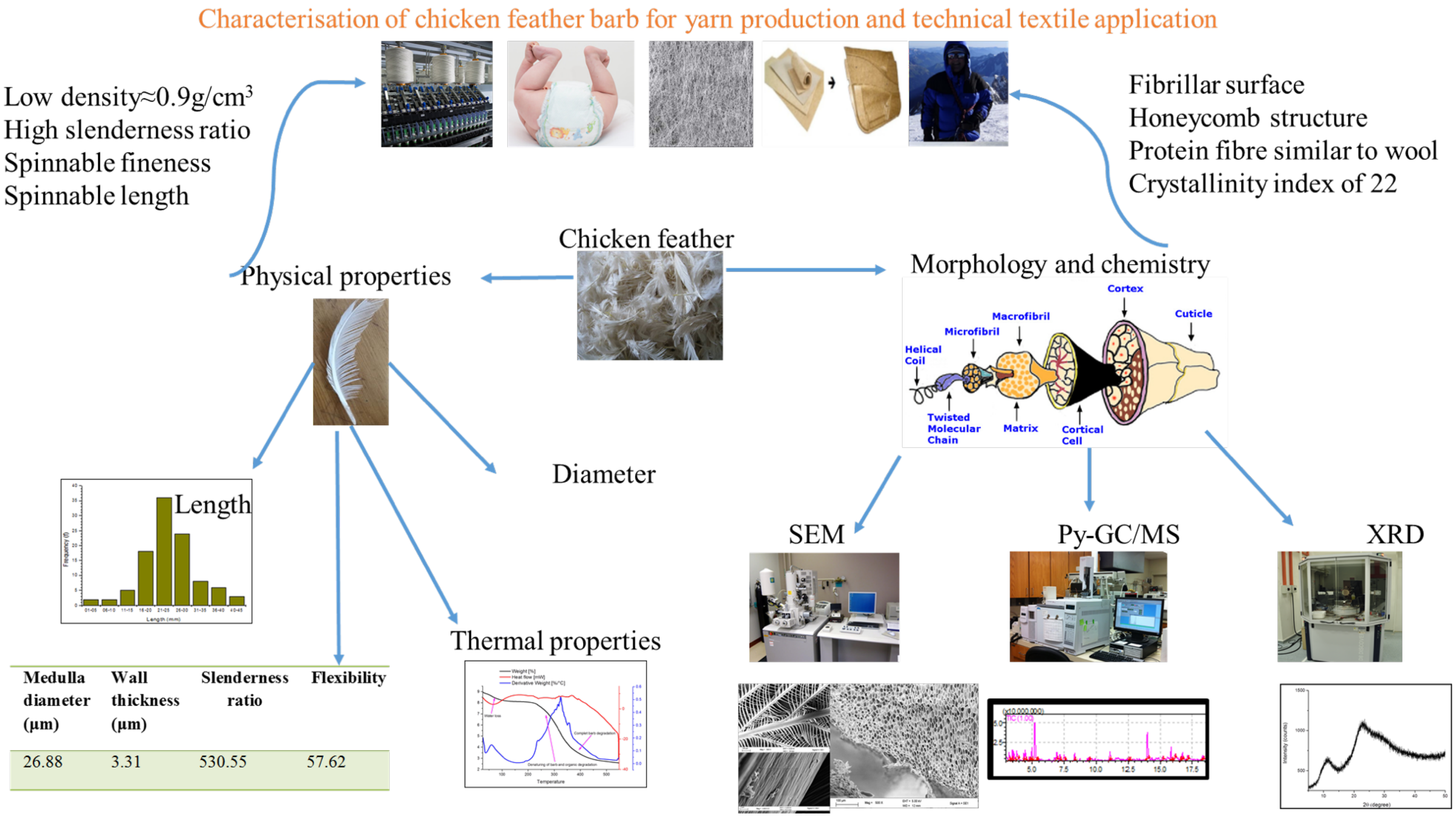
ABSTRACT

Waste chicken feathers represent 5-10 % of the total weight of mature chickens. Thus, they are produced in large quantities as a by-product of poultry meat processing industries. Currently, disposal of waste chicken feathers is problematic and the methodologies used are not environmentally sustainable. Consequently, technologies for beneficiation of the feathers are needed in order to overcome these problems. Considering that chicken feathers are similar to natural fibres (wool and silk) used in textile applications, it is plausible that protein in feathers can be exploited and used likewise. This paper reports on the physiochemical properties of proteinaceous fibre obtained from chicken feather barbs with the objective of assessing their potential for use in yarn production and technical textile applications. It is demonstrated that chicken feather barbs exhibit the following properties: hollow honeycomb structure, low density, high slenderness ratio, high flexibility, spinnable length, fineness, and high flexibility. These are unique properties that are not found in any other natural or synthetic fibres – the implication being that chicken feathers can be used in diverse manufacturing applications such as production of composites, yarns, technical textiles, nonwovens, and pulp and paper. However, this paper focuses on textile applications and illustrates how the physicochemical properties of fibres from feathers can be useful and applicable for textile applications. Beneficiation of waste chicken feathers in this manner will result in use of environmentally sustainable methods for disposal of the waste.

Keywords: characterisation, chicken feathers, barbs, technical textiles, yarn, beneficiation

Graphical Abstract



5.2.1. Introduction

Natural fibres [from wool, silk and lignocellulosic (cotton, pulp) fibres] and synthetic fibres (made from petroleum-based materials) are widely used for applications in the textile industry. However, the industry is on the lookout for new sources of natural fibre (s) that can compare with the performance properties of major natural fibres like cotton and linen. However, use of these fibres is fraught with problems, e.g., shortage of land space to grow natural fibres, depletion of petroleum-based materials, and pollution caused by production of non-biodegradable synthetic fibres. Growing cotton is environmentally unfriendly because it consumes >25 % of total insecticides used in the world (Aktar et al., 2009). Synthetic fibres are made from non-renewable petroleum resources and consume more energy than that required to produce fibres from a renewable resource (Jones, 1998). Their production processes are environmentally unfriendly and the products made from them are difficult to dispose of after use and/or no longer useful.

In the textile industry, fibres extracted from natural sources should have a certain aspect ratio, i.e., ratio of length to diameter (Reddy and Yang, 2005). Aspect ratio for fibres typically ranges from 200 to several thousand, which could result in different levels of strength in yarns and fabrics. High aspect ratio usually leads to strong yarns (Hearle and Morton, 2008). In fibre-reinforced composites, fibres with high aspect ratio are highly preferred. For example, a high aspect ratio, between 100 and 200, of fibres is essential to endow fibre rubber composites with good performance properties (Munawar et al., 2007). In textiles, the length of fibres is also crucial to their spinnability. Only fibres with a minimum length of greater than 20 mm are processable in the traditional yarn spinning system. In addition, fibres should have similar mechanical properties compared to other natural fibres (Jones and Tucker, 1998), in order to meet the requirements of textile and other industrial applications.

It is estimated that there are 67×10^9 kg of synthetic and natural fibres currently in use worldwide (Reddy and Yang, 2005). Due to the diminishing accessibility and potential cost increases of the raw materials and natural resources required to manufacture textiles and composite products, it is important to discover alternative sources. Attempts to use the by-product of a major food crop as a source for fibres will be significant since the world's growing population will require more efficient land use in order to feed and clothe those in the poorer parts of the world. Thus, endeavours are being made to utilise renewable agricultural by-products such as pineapple leaves, soybean husks, corn husks, and rice husk, as unconventional sources for cellulosic fibres (Reddy and Yang, 2006). The production of regenerated fibres from agricultural by-products containing proteins such as zein in soya has been tried (Boyer, 1940). However, none of the attempts to produce high-quality protein fibres from agricultural by-products has been commercially successful.

Worldwide, the poultry–processing industry generates large quantities of feather by-products that amount to $40x10^9$ kg annually. Considering that feathers represent 5-10 % of the total weight of mature chickens (Jeffrey, 2006), it is evident that the industry generates a lot of feathers as a by-product, e.g., more than $258x10^6$ kg of chicken feathers are produced in the Republic of South Africa alone (DAFF, 2014). Currently, the feathers are considered as wastes that need to be disposed of, e.g., land-filling and incineration (Veerabadran et al., 2012; Stingone and Wing, 2011). However, improper disposal of these biological wastes by landfilling contributes to environmental damage and transmission of diseases (Tronina and Bubel, 2008). Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers.

The poultry industry has struggled with the question of what to do with the more than $40x10^9$ kg of poultry feather waste their business generates each year. Poultry feathers contain about 90 % protein and thus can be a cheap and renewable source for protein fibres. The secondary structures of the feathers, the barbs (see Figure 5.2.1), are in fibrous form and could be a potential source of protein fibres. Understanding physicochemical properties of these fibres are necessary so as to ascertain their suitability for use in various applications. In this research, chicken feather barbs were characterised for their physicochemical properties and the data was used to evaluate their suitability as textile fibres for the production of yarns and various technical textiles.

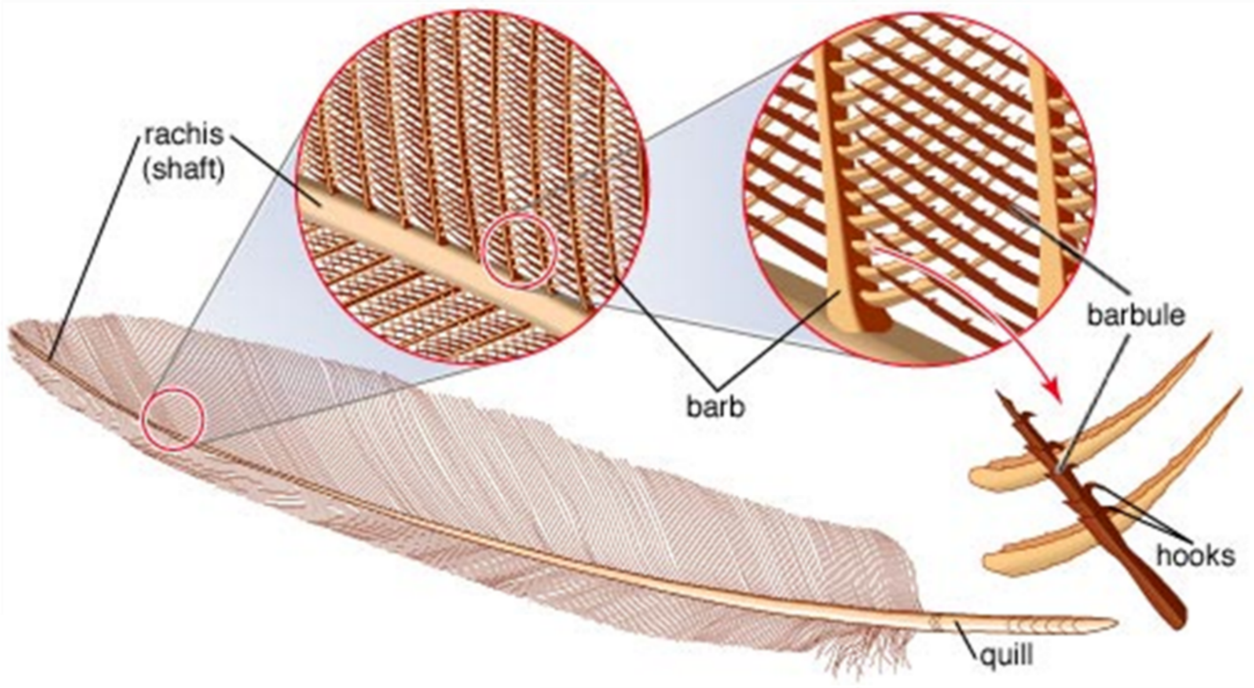


Figure 5.2.1. Structure of chicken feathers

5.2.2. Materials and methods

5.2.2.1. Sample preparation: Chicken feathers were obtained from a slaughterhouse in the province of KwaZulu-Natal, South Africa. The feathers were dried and conditioned at a relative of humidity 65±2 % and a temperature of 20±2 °C. The barbs with the barbules were separated from the rachis manually by cutting with scissors. The cutting of fibres was performed near the rachis so as not to lose length and the natural properties due to the format of the fibre along the extension. For all samples prepared, their characterizations were conducted in a laboratory environment (temperature of 22±2 °C and a relative humidity of 65±2 %).

5.2.2.2. Characterisation of physical properties and morphological structures

Physical properties: - Fibre length was determined by the "Oiled plate method" (ASTM, 2003) adapted from ASTM D5103-07. Fibre diameter, fibre dimensions (slenderness ratio and flexibility ratio were measured at three different points along each barb using an optical microscope (Nikon H600L). The density of the chicken feather barbs was measured using a liquid pycnometer (Rude et al., 2000). Surface areas of the samples were determined via Brunauer-Emmett-Teller/BET analyser. The BET surface area and micropore volume are determined using the nitrogen adsorption/desorption isotherms collected at liquid nitrogen temperature (77K) using a Micromeritics TriStar II surface area and porosity analyser (USA). The colour of the samples was determined by using a Konica Minolta CR-410 Chroma instrument. The metre was calibrated with a white plate. Absolute colour readings were recorded in L*, a* and b* space.

Morphological and fine structure: - The morphological structure of chicken feather barbs were conducted with the scanning electron Microscope (Carl Zeiss, Oberkochen, Germany) and the Atomic Force Microscopy with a Solver P47H base with a SMENA head, manufactured by NT-MDT was performed to see the fine structure of barbs.

5.2.2.3. Characterisation of chemical properties

Proximate and Ultimate analysis: - Moisture content (ASTM D 1576-90, 2001), ash content, crude protein content, crude fat content, crude fibre content and nitrogen content (AACC, 2000) were measured to know the proximate properties of the barbs. The amount of elemental carbon, nitrogen, hydrogen and sulphur in the chicken feather barb were determined using an elemental analyser (CHNS analyser).

Other chemical properties: - Buring test was conducted to ascertain the fibre types and the fire resistance properties when subjected to fire or high temperature. Feather barbs were burnt at a temperature of 575±25 ^{o}C. The burning behaviour, odour and the type and nature of the ash formed were noted. Feather barbs were placed in Petri dishes with various concentrations of cold water, hot water, strong and weak acid, and strong and weak alkali until the fibres were fully covered, for the duration of 2 hrs, 12 hrs, 24 hrs and seven days. chemical resistance of the fibre was calculated after reweighed. The hydrophobic behaviour of chicken feather barbs was examined by comparing it to that of hydrophilic compounds (cotton and wood pulp). Dried chicken feather barbs and hydrophilic compounds were immersed and shaken in excess water-ethyl ether mixture separately, then allowed to stand overnight at room temperature (Takase and Shiraishi, 1989). The swelling of chicken feather barbs was investigated in different solvents such as water, ethanol, dimethylformamide and n-Butanol. The 100 mg of samples were immersed in 100 mL volume of solvent for 24 hours. A Fourier transform infrared (FTIR) spectroscope was used to characterise the functional groups of the chicken feather and its barbs. Each spectrum contained an average of 4 scans, recorded at a resolution of 4 cm^{-1} in the range of 4000–400 cm^{-1}. XRD analyses of the barbs were ascertained using a Bruker D8 Discover model diffractometer, equipped with a diffracted beam monochromator, and a copper target X-ray tube set to 40 kV and 30 mA (Bruker South Africa, Johannesburg). The crystallinity index (Cr) was calculated using empirical equation (Das, and Ramaswamy, 2006).

5.2.2.4. Characterisation of thermal and mechanical properties

Thermal properties: - Thermogravimetric analysis (TGA) was performed using TA Instruments Q500, under nitrogen gas purge and a heating rate of 5ºC min^{-1}. The samples were pyrolysed using a multi-shot pyrolyser, EGA/PY-3030 D, (Frontier Lab, Japan) attached to a Shimadzu gas chromatograph/ mass spectrometer (QP2010 SE). The pyrolysis products were identified by comparing their mass spectra with the mass spectrum NIST library attached to the instrument.

Mechanical properties: - For mechanical properties, the samples were prepared by carefully removing single barbs from the rachis of waste chicken feathers and combed with a fine comb, and then 11.8 mm long feathers were prepared. The bundle tensile test was carried out on the Instron tensile tester (Model 3345) at 0 mm gauge length using pressley clamps with leather facing (ASTM D1776, 2013).

5.2.2.5. Sampling of chicken feathers for characterisation: Feathers differ in size depending on their location on the body of the chicken. Feathers can be distinguished as primary and auxiliary feathers depending on the body area from which they originated. Primary feathers are in the area of the wings and are not uniform in size. Therefore, to optimise measurements of weight and diameter, a random sampling technique was used. For measurement purposes, five different sampling positions were marked at specific distances along the length of the specimen as illustrated in Figure 5.2.2: the average of three replicates was considered as one measurement for each test except for length measurements.

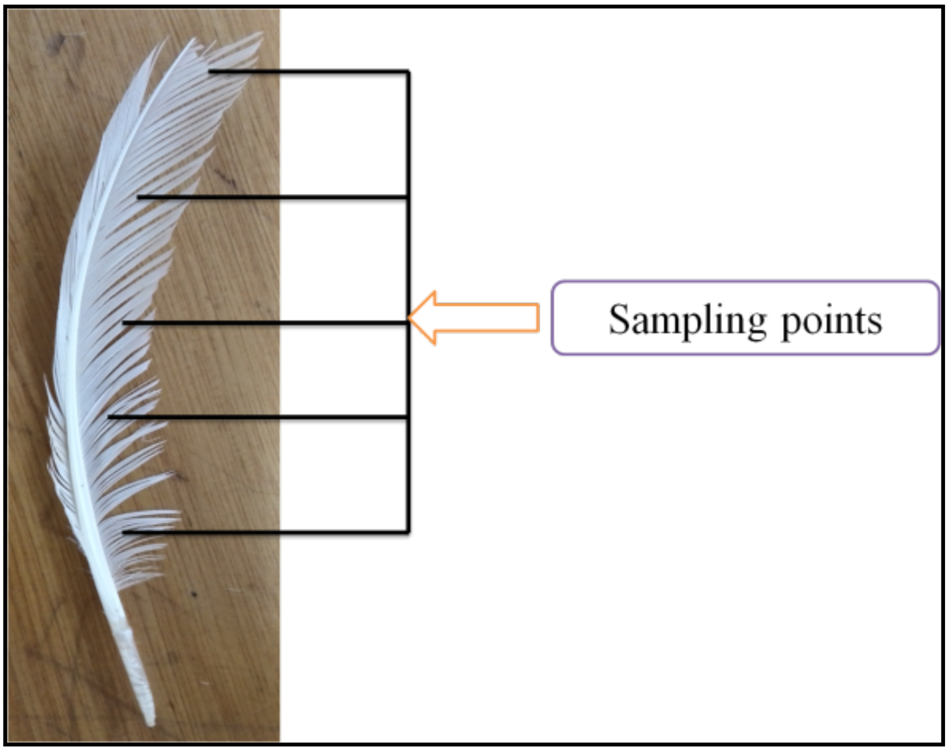


Figure 5.2.2. Selection of sampling points for measurement along a chicken feathers (Tesfaye et al., 2017).

5.2.3. Results and discussions

5.2.3.1. Characterisation of physical properties and morphological structures

Physical properties

Length: - Figure 5.2.3 shows the fibre length distribution of chicken feather barb. The averages of 100 readings at different sampling positions for a total of 100 samples were noted. The distributions of chicken feather barb were not normal but rather showed a positive degree of kurtosis from 21-30 mm (Figure 5.2.3). The lengths of the barb ranged between 1 mm to 45 mm. This gave the range of the fibres as 44 mm. The data in Figure 5.2.3 indicate that barbs of chicken feathers are of a length that is suitable for spinning into yarn fibres (Hearle, and Morton, 2008). However, the fibre lengths of the barbs lie between short staple and medium staple textile fibres: this will affect the spinning limit, handling of the product, the lustre of the product, quality of the yarn. The higher the amount of short fibres the more end breakage will occur during processing, which negatively affects the quality of the product and the production rate. The length distributions of each chicken feather barb along the length of one rachis were not consistent along their lengths; the mean coefficient of variation for ten samples at five sampling positions was 53.53 % demonstrating the heterogeneity of the sample. However, variations of barb length up to the third sampling position were consistent varying by less than 15 %.

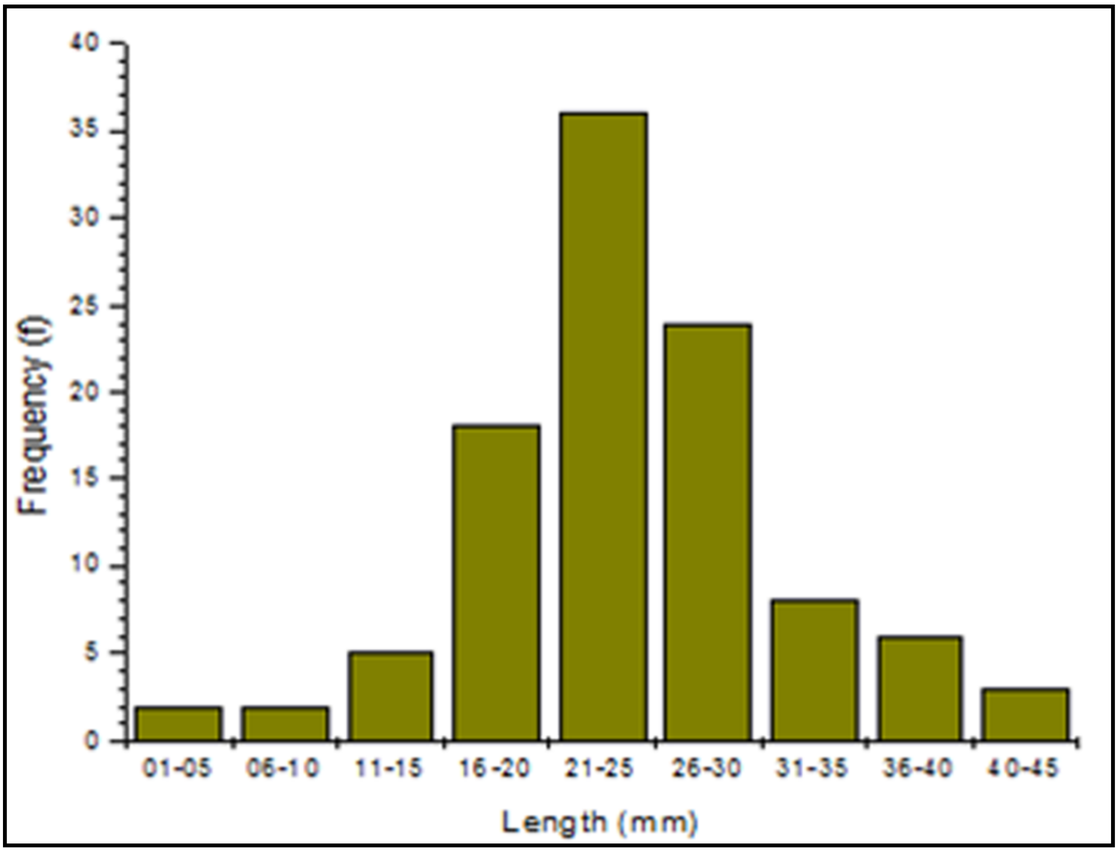


Figure 5.2.3. Fibre length distribution of chicken feather barbs

The rachis of feathers comprises approximately half of the weight of the feather while the barbs make up the other half: more than 30 % of the barbs are longer than the 20 mm fibre length required for textile applications. This means that, on an annual basis, approximately $12x10^9$ kg of barbs (Table 5.2.1) could be available as natural protein fibres worldwide, with $77.4x10^6$ kg of barbs obtainable in South Africa (Tesfaye et al., 2017). This translates into an availability of 20 percent of the natural and synthetic fibre consumed annually.

Table 5.2.1. Availability of chicken feathers

	World	**South Africa**
Chicken feathers	$>40x10^9$ kg	$>258x10^6$ kg
Barbs	$20x10^9$ B kg	$129x10^6$ kg
Barbs > 20mm	$12x10^9$ kg	$77.4x10^6$ kg
Barbs < 20mm and Rachis	$28x10^9$ kg	$180.6x10^6$ kg

Fibre diameter: - The data in Figure 5.2.4 illustrate the diameter of the barbs of chicken feathers. The diameter of the barb was relatively small: the mean diameter was 46.65 µm, with a standard deviation of 34.37 µm and a coefficient of variation of 73 %. The variation in diameter was high indicating that the barbs were of widely different diameters. Uniformity of barb width is an important aspect in the quality and flexibility of yarn spinning. Due to its contribution to softness and to the fact that finer fibre generates finer yarns which produce lightweight fabrics, fibre diameter is the first requirement in yarn production. As the demand by the modern consumer is to seek comfort and enjoyment in wear, this is critical in the modern textile industry which is found especially in light weight fabrics.

The diameter of fibres affects the spinning quality and flexibility of the fibre: the finer the fibre the better the spinning quality. The diameter of the barb of the chicken feathers was in the range of spinnable diameter for the textile application (Hearle, and Morton, 2008). The distributions of diameter widths of chicken feather barb were very consistent along their length, varying by less than 10 % and 4 %: only the extreme distal ends of the barb and barbules differed in diameter from the rest of the samples. As shown in Figure 5.2.4, the fibre diameters of the barb were narrower (i.e., exhibited a negative degree of kurtosis from 5-50 μm and a positive degree of kurtosis from 3-4 mm). ANOVA statistics showed that the diameter width distributions of the different feather barbs were significantly different from each another. The variation in fibre length and diameter of the barbs was very large, most probably because the feather samples originated from different positions on the chickens and different sized chickens. Barbs from big chickens are longer than those from smaller chickens whereas barbs of small chickens are fluffier than those from large chickens. Additionally, barbs from big chicken feathers originating from the outer body of a chicken are much longer than those of small feathers from the inner body part of a chicken.

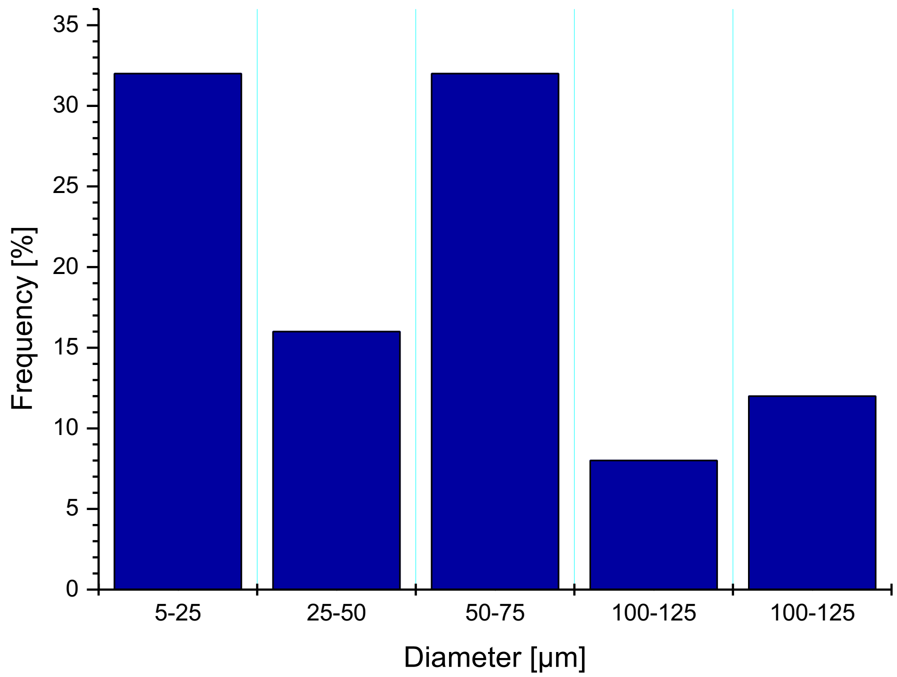


Figure 5.2.4. The distributions of diameter widths of chicken feather barbs

Dimensional measurements: - Data for medulla diameter, cell wall thickness and length and diameter results for barbs were summarised in Table 5.2.2. Higher cell wall thickness/cortex of fibres causes more flexibility of fibres in further processing of fibres, e.g., in textile applications. The increase of cell wall thickness has a direct positive effect on strength properties of fibres. The calculated values for aspect ratio/slenderness ratio and flexibility ratio are shown in Table 5.2.2: the barbs exhibited higher slenderness ratio and flexibility ratio. Slenderness ratio/aspect ratio is related to the dimensional parameters of fibres such as length and breath. The preferred length to width ratio for use in textile industries is between 200–600 (Fathima and Balasubramanian, 2006). Thus results from the present work suggest that chicken feather barbs can be used as fibres in textile industries.

The use of any textile fibre for composite applications is dictated by its geometric dimensions, specifically a very high length-to-diameter ratio. In weight-sensitive applications such as automotive, aircraft and space vehicles strength-to-density and stiffness-to-density ratios are commonly used as indicators of the effectiveness of a fibre (Ververis et al., 2004). The longer the fibre, the lower the number of ends, and hence the higher will be the load carrying capability. In general, the strength of fibre composites is managed by the critical length of the fibre: the strength will be higher if the fibre length exceeds its critical length. If the aspect ratio is greater than 15, the fibre is termed continuous; otherwise, it is termed discontinuous (Gejo et al., 2010).

In this study, the average aspect ratio was greater than 15. Hence, chicken feather fibres can be considered as continuous fibres, but their diameters and lengths varied depending on their location on the body of the chicken. Chicken feather fibres are naturally of short length which allows for accommodation of some fibres for the same volume fraction; hence increase in surface area improves the efficiency of load carrying (Fatima and Balasubramanian, 2006). The workability-reducing effect of fibres depends largely on aspect ratio. Ideally, the aspect ratio should be as small as possible to minimise the loss of workability and as large as possible to maximise the resistance of fibres to pull-out from the matrix and thus maximising their reinforcing effectiveness.

Fibres with high aspect ratios are thin and long whereas fibres with low aspect ratio are shorter and broader in the transverse direction. It is advantageous to retain as much fibre length as possible since higher aspect ratios give rise to good surface contact and fibre-to-fibre bonding. Long fibre lengths (up to 500 aspect ratio); result in high strength (Fowler et al., 2006). Short and thick fibres produce a poor slenderness ratio which in turn negatively affects the quality of the final products. This is partly because short and thick fibres do not produce good surface contact and fibre to fibre bonding.

Table 5.2.2. Dimensions of chicken feather barbs

Length (mm)	Diameter (µm)	Medulla diameter (µm)	Wall thickness (µm)	Slenderness ratio	Flexibility ratio
24.75	46.65	26.88	3.31	530.55	57.62

The flexibility ratio of chicken feather barbs was 57.62. According to the classification of textile fibres on their flexibility ratio, the flexibility coefficient of chicken feather barbs places them in the elastic fibres group. The flexibility and ability of the barbs to twist and bend will provide good strength, cohesiveness, and spinnability to yarns and fabrics made from them. If barbs are blended with other fibres, the morphological structures of the barbs, barbules and the hooks in the barbules will provide better cohesiveness to the blended yarns.

Fibre diameter and wall thickness govern fibre flexibility. A thick walled fibre adversely affects burst strength, tensile strength, and folding endurance of the final product (e.g., textile fabric, composites, and paper). Product manufactured from thick-walled fibres will be bulky, coarse-surfaced and will contain a large amount of void volume whereas products from thin walled fibres will be dense and well formed.

Density of chicken feathers: - The mean relative density of the barbs was 0.91 g/cm^3 with a standard deviation of 0.22 g/cm^3 and coefficient of variation 24.29 %, a relatively low variation indicative of sample homogeneity. The density of chicken feather barbs varied between 0.5 g/cm^3 and 1.5 g/cm^3. The variation in results may be related to the composition differences in the barb samples studied. Chicken feather barbs consist of a large concentration of alpha helices structures (Xu et al, 2006; Zhao et al., 2012). SEM micrographs of cross sections of feather barb show an open cell porous structure, which very probably, is responsible for the low-density value of the feather. Considering that the chicken feathers used in this study were collected from one chicken processing plant, it is plausible that the density of the chicken feather barb is likely to be influenced by the effectiveness of the chicken feather segregation process employed at the plant. Thus, density measurements may be used to gauge the degree of the segregation process. Such properties are important in the valorisation of feathers into many applications such as textile yarn and composites.

The density of chicken feathers barbs thereof, were measured to be 0.44-0.91 g/cm^3: These values correlated well with literature values for protein and cellulosic fibre but were lower than those of animal and plant fibres such as wool (1.31 g/cm^3), silk (1.27g/cm^3), jute (1.3 g/cm^3), coir (1.2 g/cm^3), and cotton (1.5-1.6 g/cm^3), etc. (Hearle, and Morton, 2008). Considering that the density of composite materials increases as the amount of reinforcing fibre content increases, the inclusion of chicken feather barbs in a composite could potentially lower the density of the resultant composites. Thus, production of lightweight composites containing chicken feather barbs will result in substantial savings regarding transportation and construction costs due to the inclusion of the lightweight feather barbs. No natural or commercially available synthetic fibres today have a density as low as that of chicken feathers barb.

Colour measurements: - Table 5.2.3 shows the colour measurement data for chicken feather barb. Chicken feather colour varies due to the biological nature of the chicken and how it was processed. The amount of preen oil in chicken feather contributes to the yellowness of the feather, and these fatty acid compositions varies for different age intervals. Particulates from dust bathing, pieces of feed and faecal matter may also be present in chicken feathers. Unprocessed white chicken feather collected from poultry industries appeared straw-like, and the barbs were stuck to the rachis in a greasy tangle and turned dark brown after two days when left at room temperature. A rotten odour was also evident due to the development of bacteria, and the bacterial excrement caused the feathers to darken (Figure 5.2.5). As it is shown in Figure 5.2.5, the untreated white chicken feather also contains blood, which looks pink just after collection but turns brown as it dries. The method of transporting the feather, in the poultry industry (from the section to temporary waste storage area) may also affect the colour of the chicken feather and the amount of impurities. The CIE tristimulus (L*, a* and b*) values, whiteness index, yellowness index and colour difference result from Table 5.2.3 shows that there is a need to pre-treat the chicken feather in order to improve the colour of the chicken feather before valorisation.

a b

Figure 5.2.5. Chicken feather from poultry industry (a: during collection; b: after three days)

Table 5.2.3. CIE tristimulus values, whiteness index and colour differences (ΔE) for barbs

	L^*	a^*	b^*	ΔE	WI CIE	YI E313
	75.36	2.81	19.59	77.91	-57.75	43.18

BET analysis: - The absorption properties of the chicken feather barbs are shown in Figure 5.2.6. The surface area of the barb was 0.7845 m^2/g with a single point surface area at P/Po = 0.201083043: 0.8712 m^2/g. The pore volume of barb for single point adsorption total pore volume of pores less than 139.3977 nm diameter at P/Po = 0.986439263 was 0.007904 cm^3/g. The barbs have a pore size of adsorption average pore width (4V/A by BET): 40.29871 nm, BJH adsorption average pore diameter (4V/A): 87.0263 nm and BJH desorption average pore diameter (4V/A): 25.8096 nm. Since the pore size of barbs falls in between 2-150 nm, it can be concluded that the barbs are mesoporous and microporous materials (Weber, Schmidt, Thomas, and Bohlmann, 2010).

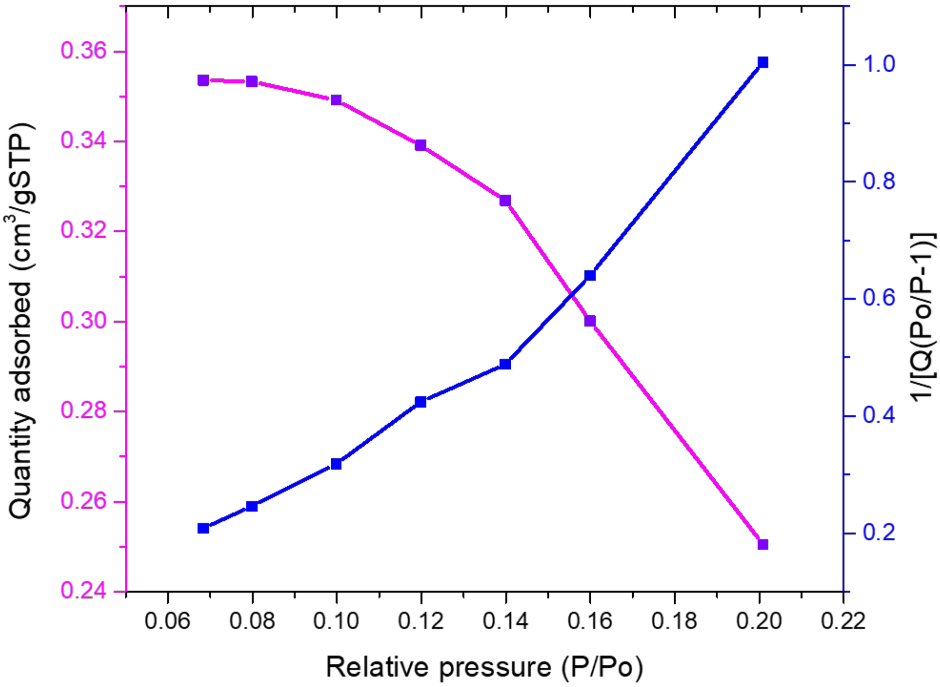


Figure 5.2.6. BET specific surface area analysis of chicken feather barbs

Figure 5.2.6 shows the BET specific surface area of chicken feather barbs. Figure 5.2.6 demonstrates that the amount of the adsorbed nitrogen in this region is the representative of adsorption in micropores, which are the internal adsorption sites inside the chicken feather barb. These results showed that the material produced from barb have very stable adsorption and desorption resulting in the higher surface area compared. Nitrogen adsorption/desorption isotherms at 77 K of the barb of the chicken feather samples were shown in Figure 5.2.7. Barb exhibited the type-III isotherms and explains the formation of multilayers. Figure 5.2.7 shows considerable differences between the adsorption/desorption isotherms of the barb of the chicken feather: the uptake amount of low pressure by barbs were much higher this is the indication for the presence of more mesopores. The uptake of nitrogen at very low pressures is due to mesopore and micropores filling from the enhanced adsorbent–adsorbate interactions in the mesopores and is distinct from adsorption in macropores because adsorption in mesopores material is due to multilayer adsorption and capillary condensation (Gil and Montes, 1994)

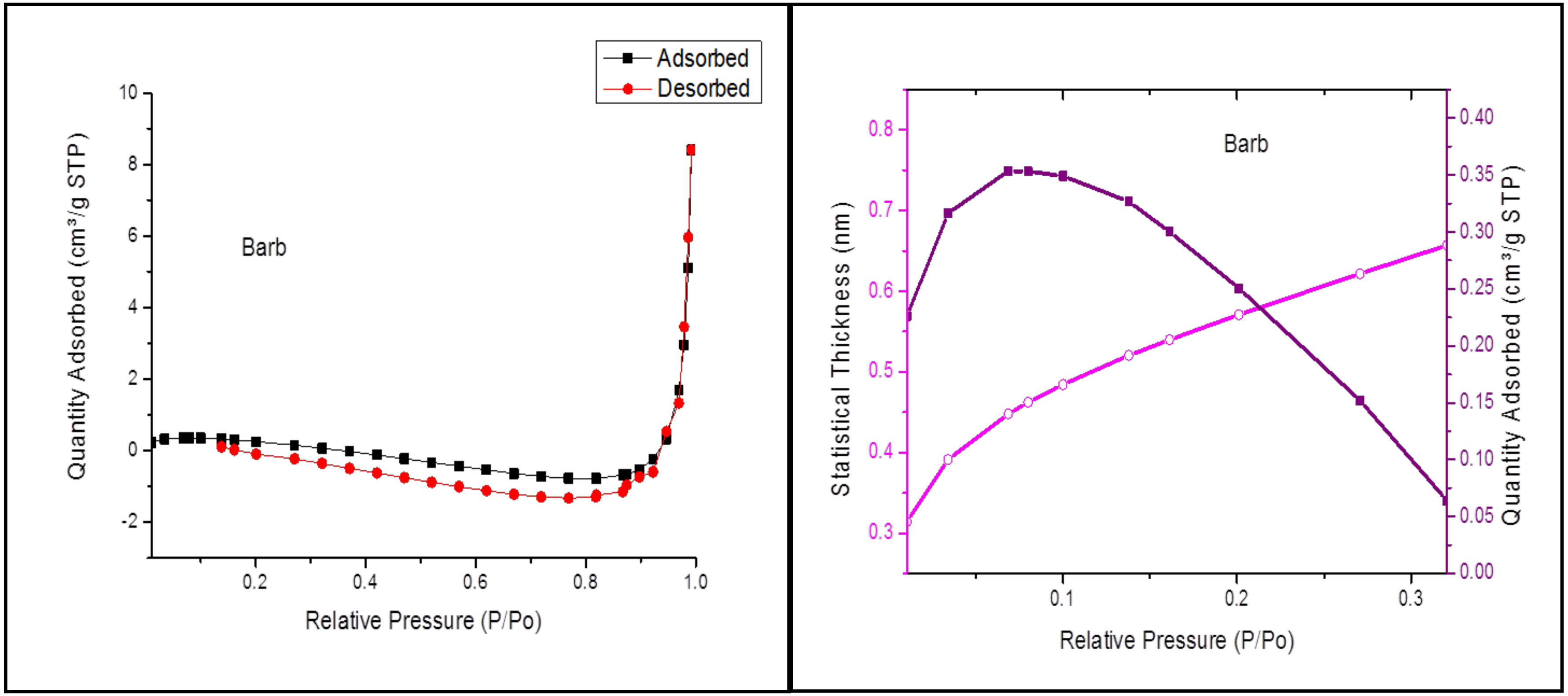


Figure 5.2.7. Adsorption/Desorption Isotherms and thickness curve of chicken feather barb respectively

Morphological and fine structure

Morphological structure: - The morphological features of chicken feather barbs were shown in Figure 5.2.8. As can be seen in Figure 5.2.8a the chicken feather is composed of three distinct units: the rachis, the central shaft of the feather that runs the entire length of the feather to which is attached the secondary structures, the barbs and the tertiary structures, the barbules (Figure 5.2.8c). Additionally, barbs display a fibrillar surface but no scales (Figure 5.2.8b). From this information, it can be postulated that mechanical properties of fibrous composites made from feathers will be improved due to the entanglement of barbules with other fibres. Also, the occurrences of microfibrils in chicken feathers barb that are twisted from helixes imply that their use will impart high mechanical strength to the fibres. The flexibility and length of feather barbs make them suitable to be used as natural protein fibres. As can be seen in Figure 5.2.8d feather barbs show honeycomb shaped hollow cells in the cross-sectional direction. These honeycomb structures can act as a raw material for light weight high tech materials. The voids inside chicken feathers barb may be more accessible to fluids or air as length decreases. The presence of hollow honeycomb structures provides high resistance to compressibility and also imparts light-weightiness to the barbs.

The air pockets in the feather barb contribute to the high thermal resistance and good moisture transport characteristics of feathers and impart good resilience. The presence of two different structures inside the bio-fibres are evident: they are microfibrils and protofibrils. The former have a more ordered and crystalline structure than the feather matrix. The protofibrils exist inside the microfibrils and are also surrounded by the matrix. Additionally, the images in Figure 5.2.8d confirm that the microstructure of feathers is nearly round; the medulla in coarse fibres are concentric and irregular in size.

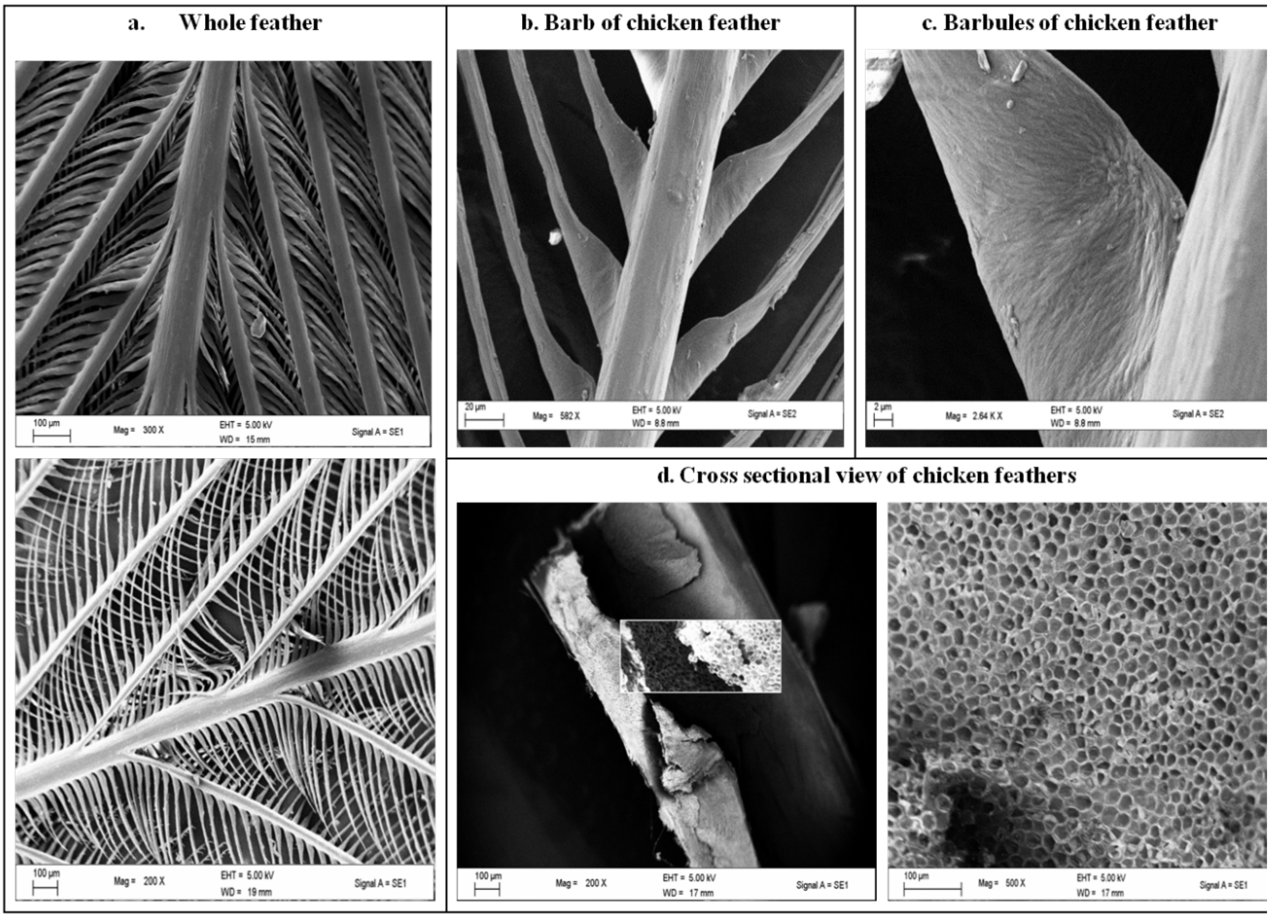


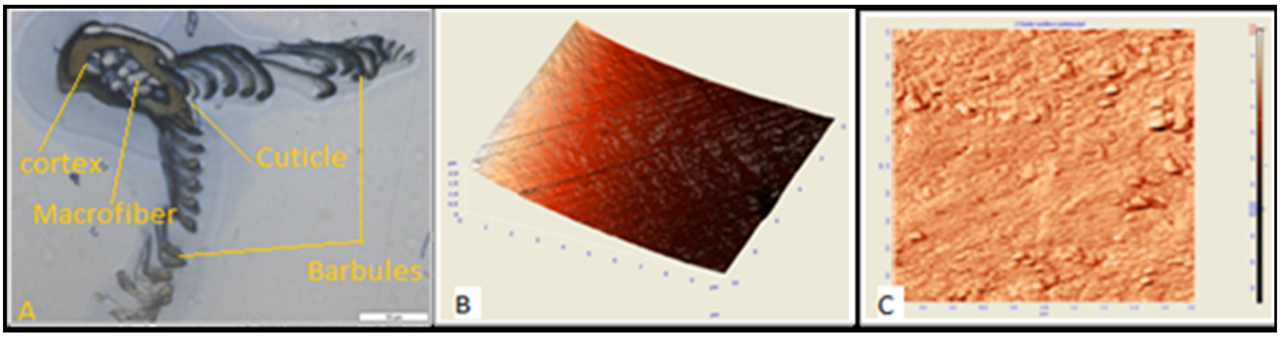
Figure 5.2.8. Morphological structures of chicken feather barb

Fine details of chicken feather barbs cellular structures: - From the AFM images of barb cross-section image, the cuticle, cortex, and epoxy resin regions can be easily recognised (Figure 5.2.9). Morphologically, the chicken feather barb consists of two components, outside layers of protecting cells, called cuticles which surround the cortex that consist of macrofibrils (Figure 5.2.9). The cell membrane complex separates cortex from those of the cuticle, and a group of cortical cells were also linked together by cell membrane complex. The cross-sectional shape of the barb was less varied in shape and was approximately oval-shaped.

Cuticle: As it is seen in Figure 5.2.9 (5.2.9.1 (a) and (b)) a dark region surrounded the barb cross-section and this represented the cuticle. The cuticle, which were plate-shaped, form the outer part of the barb surrounding the cortical cells in layers of flat scales and was only one scale in thickness over most of its area (Figure 5.2.9). The cuticle of chicken feather barb were smooth with low scales, indicates the lusterity of the fibre is good. As it is also observed in wool fibre, all interactions with the environment occur through the cuticle, providing resistance to potentially harmful agents that may come into contact. Since the cuticle is such a small part of barb cross section, it is unlikely to contribute to the tensile properties.

Cortex: The cortex forms the central/principal part of barb cross-section of the chicken feather and two different morphological regions can be seen: the macrofibril and cell membrane complex (Figure 5.2.9 (5.2.9.1 (a) and (b - 3x3 µm)). It consists of small spindle-shaped cells which are a bundle of the intermediate filaments, oriented parallel to each other (Figure 5.2.9). A cortex cell of barb contains a group of macrofibrils and they were separated by fibril matrix and between macrofibrils, there were nuclear remnants of keratinocytes (Figure 5.2.9.2). Microfibrils are a relatively early stage of development, organised to form macrofibril structures which were also observed (Figure 5.2.9.2 (c - 1x1 µm)).

5.2.9.1. Cross-sectional image of barb (a), Cuticle (b-3x3 µm) and the cortex (c- 2x2 µm*)*



5.2.9.2. Ultrastructure of chicken feather barb (cortex, macrofibrils, fibril matrix, and microfibrils), a-3x3 µm, b-2x2 µm, and c-1x1 µm.

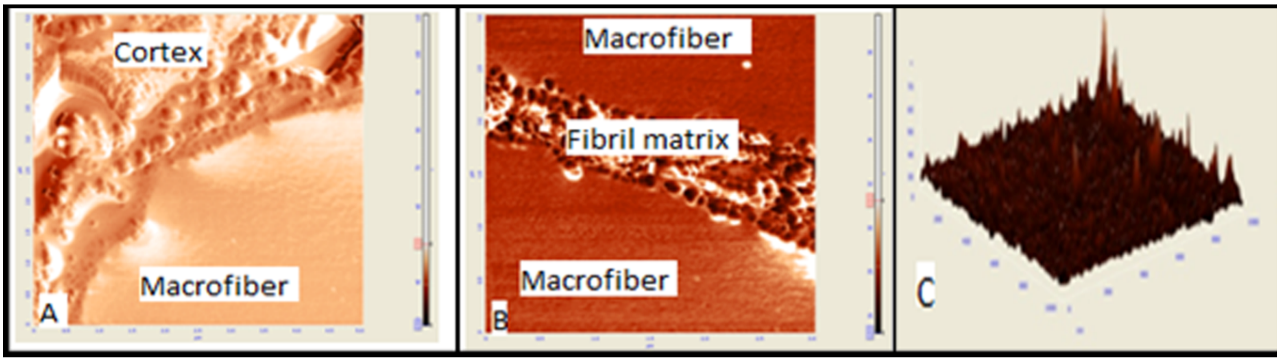


Figure 5.2.9. Cross-sectional images of chicken feather barb and fine detailed images of the cuticle region and cortex region.

5.2.3.2. Characterisation of chemical properties

Proximate and Ultimate analysis

Ultimate analysis: - Results from CHNS analysis of the examined feather barbs are shown in Figure 5.2.10. Overall, carbon and nitrogen show the highest content.

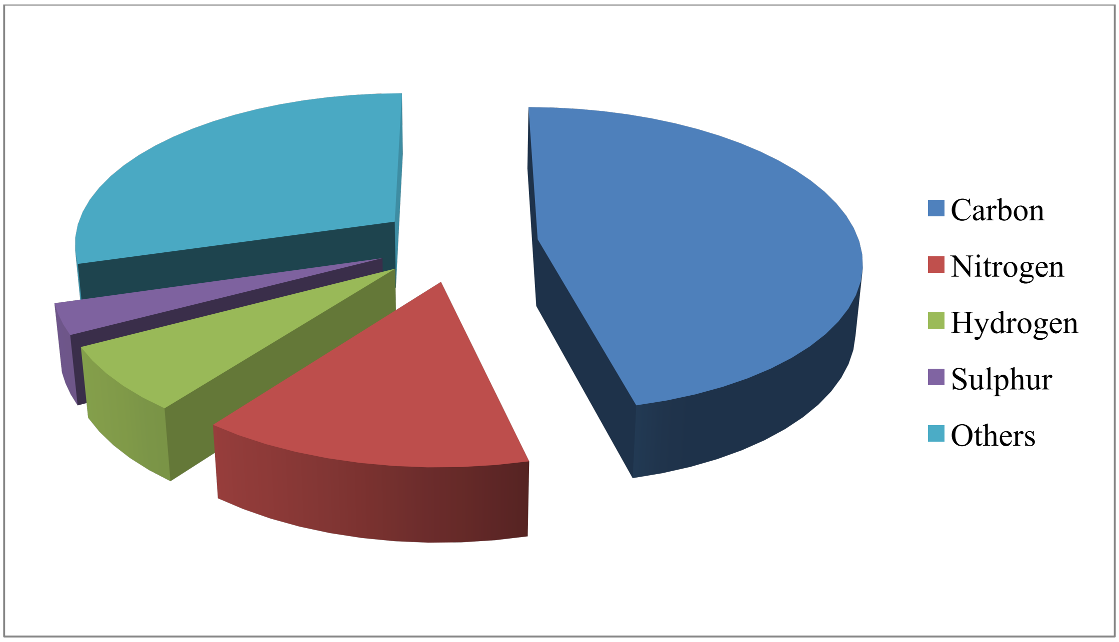


Figure 5.2.10. Elemental analysis of chicken feather barb

Basic composition: - Crude protein is comprised of true protein and non-protein nitrogen. True protein is sometimes called natural protein. Based on these findings the crude protein content for the barb is about 80 % (Tesfaye et al., 2017). Crude fibre consists of cellulose, hemicelluloses, lignin and other soluble fibres. The data in Figure

5.2.11, indicates feather barb contain a low percentage of crude fibre since they have a low percentage of cellulose, hemicelluloses, and lignin. The results obtained for crude fibre in barbs was between 3-5 % (Tesfaye et al., 2017). Crude fat is an estimate of total fat content and includes true fat (triglycerides) as well as alcohol, waxes, terpenes, steroids, pigments, esters, aldehydes and other lipids. The results for the chicken feather barbs varied between 2-4 %. Further processing of fibres requires the residual grease content to be below 2 % (Bateup, 1986). Hence, since in most cases, the grease content of the chicken feather is more than 2 %, the fibres need to be pretreated and scoured to remove the fat before further processing.

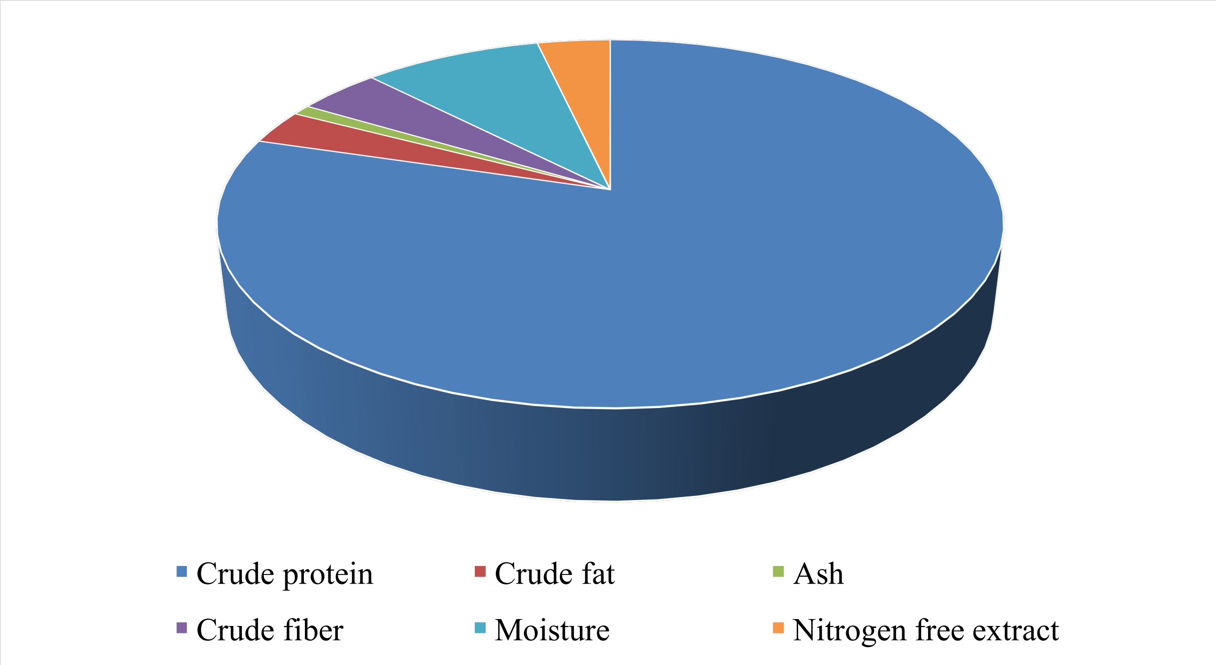


Figure 5.2.11. Proximate analysis of chicken feather barbs

The data in Figure 5.2.11, illustrate the results of the moisture content of chicken feathers barbs thereof. Moisture regain values are more commonly used in textile business transactions than moisture content values since buyers of fabrics are concerned with the weight of fibres and excess moisture impacts the weight of the purchased fabrics (fabrics with higher moisture regain values will weigh more that those with low regain values). The moisture content of the barbs was 12.33 % (Tesfaye et al., 2017). The ability of chicken feather barbs to absorb moisture from the environment has important implications for processing, storage, transportation, and durability of barb containing composite materials, since increases in the moisture content may interfere with processing or bonding, increase weight of the products (and hence transportation costs), or lead to rapid deterioration of the product. However, the average moisture content of the chicken feathers barb did not exceed 10.54 %: this implies that the material could be safely stored for long time periods with no concerns of deterioration. Moisture contents of 8-13 % indicate that chicken feather is hygroscopic. The hygroscopicity increases in chicken feather barbs. This implies that they can absorb enough water to prevent static build-up – hence being useful in applications where static build-up is of importance.

In structural morphology considerations, the presence of a honeycomb structure will enable accumulation of liquids in its interior, in addition to the amount of water already absorbed by the dry material: 3.11 % for barbs. Using chicken feather barbs could be ideal for applications that require liquid retention, e.g., in medical applications. Fibres with big regain values probably exhibit many more amorphous regions than those with low regain values. The value of moisture regain of the chicken feathers barb was considered low compared to other fibres that have a moisture regain of up to 20 %. This probably implies that fabric products made from this material will provide fabrics with comfortable texture to the end users. Moisture content influences the comfort of textile fabrics and fibres with excellent moisture regain, accept dyes and finishes more readily than fibres with low regain (Joseph, 1986); therefore, it appears that application of water-born dyes and finishes onto fabrics made from chicken feathers barb. Further research is required to determine the maximum suitable moisture content of barbs and also to assess the effect of variations in moisture on processing, storage, transportation, and durability of the fibres.

Other chemical properties

Burning Test: - The result summarised in Table 5.2.4 indicate that the feathers are similar to wool fibre. Thus chicken feathers barb are categorised as a protein fibre. From the data in Table 5.2.4, it was observed that barbs do not support continuous burning, and emit an odour like that of burning human hair. They burn with an orange sputter colour and do not melt. When the flame died, the feather barb supported combustion very slowly for a short period. This indicated that the barbs are self-extinguishing, but for them to be used safely near the fire, they require appropriate fire-retardant and protective finishes, to be fire-proof.

Table 5.2.4. Burning characteristics of chicken feather barbs

Characteristic	Effect on barbs
Approaching flame	Smoulders and curls away from flame; ignites slowly
In the flame	Burns slowly with small flickering /orange flame; sizzles and curls
Away from the flame	Supports combustion for a short time melts ahead
Odour	Burning hair
Residue	Completely fuses

Chemical Resistance: - Results were compared with control samples of chicken feather barbs stored in deionised water. Alkali (both strong and weak alkali), rapidly and completely dissolves the chicken feather, but significantly less near neutral and slightly acidic condition. It was observed that the barb weight was decreased by 58-65 %, in all reagents except in 5 % NaOH. Since feathers are naturally porous, they can be used as fluid absorbers. After 24 hrs of drying at room temperature, they were reweighed, and losses in weight were found. From Figure 5.2.12 it is clear that the barbs lost weight and became brittle. Treating fibres with NaOH is essential for enhancing some of the properties, but it is not recommended to treat them for more than 1 hour, to maintain stability in the fibres. Data for degradation of barbs exposed to concentrated NaOH for up to 7 d are depicted in Figure 5.2.12. By day 7 the barbs experienced greater than 99 % mass loss, indicating that they are unstable in strongly alkaline environments.

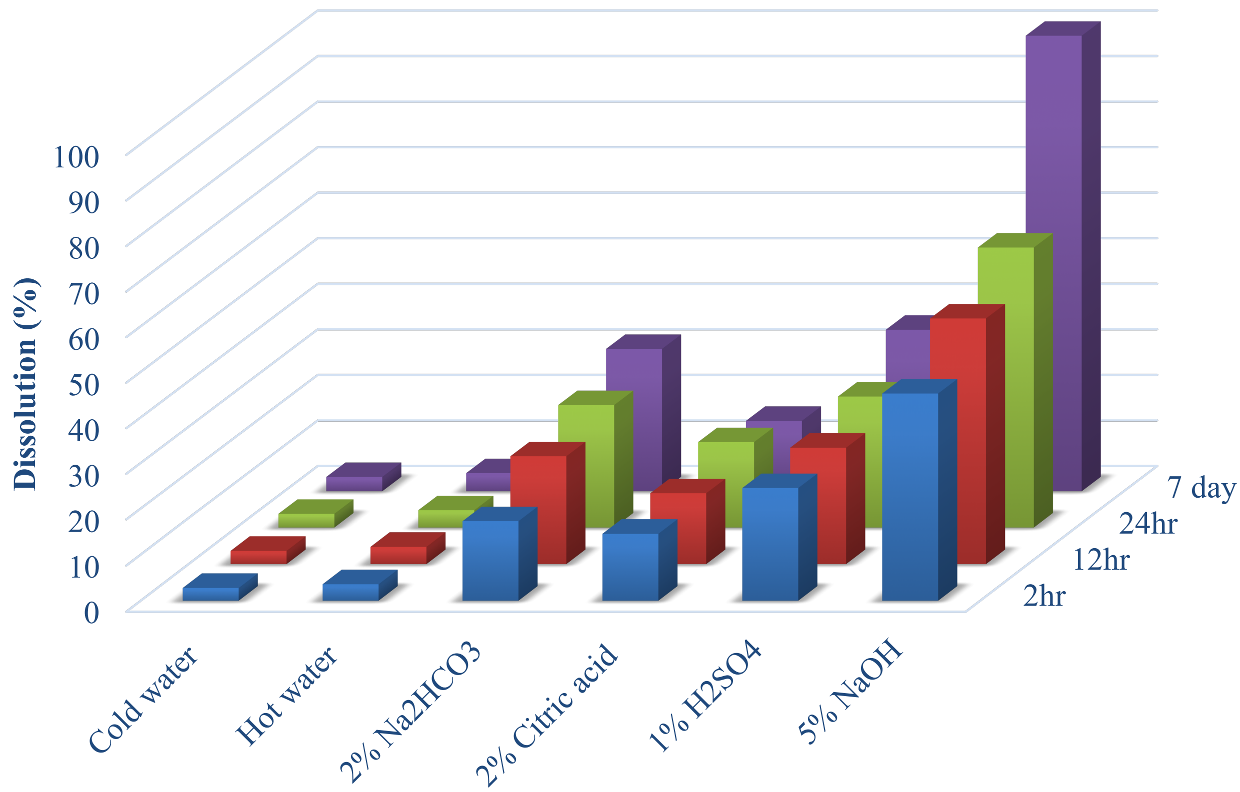


Figure 5.2.12. Chemical resistance of chicken feather barb

The feathers have good resistance to mild acids but have poor resistance to strong acids, where they dissolve. Figure 5.2.12 shows a lowest mass loss percentage result, about results of chicken feather barbs stored in deionised water. In concentrated sulphuric acid, chicken feather barbs were disintegrated, and weight loss was observed. While they were slightly dissolved by both concentrated hydrochloric acid and nitric acids. This indicates that chicken feathers barb are damaged by strong acids: the bonds connecting the subunits are made unstable by acidic media, with a corresponding high loss in tensile strength. Under room temperature conditions, the most commonly occurring reagents used on fibres, are bleaches, and detergents. They are not strongly alkaline or acidic, and thus, can be safely used on the chicken feathers barb, with low effect on the structure and tenacity thereof. When reacted with concentrated sodium hypochlorite, the chicken feather barbs were bleached, but after prolonged exposure, the chicken feather barbs weakened and disintegrated. This indicates that oxidising solutions like sodium hypochlorite should only be used when cold and diluted, for a short period, i.e., chlorine bleaches should be used for a short period, and must be rinsed out thoroughly to avoid damage. Hot water removes some of their extraneous components, such as inorganic compounds, sands, gums, and colouring matter.

Swelling behaviour: - Figure 5.2.13 shows the swelling properties of chicken feather barbs in different solvents. Different trends in swelling behaviour were observed in different solvents with the barbs swelling most in water. This may be due to a greater affinity of the hydrophilic hydroxyl (-OH) groups, present in barbs, toward the water. The swelling behaviour in different solvents follows the trend: water > ethanol > DMF > n-Butanol. Water can then penetrate more easily and deeply into feather barbs, resulting in much swelling. However, in another comparison, the feather barbs showed more swelling in methanol than ethanol. This may be due to the presence of the bulkier ethyl ($-C_2H_5$) group in ethanol providing a hindrance to sorption. Also, the presence of alkyl groups in chicken feather barbs make them hydrophobic in nature; therefore, these hydrophobic chains have a strong affinity toward non-polar solvents like carbon tetrachloride.

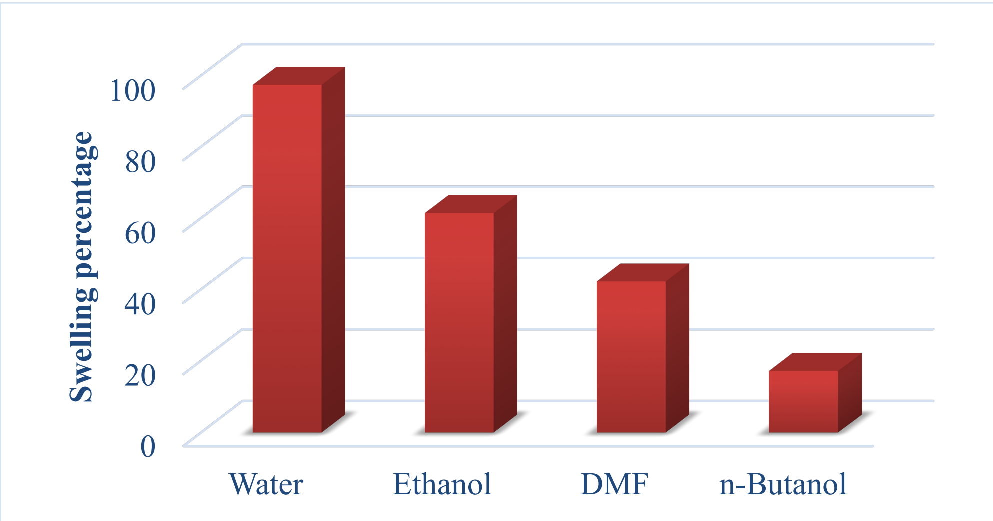


Figure 5.2.13. The swelling property of chicken feather barb

Hydrophobicity test: - As shown in Figure 5.2.14, it is apparent that cotton and wood pulp settled in the second layer (water layer), indicating the complete wettability of these fibres, while chicken feather barb were gathered together around the interphase between water and ethyl ether. This indicates a poor wettability of chicken feather barbs compared with cotton fibre and wood pulp; these observations confirm the hydrophobic properties of chicken feather barbs.

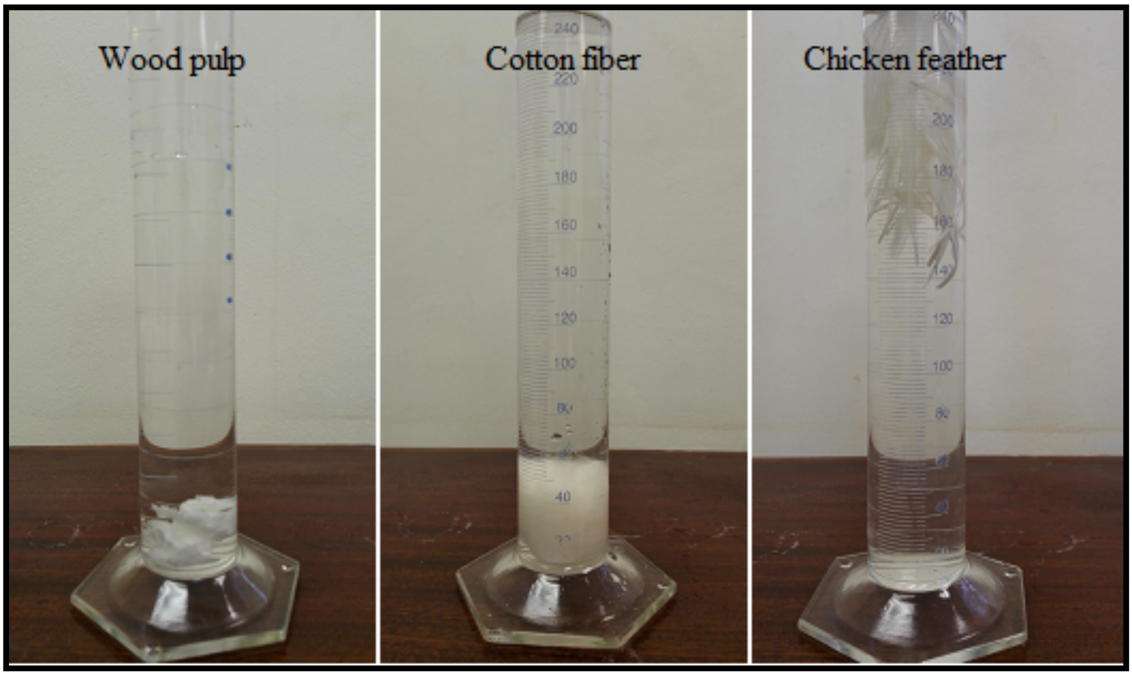


Figure 5.2.14. Hydrophobicity test for wood pulp, cotton fibre and barbs (Tesfaye et al., 2017)

Crystallinity index analysis: - The crystallinity of chicken feather barb plays an important role in their physical. chemical, optical and thermal properties. Similar to all animal fibres feather barb could have a kind of macromolecular polymer structure between the crystal and amorphous region. As can be seen from the crystal diffraction peak, all chicken feather barb show a medium diffraction peak around $2\Theta=9^{o}$ (for the α-helix structure of peptide chains in feather barb) and a prominent peak around $2\Theta=22^{o}$. Moreover, a diffraction peak-valley was observed at $2\Theta=14^{o}$ (Figure 5.2.15) between the two characteristic diffraction peaks mentioned above, which was assigned to the amorphous region of chicken feather barbs. Peak intensity indicates the crystal structure content. The peak at about 9° corresponds to the α-helix configuration (Zhao et al., 2012). The peak around 17° corresponds to the diffraction pattern of the α-helix, whereas the peak around 20° is a typical peak of the β-sheet structure (Zhao et al., 2012). The result indicates that feather barb possesses two kinds of crystal structure, i.e., α-helix and β-sheet. From the crystalline peaks, the crystallinity indexes were obtained using software (Origin), and the crystallinity of the barb of the chicken feather is 22.09 %. The decrease of crystallinity and decomposition of the β-sheet structure could improve the extraction, dissolubility, and enzymatic accessibility of the feather keratins. A completely crystalline polymer would be too brittle to be used as a source of textile fibre. The amorphous regions give a textile fibre toughness, that is, the ability to bend without breaking will lead improvement in mechanical properties.

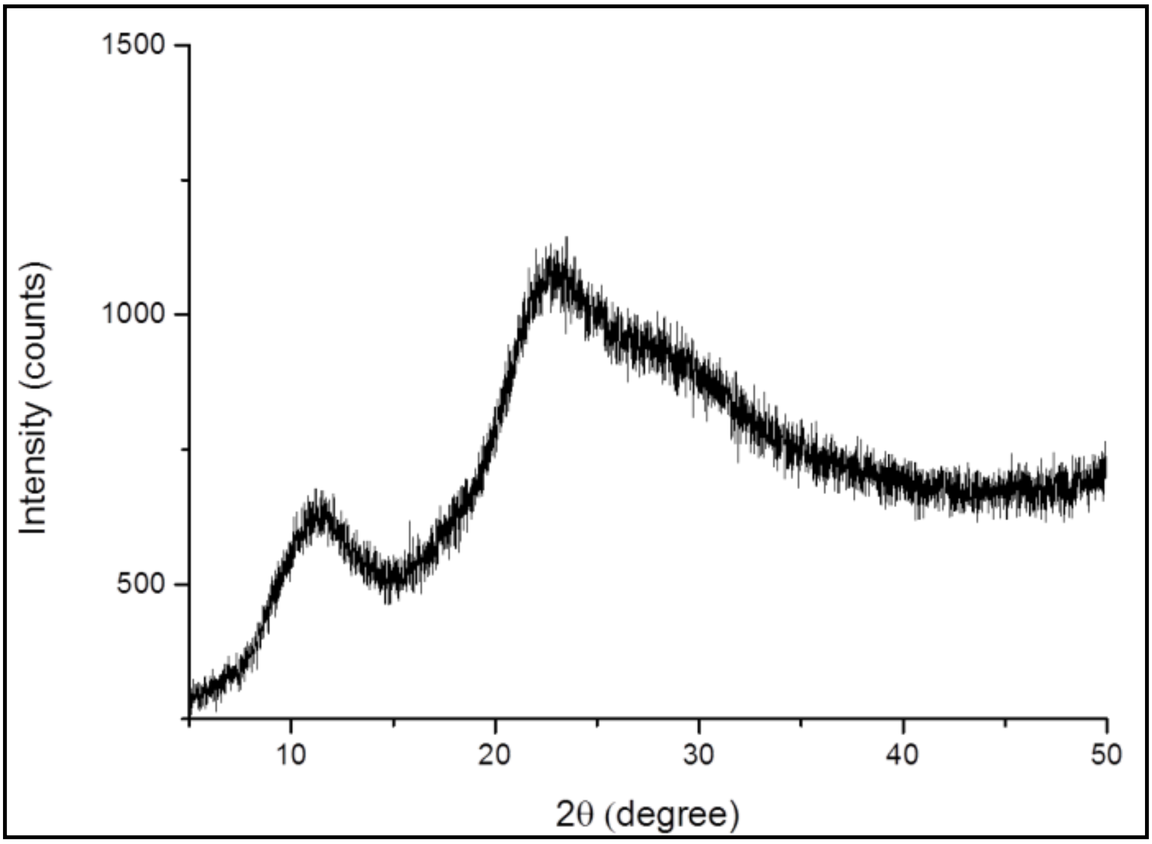


Figure 5.2.15. XRD pattern of feather barbs.

FTIR spectroscopy: The wave numbers and approximate assignments for the vibrational modes of the FTIR spectra (Figures 5.2.16) obtained in this study, in agreement with the assignations, are shown in Table 5.2.5. The result from Figure 5.2.16 revealed barb of the chicken feather is categorised under animal fibre (wool and silk).

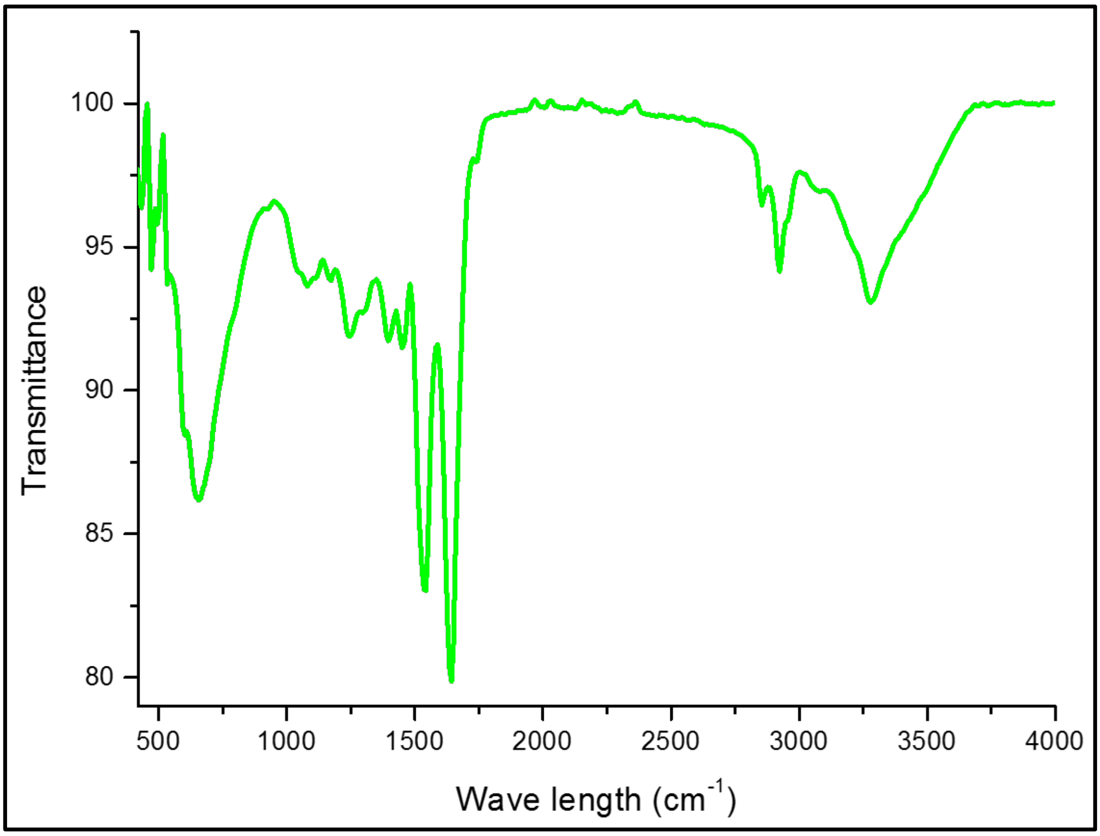


Figure 5.2.16. FTIR spectra of feather barb

Table 5.2.5. Assignment of peaks in FTIR spectra of chicken feather barbs.

Wavelength	Assigned peak	Remark
475	S-S	Symmetrical stretching
685	C-S	Symmetrical stretching
980	C-C	Symmetrical stretching
1075	C-C	Symmetrical stretching
1170	C-C	Symmetrical stretching
1230	(CN) Amide III	Symmetrical stretching
1315	$C-H_2$	Symmetrical bending vibration
1385	$C-H_3$	Symmetrical bending vibration
1436	$C-H_3$	Symmetrical bending vibration
1455	$C-H_3$	
1530	(N-H) Amide II, β sheet	Symmetrical bending vibration
1655	(C=O) Amide I, αhelix	Symmetrical stretching
1666	(C=O) Amide I, β sheet	Symmetrical stretching
1680	C=O	Symmetrical stretching
2870	CH_2	Symmetrical stretching
2930	CH_3	Symmetrical stretching
2965	CH_3	Asymmetrical stretching vibrations
3070	NH Amide B	Asymmetrical stretching vibrations
3300	NH Amide A, αhelix	Symmetrical stretching

5.2.3.3. Characterisation of thermal and mechanical properties

Thermal properties: - The thermal stability of chicken feather barb were investigated by TGA and DSC as shown in Figure 5.2.17. The first mass loss observed in the temperature range of 25–235 °C can be attributed to water release. The second and third mass loss stages (around 235–350 °C and 350–550 °C respectively) are related to denaturation of chicken feather barb. The complete degradation of the chicken feather carbonic chain takes places in the temperature range of 350–550 °C (Figure 5.2.17). Figure 5.2.17 shows rapid decomposition in the temperature range between 235–550 °C.

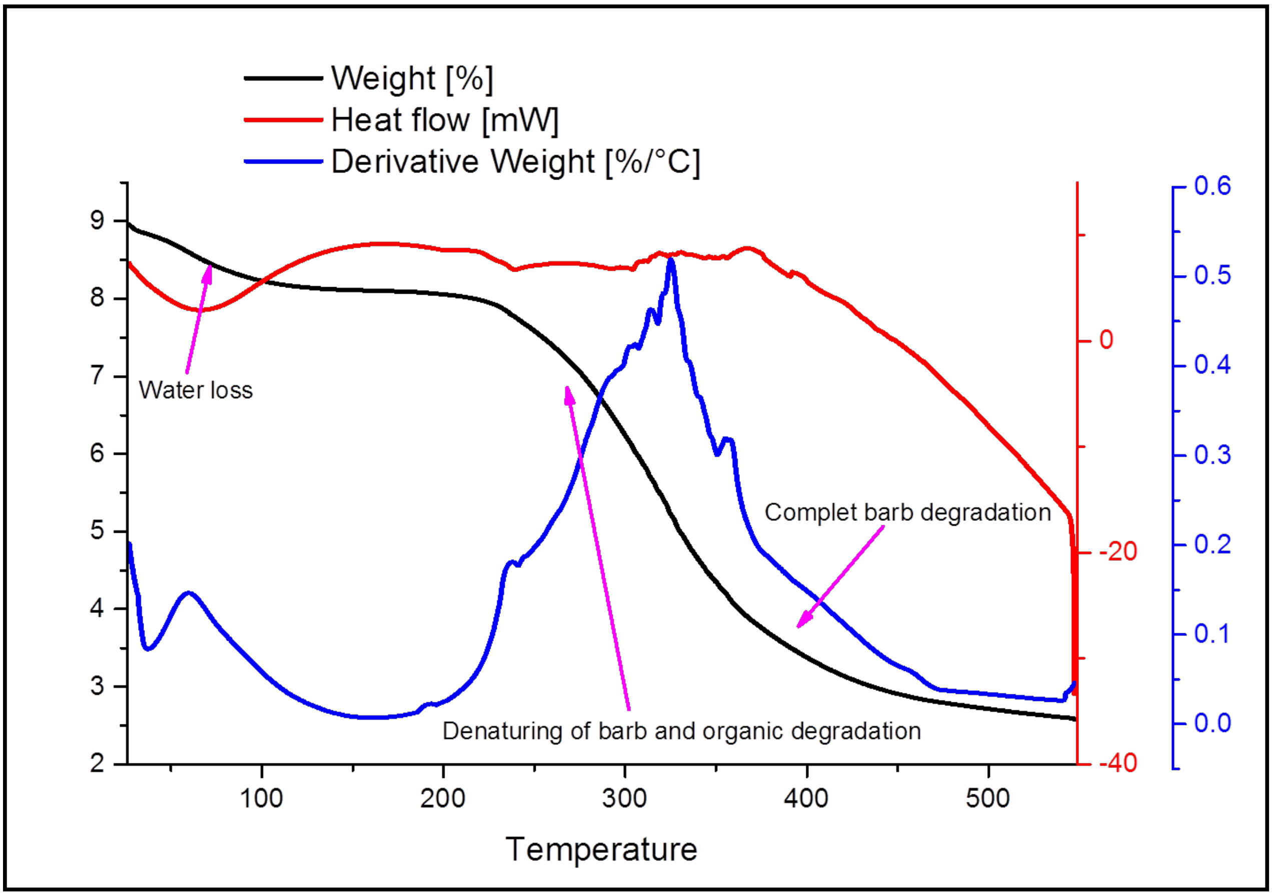


Figure 5.2. 17. Thermal analysis of chicken feather barb

Pyrolysis-Gas Chromatography mass spectrometer: - Figure 5.2.18 shows the pyrolysis-gas chromatography mass spectrum of a chicken feather barbs (pyrogram). The main degradation products obtained from pyrolysis-gas chromatography of chicken feather barb were carbon monoxide, carbon dioxide, methane, hydrogen cyanide, hydrogen, hydrogen sulphide, ammonia, ethylene, ethane, propylene, propane, butane, butane, methanol, ethanol, acetone, acetic acid, methyl, ethyl, ketone, acetylene-hydrogen sulphide, methanethiol, toluene, methylfuran, styrene, dimethylfuran, benzene, pyrrole, acetaldehyde, acetonitrile, naphthalene, phenol, indole, p-cresol, and skatole. The major peaks (pyrrole, pyridine, pyrazine, 2-pyrrolidone, toluene, phenol, pyrazole, three methylindole, linear amide, 2-ethyl-4-methylimidazole, indole, p-cresol and skatole) are related to the aromatic amino acid residue in chicken feather barb. The pyrogram of chicken feather barb indicates the Py-GC/MS properties of the chicken feather is identical to wool fibre.

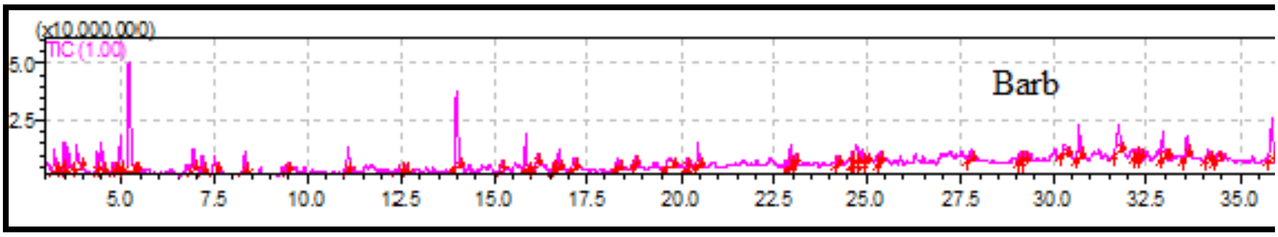


Figure 5.2.18. Py-GC/MS pyrogram of the chicken feather barbs

Mechanical Properties: - The mean tensile properties of chicken feather barbs are shown in Table 5.2.6. The chicken feather barbs are extremely fine and break under small stresses. The mean values of Young's modulus and stress at break were very similar to those previously reported for duck and goose down (Bonser and Dawson, 1999; Bonser and Farrent 2001). As seen from Table 5.2.6, the tensile properties of chicken feather barbs indicate that barbs have strength characteristics similar to those of other natural fibres routinely processed on textile machines - therefore, chicken feather barbs are natural fibres that are suitable for processing in textile applications. However, the elongation of the chicken feather barbs is lower than that of wool and hair fibres. This is due to the arrangement of proteins in the fibres: the post-yield region that correlates with straightening of α-helices in wool and hair is much larger (Jachowicz, 1987) than that of avian keratins that cannot unravel and elongate under stress because the proteins are essentially fully-elongated in their native state (Wortmann and Zahn 1994).

Table 5.2.6. Tensile properties of chicken feather barbs

	Tensile properties				
	Maximum load [cN]	**Tenacity at maximum load [cN/tex]**	**Tensile extension at maximum load [mm]**	**Tensile strain at maximum load [%]**	**Linear density [Tex]**
	820.81	16.93 *CV 18.44*	0.48 *CV 15.67*	18.56	0.39 *CV 16.39*

CV = Coefficient of variation

Linear density of barbs: - The diameter dimensions of chicken feather barbs show that they have similar linear density compared to wool fibre – hence determination of the linear density of barb is very complicated. Nevertheless, the measurements were done and the results show that the linear density of a chicken feather barb is about 0.39 Tex. The coefficient of variation of the linear density was 16.39 %, and this low variation indicates that the sample was naturally homogeneous. Potential applications for this type of linear density may be in composites for applications in diverse areas such as automotive, aerospace, geotextile, decorative, and even textile industries (e.g., fabrics blended with wool or cotton).

5.2.4. Potential valorisation of chicken feather barbs in yarn production and manufacture of technical textile

The results on physicochemical characterisation chicken feathers barb imply that they could be used in textile industry for the production of yarn, diaper production, apparel, geotextile, filters, upholstery, mat, nonwoven fabric, technical composite materials for construction industries, automotive interiors, light weight ships, aeroplane industries, and can be used as a filler material for winter clothing (Figure 5.2.19) (Tesfaye et al., 2017).

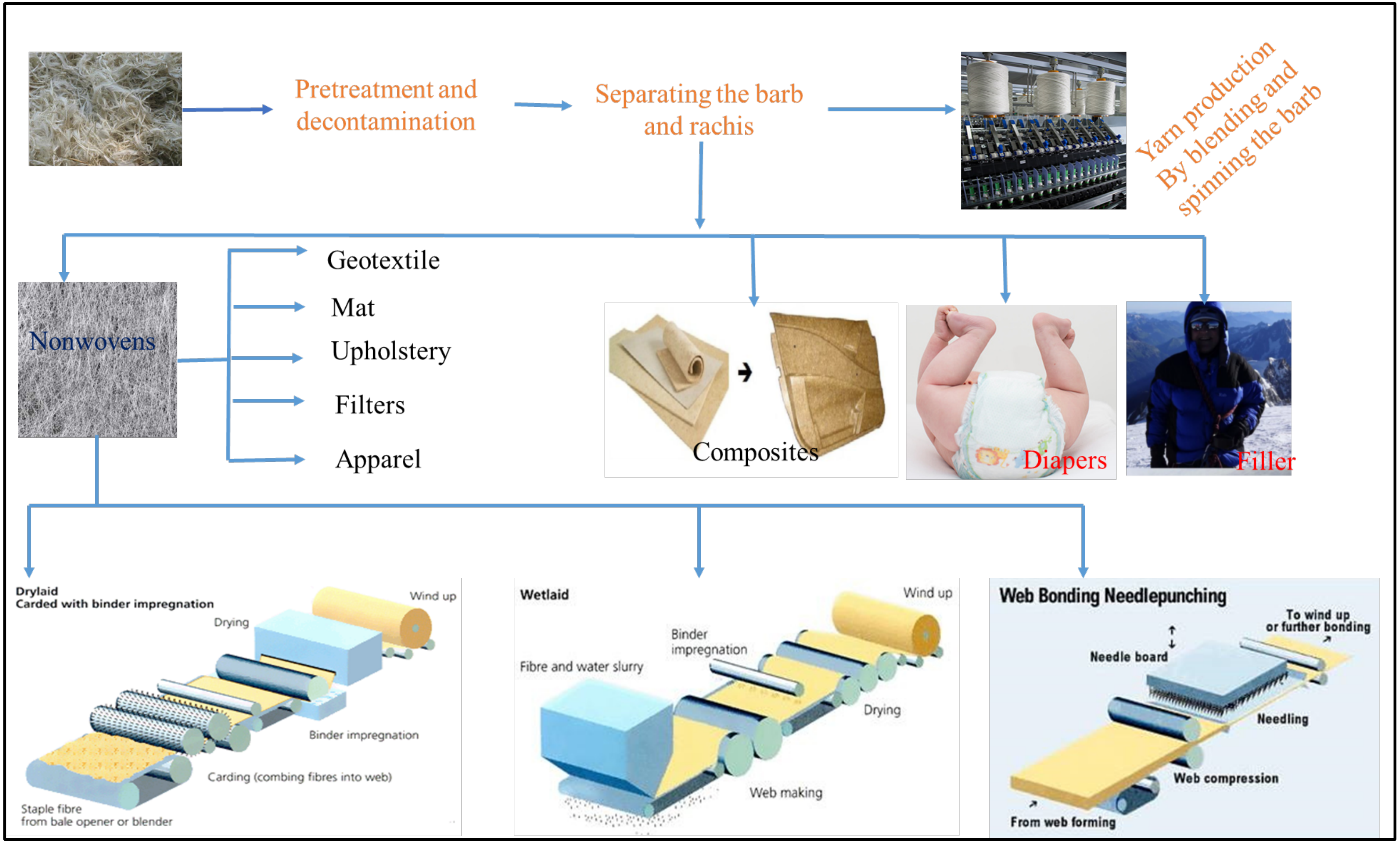


Figure 5.2.19. Possible valorisation in yarn production and manufacture of technical textiles

5.2.5. Conclusions

The chemical functional groups, physical properties, thermal stability, chemical properties, microstructure, and the mechanical properties of chicken feather barb were determined with the target to consider this fibre as a possible yarn production and technical textile raw material. The structure and properties of chicken feather barb are similar to the two most common natural proteinous fibres, viz., wool and silk. The unique properties of chicken feather barbs such as low density, high slenderness ratio, good pliability, moderate strength, spinnability, fineness and length, durability, and high moisture regain provide unique properties that make barbs suitable for use in textile applications. Blending the low-density barbs with other natural fibres (such as wool, silk and cotton) offers potential to develop textiles with unique properties. The proper utilisation of feather barb opens research possibilities to understand the behaviour and contribution of barbs to the processability and properties of various products. Processing of waste chicken feathers by using their barbs in the manufacture of textile products offers an environmentally sustainable way of beneficiation of this organic waste material.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the DST/NRF South African Research Chairs Initiative (SARChI), the Biorefinery Industry Development Facility at the CSIR, the Ethiopian Institute of Textile and Fashion Technology at Bahir Dar University, and the Department of Science and Technology, Waste Research Development and Innovation Roadmap Implementation Unit for support of this research.

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5.3. VALORISATION OF CHICKEN FEATHERS: APPLICATION IN PAPER PRODUCTION

(BASED ON PAPER EIGHT)

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ABSTRACT

Reducing waste materials through reuse has in the recent past contributed to sustainable manufacturing in many industries. With the development of large-scale poultry farming, the treatment of large amounts of chicken feathers has become a problem and threatened its use as a renewable resource. This paper examines the use of chicken feathers in the paper making process; a process which would traditionally use wood as the raw material. The effects of combining feather fibre and wood pulp on paper performance were studied and compared to the properties of handsheets made with 100 % wood pulp. With the increase of feather content, properties such as tightness, tensile index and bursting index decreased, whilst air permeability improved. There was no significant difference in water absorbency between various chicken feather/wood pulp handsheet samples however, the water absorbency started to decrease above 80 % of chicken feather content. This could potentially open up a new avenue for the use of chicken feathers in applications that are meant to tolerate high humidity conditions, e.g., packaging products.

Keywords: *Feather; wood pulp; handsheet; sustainable*

5.3.1. Introduction

Paper is an integral part of everyday life, even with the advent of the digital age (The Paper Story, 2016; Eric and Ariane, 2014). An estimated 95 % of all business information is stored on paper and 500×10^6 newspapers are printed and read around the world every day (Fibre Processing and Manufacturing Sector Education and Training Authority, 2014). South Africa is ranked the 15th largest producer of pulp in the world and 24th in paper production (Fibre Processing and Manufacturing Sector Education and Training Authority, 2014). In 2013, the paper industry added \$1.36×10^9 to South Africa's economy – this equates to 0.6 % of the country's gross domestic product (The Paper Story, 2016). The industry now produces more than 2.5×10^6 tonnes of product each year, i.e., ca. 1 % of international capacity. In terms of land use, the afforested area used in paper production is ca. 1.27×10^6 ha or about 1 % of the total South African land area – 122.3×10^6 ha (Pogue et al., 2008). In the South African context, per capita consumption of paper products is 46 kg per annum, which approximates to the international average (Macdonald, 2004; The Paper Story, 2016). The pulp and paper industry generates income greater than \$200×10^9 per annum (Pogue et al., 2008).

Worldwide, more than 90 % of total production of fibre for paper production come from wood (Eric and Ariane, 2014; Sridach, 2010; Mohd, 2014). Insufficient planted trees and huge environmental issues due to deforestation are the major constraints to growth faced by the sector. Due to the awareness of sustainability, the environmental problems have brought forward the need for cleaner technologies where new non-wood resources have to be introduced (Mohd, 2014). Cleaner production technologies should be applied to achieve increased production with minimum effect on the environment. The abundance of non-wood fibres may be considered as the best and more profitable alternative in the paper-based industry (Gonzalo et al., 2017; Sridach, 2010; Mohd, 2014). Studies have shown that sugarcane bagasse, hemp, bamboo, flax (Sridach, 2010), Tunisian alfa (Marrakchi et al., 2011), wheat straw (Jiménez et al., 2002), grass, giant reed (Shatalov and Pereira, 2006), tobacco (Shakhes et al., 2011), canola straw (Hosseinpour et al., 2010), vine (Mansouri et al., 2012), rags, cotton linters and other textile wastes (Paterson et al., 2003; Sczostak, 2009; Mohd, 2014) can partially substitute wood pulp in paper production.

Chicken feathers are considered as waste material from the poultry industry; however, they are a sustainable and renewable source of proteinaceous fibres. In South Africa, there are approximately 258×10^6 kg of chicken feathers produced per annum (DAFF, 2014) with the majority being considered as waste for disposal. Small amounts are often processed into valuable products such as feather meal and fertilisers (Veerabadran et al., 2012; Stingone and Wing, 2011). The remaining waste is disposed of through incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases (Tronina and Bubel, 2008). Are there better ways to beneficiate these wastes?

Studies have shown that waste chicken feathers can be beneficiated in, e.g., textile applications (Reddy and Yang, 2005; Paul et al., 2014; Reddy et al., 2014); composite building applications (Winandy et al., 2003; Jeffrey, 2006); biobased plastic resins (Roh et al., 2012); removal of heavy metals from wastewater (Al-Asheh and Banat, 2003); fibre and fibre products (Gassner et al., 1998; Bartels, 2003). However, very little work has been done on beneficiation of waste chicken feathers for partial or full replacement of wood fibres in the paper industry. The only known report is a patent by Gassner whereby fibre and fibre products were made from chicken feathers and used as a binder or filler in paper products (Gassner et al., 1998). No other reports have been written on application of feathers in the paper industry. This paper discusses the potential utilisation of waste chicken feathers in the manufacture of paper: handsheets made from chicken feather and wood pulp mixtures were prepared and then characterised to ascertain their papermaking qualities. The data from this paper provides new knowledge into possible valorisation of chicken feathers for use in paper manufacturing.

5.3.2. Materials and methods

5.3.2.1. Materials

Feathers: Chicken feathers were obtained from a slaughterhouse in the province of KwaZulu-Natal, South Africa.

Cleaning agent: Sodium dodecyl sulphate (SDS) 99.0 % was purchased from Sigma-Aldrich.

Pulp: A fully bleached sulphite pulp was produced from a Eucalyptus species via the acid bisulphite pulping process.

5.3.2.2. Methods

Pre-treatment of chicken feathers

Freshly plucked wet untreated chicken feathers were purified by washing with a 1 g/L aqueous solutions of SDS. Untreated waste chicken feathers (10 g) feather samples were placed in a beaker to which was added the SDS solution at a liquid to solid ratio of 40:1.

The sample was agitated at 500 rpm using a magnetic stirrer with the beaker on a hot plate maintained at 50 °C for 30 min. The treated feathers were further purified by rinsing in distilled water for 10 minutes and then laid on aluminium foil and dried to a constant mass at 100 °C in an air-forced dryer. Thereafter the sample was placed in plastic bag that was sealed and then stored in a controlled laboratory environment (20 °C, 65 % relative humidity). The treated feathers were subsequently milled to 350 µm size using a heavy-duty milling machine before use. Ten replicate samples were processed in this manner.

Preparation of handsheets

Suspensions of feather and pulp mixtures were prepared in 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100 ratios and defibrillated in a disintegrator (Disintegrator MK.III C, Messmer Instruments Limited, UK) (5 min and 5000 revolutions) containing 1000 mL of water. Once defibrillated, 9000 mL water was then added to bring the volume to 10,000 mL of chicken feather/pulp suspension that was then mixed by sparging with compressed air in a stock divider (NG Brown and Associates, Melbourne, Australia). Each handsheet was made using 1000 mL of suspension to obtain ten handsheets per mixture, except for the samples containing 100 and 90 % chicken feathers handsheets where 2000 mL/handsheet was used due to the low wood fibre content. The handsheets were made on a Rapid-Kothen Blattbildner sheet former (PTI laboratory equipment, Vorchdrof, Austria). After each handsheet was formed, it was pressed using a sheet press (William Apparatus Co., Watertown, NY). Thereafter all 10 handsheets were pressed in a compression machine for 5 minutes. The samples were then air dried on a hot plate in the handsheet former machine. Figure 5.3.1 shows a schematic of the process flow diagram for handsheet preparations.

Figure 5.3.1. Process flow diagram for chicken feathers/wood pulp handsheet preparation.

5.3.2.3. Characterisation of handsheets

All samples were pre-conditioned and conditioned using Technical Association of the Pulp and Paper Industry/TAPPI standard conditions (23 ^{o}C and 50 % RH) for 24 hours prior to characterisation. Six handsheets were used for each characterisation test.

Canadian Standard Freeness (CSF)

CSF is a measure of the rate at which a dilute pulp suspension may be drained. It is an important parameter for measuring pulp quality. The freeness of the suspension was determined as per TAPPI T 227 om-99 standard method (T 227 om-99, 1999) using L& W BK freeness tester (AB Lorentezen and welter, Stockholm Sweden).

Grammage/Basis weight

The grammage of a handsheet is defined as the mass per unit area in g/m^2. The ISO 536 standard method was used for basis weight determination (ISO 536:2012, 2012). Five handsheets (area of each sheet was 200 cm^2) were weighed on a balance to the closest 0.01 g, and the total mass of the handsheets recorded. Grammage was then calculated from Equation (1):

$$Basis\ weight = \frac{W}{5} \times 27.56 \qquad [1]$$

Air permeability

The air permeability was measured on a Messmer Büchel Roughness & Air Permeance Tester per ISO 5636-5 standard method (ISO 5636-5:2013, 2013). The differential pressure was noted for samples which exhibited air permeance greater than 5000 mL/min limit. The differential pressure relates to the air permeability of a sample.

Morphological structure

The morphological structure of the handsheets was obtained using low-resolution scanning electron microscope (SEM) (conventional SEM and X-ray microanalysis) – ZEISS, LEO 1450).

Tensile strength

The tensile strength index of the handsheets was tested according to ISO 1924-3 (ISO 1924-2:2008, 2008). The testing was done on a tensile testing machine maintaining a constant rate of elongation. The tensile strength was then used to calculate the tensile index given in Equation 2:

$$Tensile\ strength\ index = \frac{Tensile\ strength\ \frac{kN}{m}}{Grammage\ \frac{g}{m^2}} \qquad [2]$$

Bursting strength

The burst index (kPa.m^2/g) of the handsheets was determined with the ISO 2758 (ISO 2758:2014, 2014). The burst index is calculated by Equation 3:

$$Burst\ index = \frac{Bursting\ strength\ kPa}{Grammage\ \frac{g}{m^2}} \qquad [3]$$

Tear resistance index

The tear index of the handsheets was measured with the ISO 1974, which are Elmendorf-type methods (ISO 1974:2012, 2012). The apparatus used was the Elmendorf tear tester. The tear index was calculated using Equation 4:

$$Tearing\ resistance\ index = \frac{Tearing\ resistance\ mN}{Grammage\ \frac{g}{m^2}} \qquad [4]$$

Water absorbent capacity

Water absorbent capacity was measured by cutting a 100 cm^2 sample from the handsheet. After preconditioning and conditioning the cut sheet, its dry weight (W_1) was recorded. The sample was soaked in a 500 mL beaker filled containing ca. 100 mL of water for 10 seconds. The sample was then removed from the beaker and allowed to drain for 30 seconds and the wet weight (W_2) recorded. The water absorbance capacity in g/g was determined from Equation (5) (TAPPI T 441 om - 98, 2013):

$$Specific\ absorbent\ capacity = \frac{W_2 - W_1}{W_1} \times 100 \qquad [5]$$

Brightness

The ISO brightness of the handsheet samples were measured using a Zeiss Elrepho 65843 reflectance photometer. In the reflectance photometer, the handsheet samples are illuminated with a C light source CIE illuminant; a daylight illuminant containing a U.V. energy (ISO 2470-1:2009, 2009).

Fourier Transform Infrared Spectroscopy (FTIR) Analysis

FTIR analysis of the handsheets was performed using a Fourier Infrared Spectrometer (ATR-Frontier Universal, PerkinElmer) in the absorbance mode. In each case, the spectrum was obtained at a nominal resolution of 4 scans, and the spectrum region was recorded between 4000 cm^{-1} and 550 cm^{-1}.

5.3.2.4. Statistical analysis

The characterisations of the handsheets were based on a randomised design with six different chicken feathers to wood pulp combinations. Statistical analysis was done using Statistica 13.0 Stat-Ease, Minneapolis, USA and Origin 9.0 (Origin Laboratory Corporation, Northampton, Massachusetts, USA) software. The handsheet made from 100 % wood pulp was designated as a blank handsheet.

5.3.3. Results and discussions

5.3.3.1. Handsheet preparation

Figure 5.3.2 is a visual comparison of the handsheets that were prepared. Each handsheet sample exhibited two-sidedness; a smooth top and a rough bottom side. The 100 % wood pulp handsheet was white in colour, had a rough surface, but did not appear fibrous. It was soft to the touch and easily flexible. With increase in chicken feather content in the handsheet, the uniformity of the handsheet decreased and loose fibres started to appear. The 80/20-100/0 % chicken feather/wood pulp handsheets were soft and fluffy in texture, less brittle and very thick compared to the other handsheets. The fibre content was not uniform and varied in colour from light brown to amber colour; the fibres flaked off easily and appeared fibrous. Bonding among the individual fibres of the handsheets appeared loose and showed facile flaking when the chicken feather content was higher than 60 %.

Figure 5.3.2. Image of chicken feathers/wood pulp hand sheet

5.3.3.2 Canadian Standard Freeness

The CSF of the suspensions decreased from 620 to 330 mL as the chicken feather content increased (Table 5.3.1). This affects the drainage of the suspension negatively. Due to the rigidity of the chicken feather, beating is required to improve the freeness of the suspension. This indicates that the blank handsheet (100% wood fibres) has better fines content, interfibre bonding, and flexibility compared to chicken feather fibres that are rigid (Tesfaye et al., 2017). Further studies, entailing beating and refining conditions are required to optimise the fines content and flexibility of chicken feathers.

5.3.3.3. Basis Weight

An average value for basis weight of five handsheets, done in duplicate, was obtained and used to calculate the mechanical properties of the handsheets. The grammage of the chicken feather/wood pulp handsheet decreased by comparison to the blank handsheet - this may be due to the low density of chicken feather fractions. This suggests that the wall thickness of chicken feather fractions is very high (Tesfaye et al., 2017) thus resulting in a higher specific volume in the handsheets. The increase in bulk was due to a decrease in the relative bonded area of the chicken feather fractions. This suggests that chicken feathers have a bulk forming property.

Table 5.3.1. Properties of chicken feathers and wood pulp handsheets

Feather wood pulp ratio	Freeness (mL)	Basis weight (gsm)	Air permeability (mL/min)	Tensile strength (kN/m)	Bursting strength (kPa)	Tear strength (mN)
0/100	620	65	3893	0.72	40.8	130.0
20/80	600	62	>5000	0.46	41.3	98.2
40/60	610	95.7	>5000	0.44	41.4	105.0
60/40	420	95.7	>5000	0.20	41.5	45.9
80/20	410	121	>5000	0.12	41.6	36.8
100/0	330	231	>5000	0.21	42.7	73.3

5.3.3.4. Air permeability

The air permeability values of all chicken feather containing handsheets were similar (>5000) and dramatically greater than that of the blank handsheet (3893) (Table 5.3.1). This suggests that the chicken feathers are more porous (Tesfaye et al., 2017) than the wood pulp, thereby allowing more air flow through the handsheets. The lower air permeability of the blank handsheet may be due to the strong fibre-to-fibre bonding and hydrogen bonding that result in a reduced void volume in the sheets (Ren et al., 2009). This implies that there is very little fibre-to-fibre bonding among chicken feather fibres.

5.3.3.5. Morphological structure of the handsheets

Figure 5.3.3 shows the SEM images of the blank and chicken feather/wood pulp handsheets. In the blank handsheet, some of the fibres are open and flat; fibre-to-fibre interactions appear high, and in some cases twisted fibre surfaces are visible. These observations support the results presented in Table 5.3.1 where the bulkiness and air permeability properties of the handsheet are reduced whereas the tensile, burst and tear strength properties improved relative to those of the chicken feather/wood pulp handsheets. The SEM images show that as the chicken feather content increases, the sheet becomes more open and its porosity increases whereas the fibre-to-fibre interactions decrease. Ultimately this will improve air permeability and bulkiness of the handsheet, whilst reducing its mechanical properties (Hosseinpour et al., 2010).

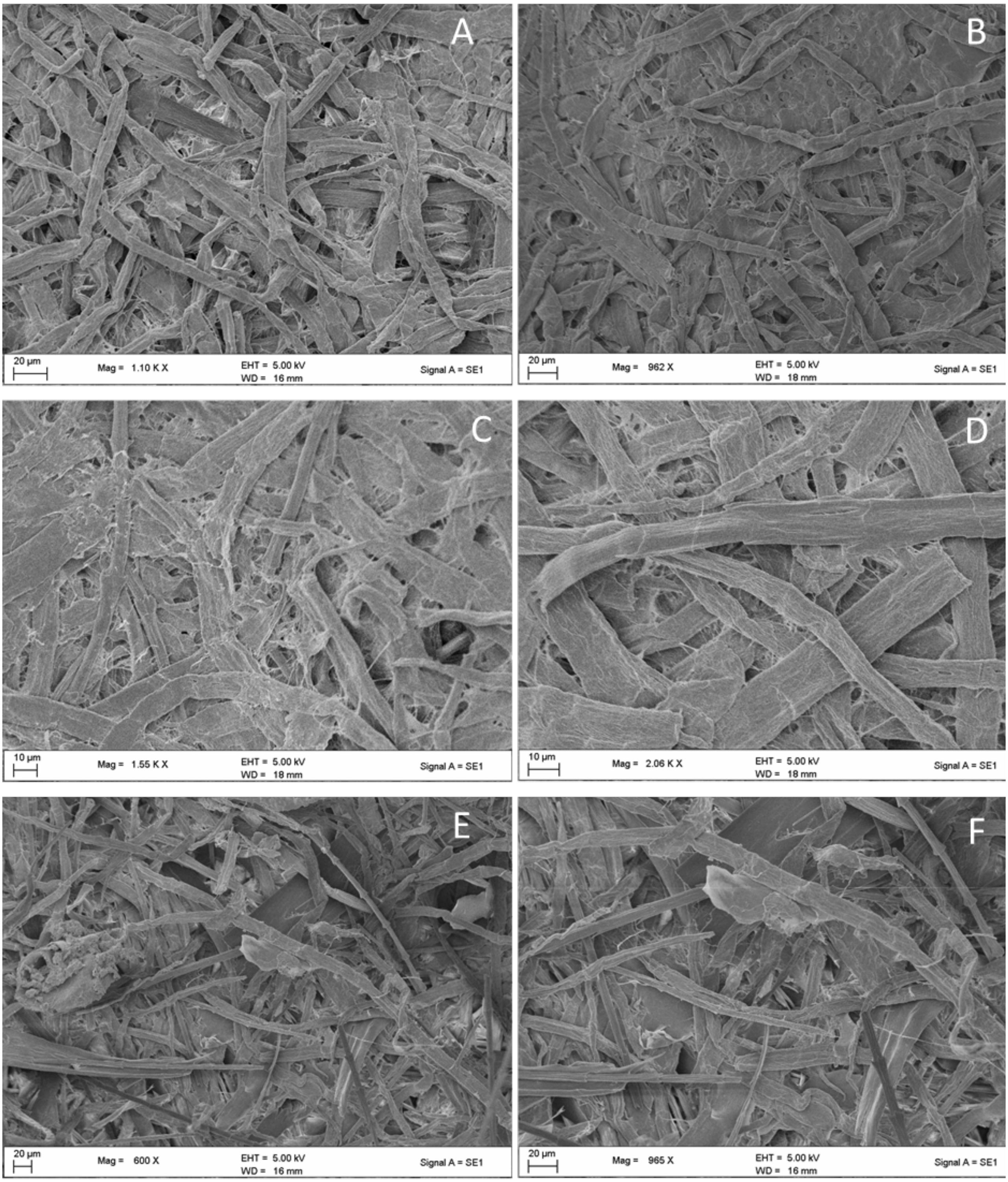

Figure 5.3.3. Images of handsheets with zero beating (A. 100 % Eucalyptus B. 20/80, C. 40/60, D. 60/40, E. 80/20 and F. 100/0 chicken feathers/wood pulp)

5.3.3.6. Tensile testing

Figure 5.3.4 presents the tensile index data of the chicken feather/wood pulp and 100 % wood pulp handsheets. The 100 % wood pulp (blank) handsheet showed a significantly higher tensile strength index (about 11 Nm/g) due to better fibrillation and fibre-to-fibre bonding (Figure 5.3.3). Addition of feathers weakened the handsheets significantly. This could be attributed to less hydrogen bonding energy amongst chicken feathers and wood pulp fibres (Figure 5.3.4). These results support the air permeance results presented Table 5.3.1, i.e., the higher the air permeance, the weaker the handsheet. The fibre-to-fibre bonding of chicken feather/wood pulp and 100 % chicken feather handsheet appear low (about 1%) (Figure 5.3.3). This results in reduction of the tensile properties of the handsheet. The tensile energy absorption (TEA) of wood pulp/chicken feather handsheets decreased significantly with increase in chicken feather content (Figure 5.3.4) however beyond 80 % chicken feather fraction TEA increased due to the uniformity of the handsheet/no weak fibre to fibre interaction will occur because of its similar nature of the fibre. The TEA of chicken feather/wood pulp handsheets decreases (8-44 %) as the chicken feather content increases (Figure 5.3.4). This indicates that the energy required to rupture the chicken feather/wood pulp handsheet is lower than that required to rupture the blank handsheet.

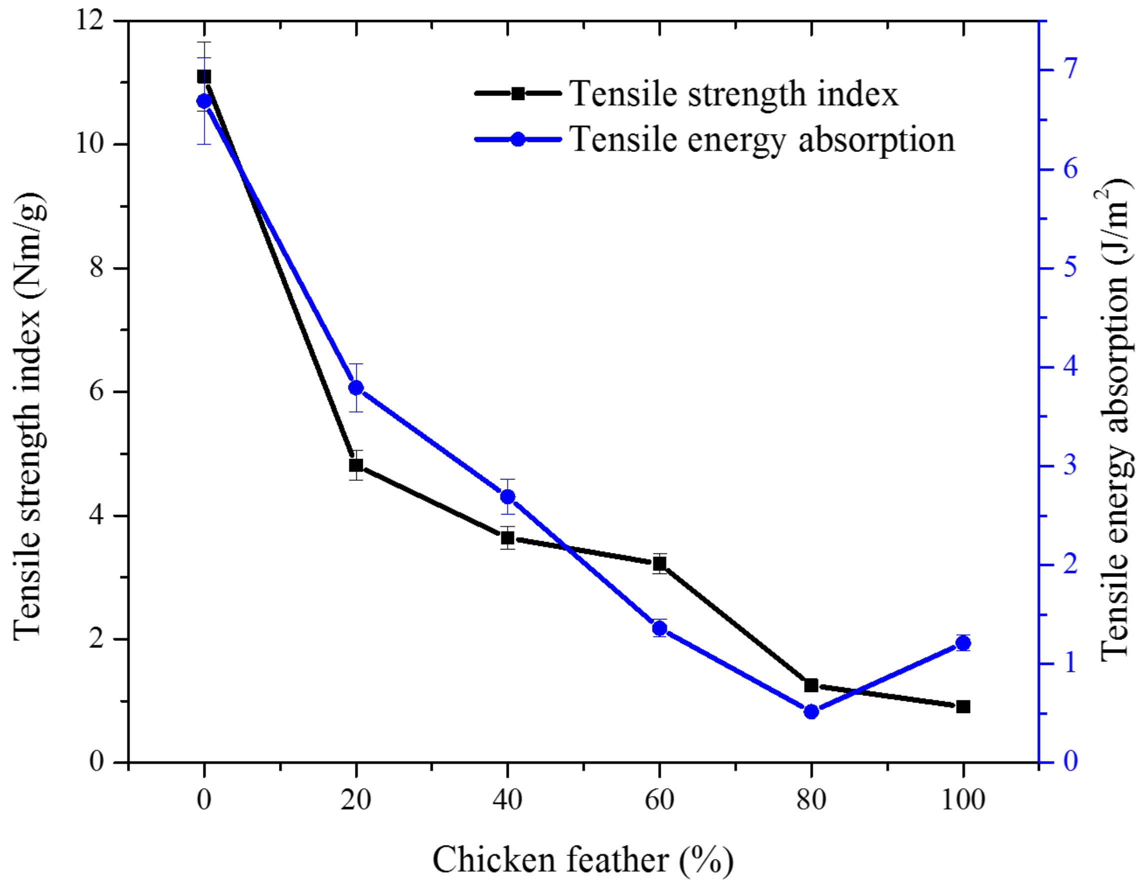

Figure 5.3.4. Chicken feather/wood pulp handsheet tensile strength index and TEA

The breaking length of the handsheets decreased with an increase in feather content in the sheets (Figure 5.3.5). This result is in agreement with the tensile properties of the handsheet (Figure 5.3.4), as the breaking length is used to characterise the inherent strength of the handsheet. Further studies are required to improve the breaking length and the tensile properties of the chicken feather/wood pulp handsheets. The weak spots and defects of the handsheets could be minimised by using different feather pulp preparation techniques. High elongation to break together with low bending stiffness is indicative of the ability of paper to conform to the desired contour and therefore is important for creped papers, towels, and bagging. The percentage elongation of a handsheet at the instant of failure is called stretch. The stretch values for all samples are below 2 %, with no significant difference among them (Figure 5.3.5). This type of handsheet is typically considered a rigid paper. Handsheet breaking length increased linearly with increasing sheet density and this agrees with a study that chicken feather fibres are less dense than any other fibre (Tesfaye et al., 2017). Handsheet stretch values, on the other hand, decreased by 15 percent (Table 5.3.1, Figure 5.3.5). The higher error value at 80 % chicken feather content could be due to high variation of the chicken feather properties (Tesfaye et al., 2017) and nonuniform fibre distribution in the sampling position due to the difference in fibre properties like density, fibre cohesion force and others. In general, the greater the stretch and breaking length, the better will be the papermaking qualities of the handsheet.

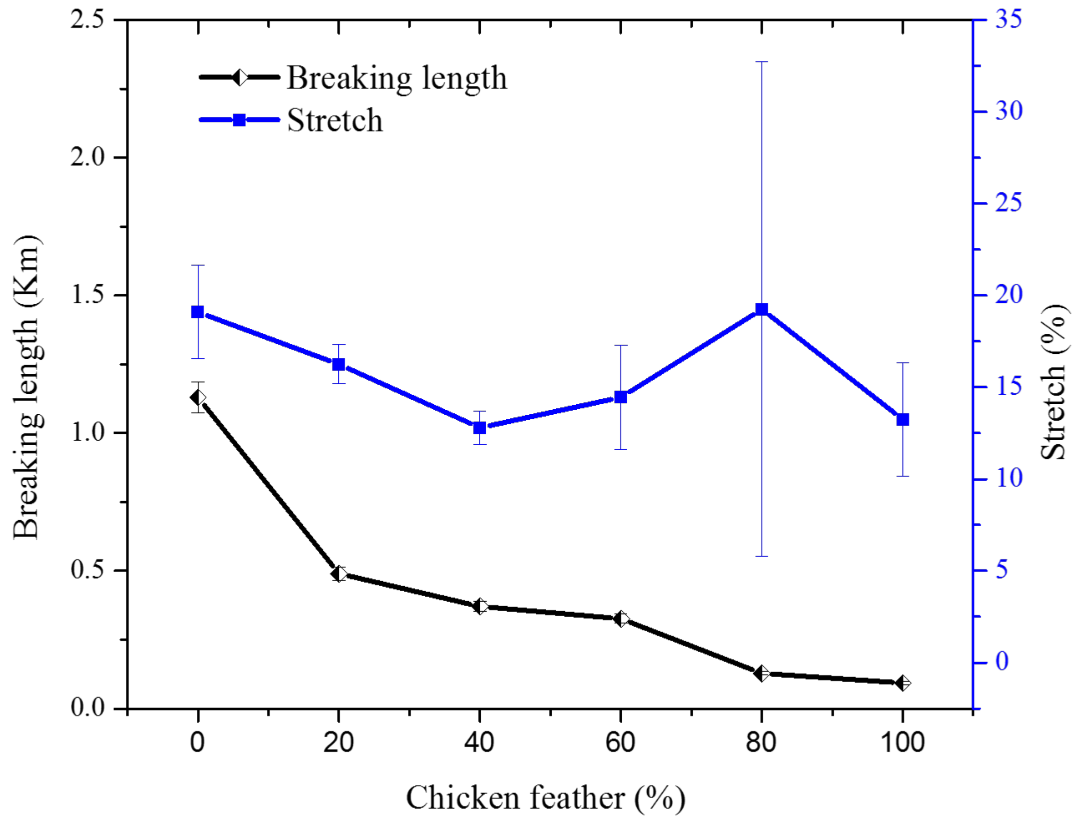

Figure 5.3.5. Breaking strength and stretch properties of the handsheets

5.3.3.7. Bursting strength

Figure 5.3.6 shows the bursting strength data of the handsheets. The bursting strength decreased with increasing chicken feather content in the handsheet. This indicates that the bursting and tensile strength exhibit similar trends since they both depend on fibre-to-fibre bonding. However, the bursting strength starts increasing at 40 % chicken feather content and reaches its highest value (about 2 $kPam^2/g$) at 60 % chicken feather, and then decreases. This could be due to the higher variability of chicken feather properties and the nonuniformity of the wood and chicken feather distribution in the handsheet.

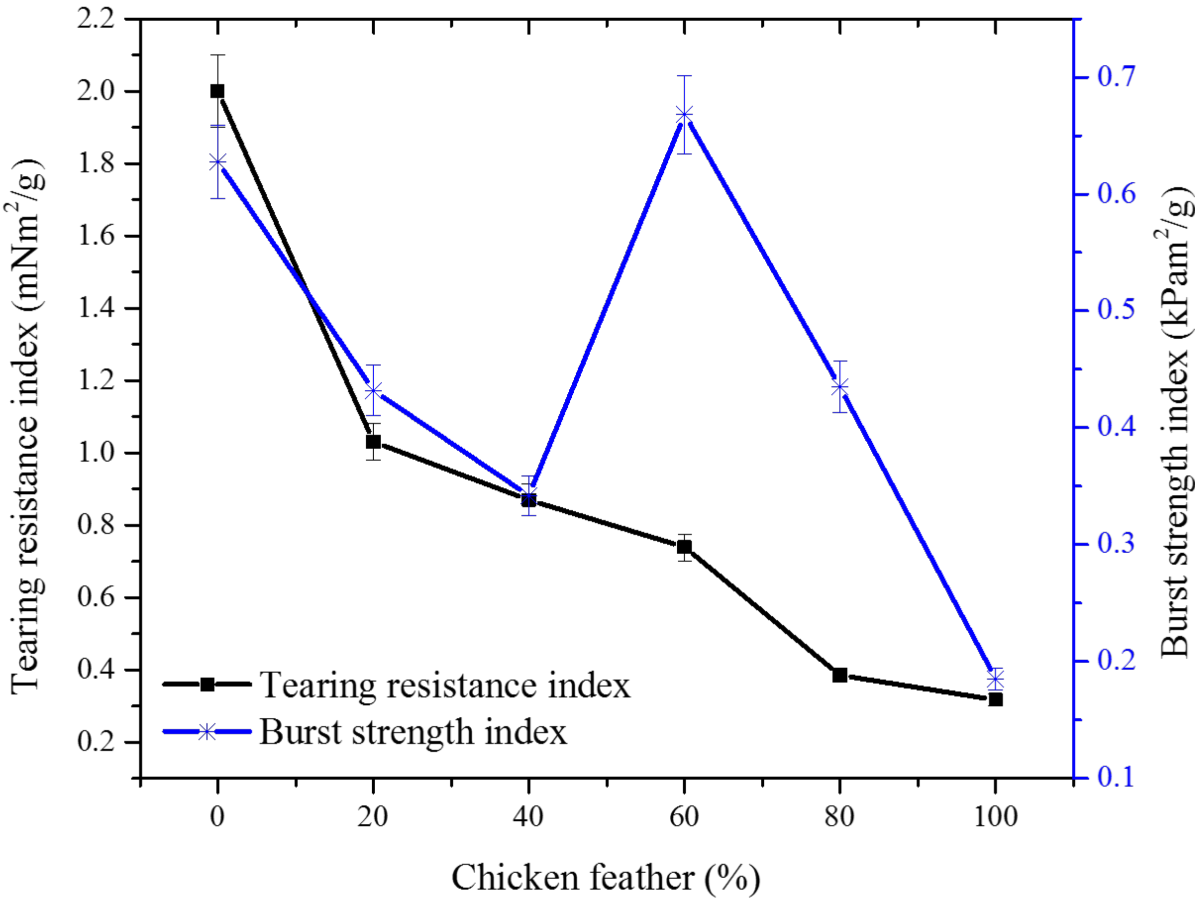

Figure 5.3.6. Chicken feather/wood pulp handsheet burst and tear strength index

5.3.3.8. Tear index

Tear resistance index depends on flexibility of the handsheet, fibre length, fibre bonding and the total number of fibres (Hosseinpour et al., 2010). The force required to tear paper is much less than the force necessary to break a strip of the paper. Tearing resistance depends strongly on the fibre length since more fibres are pulled out than broken along the length of the fibres in a weakly bonded sheet (Jiménez et al., 2002). The 100 % wood pulp hand sheet shows high fibre bonding (SEM image in Figure 5.3.3). This results in a high tear strength (about 2 mNm^2/g) (Figure 5.3.6) and can be considered as a flexible sheet. The flexibility of the sheet is determined by the number of fibres participating in the rupture. The 100 % chicken feather handsheet exhibited the lowest tear strength index and can be considered as a rigid sheet (about 0.4 mNm^2/g). The force in the rigid sheet will be concentrated on a few fibres. As the chicken feather content in the handsheet increases, the number of fibres, fibre-fibre bonding and the flexibility of handsheet are reduced and the fibre rupture requires less energy, hence the tear strength is reduced.

5.3.3.9. Water absorbent capacity

Figure 5.3.7 shows the water absorbance capacity of the handsheets. Chicken feathers are protein-based animal fibres that show both hydrophobic and hydrophilic tendencies (Tesfaye et al., 2017). The water absorbency capacity of the handsheet decreases as the chicken feather content increases. The reduction in the water retention capacity of the handsheet may be due to the hydrophobic nature of the chicken feather. The water absorbance for the 100 % chicken feather sheet decreased approximately 25 % when compared to that of the 100 % wood pulp sample (Figure 5.3.7). These results will restrict the end use of chicken feather containing papers only for applications that require low water absorbance, e.g., packaging papers.

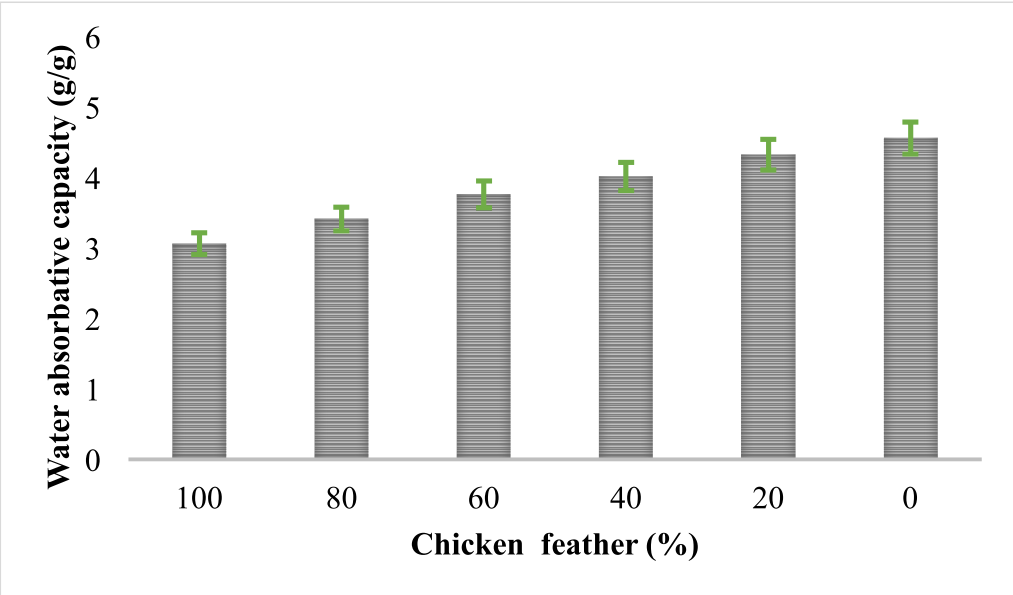

Figure 5.3.7. Water absorbance capacity of chicken feather/wood pulp handsheets.

3.10. Brightness

The ISO brightness values of the handsheet indicated that incorporation of chicken feathers lowered the brightness (Figure 5.3.8). There was a significant difference of about 30 % between the blank wood pulp handsheet and the 100 % chicken feather handsheet. To improve the brightness property of the chicken feather handsheets, further studies are needed to evaluate the effect of pre-treatment agents such as sodium dodecyl sulphate and hydrogen peroxide or the addition of optical brightening agents.

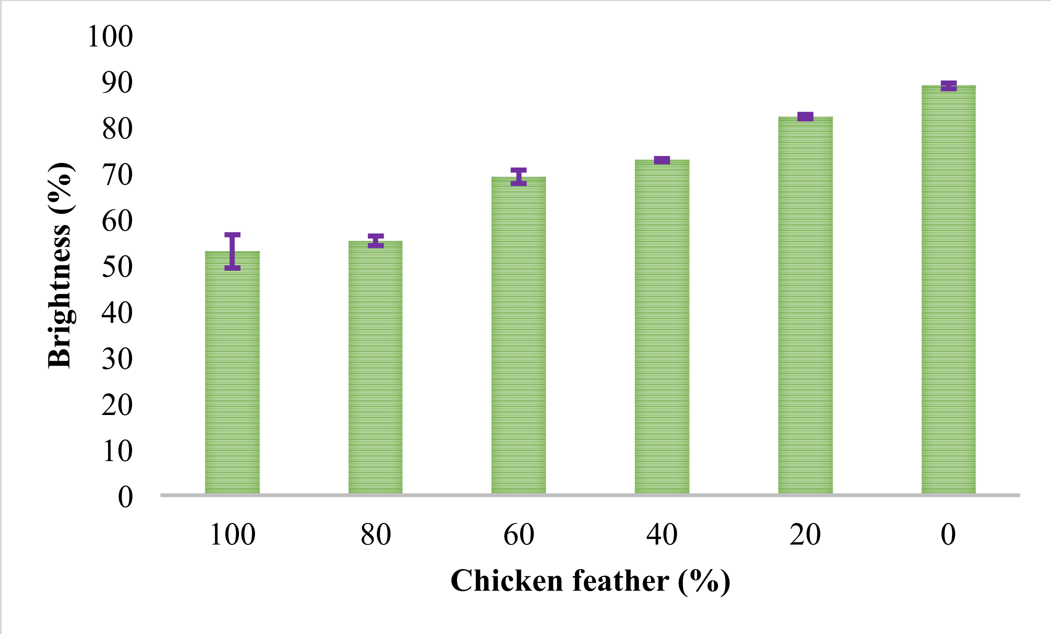

Figure 5.3.8. ISO brightness values of chicken feather/wood pulp handsheets.

5.3.3.11. Fourier Transform Infrared Spectroscopy (FTIR) Analysis

Figure 5.3.9 shows the FTIR spectra of the different handsheets. The 100 % wood pulp handsheet shows major peaks of cellulosic fibres whereas the 100 % chicken feather handsheet shows major peaks of keratin/proteinaceous fibres. The chicken feather/wood pulp handsheets share the properties of both fibres. The presence of S-S (620 cm^{-1}), C-S (1070 and 1075 cm^{-1}) and N-H (1540 cm^{-1}) groups in the handsheet confirmed the presence of chicken feather fibres. Results in Figure 5.3.2 confirmed that there is an increment of hydrogen bonding for the 100 % wood pulp and it decreased as the chicken feather content increased. Hydrogen bonding is a dominant factor contributing to paper strength characteristics. The intensity of the peak at 3200–3600 cm^{-1} is related to the OH vibration: this indicates the numerous hydrogen bonds with the hydroxyl groups of cellulose fibres that result in the higher tensile property of sheets containing wood fibres.

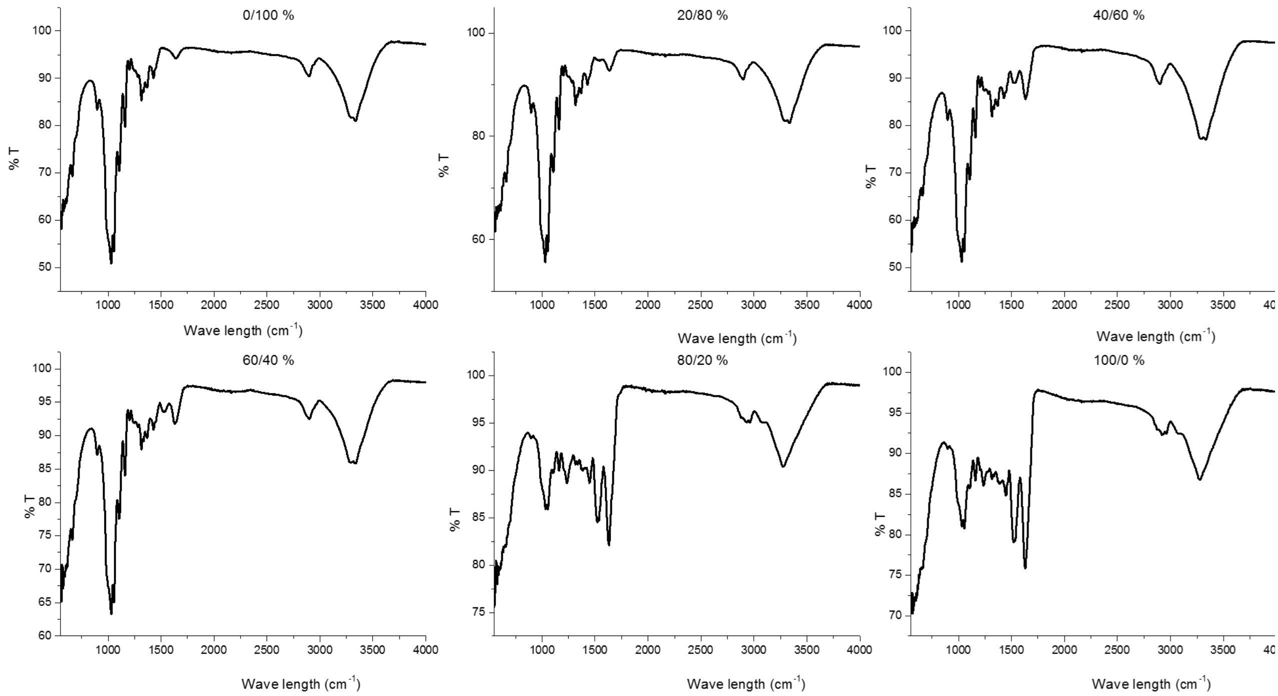

Figure 5.3.9. FTIR spectra of chicken feather/wood pulp handsheets.

5.3.4. Conclusions

From this preliminary study, it is evident that chicken feathers can be incorporated in the paper manufacturing process. The air permeability of chicken feather/wood pulp handsheets was enhanced whereas the bursting strength, tensile index and tear strength were lower than in the 100 % wood pulp handsheet. The results show that it is possible to vary the proportion of the chicken feather fibres up to 100 % for paper manufacturing. There was no significant difference in water absorbency between the various chicken feather/wood pulp handsheet samples; however, the water absorbency started to decrease above 80 % chicken feather content. This could potentially open up a new avenue for the use of chicken feathers in applications that are meant to tolerate high humidity conditions, e.g., packaging products. The paper strength qualities of the handsheets decreased with increase in chicken fibre content. However, the strength properties could be improved by addition of binders. Indeed, chicken feathers can be beneficiated into binders and these can subsequently be used to enhance the strength of papers containing chicken feathers. The performance of chicken feathers in making paper for mainstream applications will be studied further by varying process parameters (e.g., refining conditions, bleaching conditions, beating condition and change in freeness values) to improve performance characteristics of the papers.

ACKNOWLEDGMENTS

The authors are highly grateful for the financial and technical support received from the Thermodynamics Research Unit at, Chemical Engineering at the University of KwaZulu-Natal, the Biorefinery Industry Development Facility, CSIR, and the Department of Science and Technology, Waste Research Development and Innovation Roadmap. Thanks also to Mr. Vishal Bharuth (UKZN) for assisting with the morphological analysis and Mrs. Elsie Sibande (CSIR) for the preparation of the handsheets.

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5.4. VALORISATION OF WASTE CHICKEN FEATHERS AND AVOCADO SEEDS: PREPARATION AND CHARACTERISATION OF GREEN BIOFILMS

(BASED ON PAPER NINE)

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ABSTRACT

Landfill disposal of synthetic plastics poses one of the biggest threats to the environment due to their non-biodegradability. This problem can be solved by production and use of biodegradable polymers instead. Feathers are a renewable, inexpensive, biodegradable, and easily available by-product of the poultry industry. They have long been considered as a solid waste that poses a serious environmental and economic problems. Avocado seeds are an organic waste that is also disposed of by landfilling. The aim of this study was to beneficiate these two organic wastes via development of green biofilms prepared from starch and keratin extracted from waste avocado seeds and waste chicken feathers, respectively. The films were then studied for their morphological structure, fine detail structure, crystallisation behaviour, functional group content, moisture content, solubility, tensile properties, moisture regain, and dissolution characteristics. With increase in starch content in the films, the flexibility, solubility, dissolution, moisture regain, and moisture content of the films increases, whereas the tensile strength property decreases. Data on dissolution, water absorption, solubility, moisture content, mechanical properties and morphological structures of the keratin/starch blended films imply that the films could be used in the food packaging industry (as a cost-effective and environmental alternative source of raw material to the commonly used petroleum based materials used in packaging materials; as a raw material in the manufacture of hygiene products, e.g., superabsorbent materials for diaper products; and as a source of raw material for manufacture of biomedical products such as artificial skin products; and in the pharmaceutical industry (e.g., in drug delivery systems).

Keywords: chicken feathers, avocado seeds, keratin, starch, biofilms, beneficiation

5.4.1. Introduction

Plastic packaging are ideal materials for many commercial and industrial activities especially in food packaging where they are used to help keep food fresh and free of contamination. This is due to their lightness, flexibility, stability, strength, impermeability characteristics (Ferreira et al., 2016). The consumption of synthetic polymers to produce plastics is expected to grow four fold (25 % of oil production) in 2100 due to the growing human population and increasing demand for packaging materials (Chocyk et al., 2015). Accumulation of post-consumer waste due to non-biodegradability of plastics is a serious environmental problem of using plastics for packaging that cannot be solved by landfilling (Song et al., 2013). Plastic waste can be incinerated for energy recovery, but this has negative environmental impact due to greenhouse gas emissions during burning of the plastics (Al-Salem et al., 2009; Palmu and Crosso, 2003).

In order to reduce the environmental impact of synthetic polymers partially biodegradable polymers have been prepared from a mixture of synthetic and natural polymers (Chocyk et al., 2015). Recently, increased attention has been focused on replacement of synthetic polymer based films with eco-friendly biobased biodegradable packaging films for applications in food packaging, drug delivery systems, and tissue engineering (Chaosri et al., 2014, Cui et al, 2013; Van Dyke et al., 2001; Yamauchi and Khoda, 1997). Replacement of synthetic plastic packaging by biodegradable polymers from renewable biomass significantly reduces the volume of waste generated (De Carvalho and Grosso, 2004; Sothornvit and Krochta, 2000). Although bio-based plastics have some limitations in terms of their mechanical properties, their thermal resistance and water barrier function characteristics offer very desirable features (Oladayo et al., 2016; Sando et al., 2010; Zhong and Xia, 2008).

Recently it has been reported that 100 % biodegradable packaging materials can be produced from renewable sources such as starch (Chaosri et al., 2014; Chocyk et al, 2015; Zhong and Xia, 2008), proteins, cellulose, and rubber (Fang et al., 2002; Gennadios and Weller, 1991; Lim et al., 1998; Saul et al., 2011; Tanabe et al., 2004; Thonpho and Srihanam, 2016) and lipids (Garcia et al., 2000; Hada et al., 1999; Yang and Paulson, 2000). Keratins are desirable proteins due to their environmental stability, biodegradability, and biocompatibility characteristics. The abundant cysteine amino acids in keratin are oxidised to give inter- and intra-molecular disulphide bonds, and they form a three-dimensional crosslinked network that results in high mechanically strength, hydrophobicity and good thermal stability characteristics (Hill et al., 2010; Jiang et al., 2007; Wang et al., 2004; Rejak et al., 2012; Tonin et al., 2007; Verma et al., 2008). Thus, these qualities could led to development of biodegradable materials from feathers, such as films, sponges, self-assemble structures, hydrogels for compostable packaging products, tissue engineering, fibroblast cell growth, wound healing trauma and drug delivery systems. One of the renewable source of keratin is waste chicken feathers which has about 8.5 % cysteine content (Oladayo et al., 2016). Keratin films are highly ductile and have low flexibility (Zhong and Xia et al., 2008).

Starch is a completely biodegradable semi-crystalline polymer and a supplementary material for most plants (Chaosri et al., 2014; Chocyk et al, 2015; Zhong and Xia, 2008). Waste avocado seeds can be beneficiated as a viable, relatively cheap, and readily available renewable source of starch (Tesfaye et al., 2017).

Although there are some reports on production of keratin-starch films, to the best of our knowledge, there are no reports on production of avocado seed starch cross-linked keratin materials. This work highlights utilisation of biodegradable polymers from renewable resources (starch from waste avocado seeds and keratin from waste chicken feathers) in the production of keratin/starch blended films.

5.4.2. Materials and methods

5.4.2.1. Materials

Chemicals: Urea, Calcium hydroxide, sodium dodecyl sulphate (SDS), and hydrochloric acid were purchased from Sigma Aldric, South Africa.

Feathers: Chicken feathers were obtained from Rainbow Chickens Limited, a slaughterhouse in the province of KwaZulu-Natal, Durban, South Africa.

Avocado seeds: The seeds of avocado fruit were collected from Durban, South Africa.

5.4.2.2. Methods

Starch extraction from waste avocado seeds: -

Figure 5.4.1 is a schematic of the process flow diagram for the extraction of starch from waste avocado seeds. Waste avocado seeds were washed with tap water and ground to a fine powder that was then steeped at room temperature in a sodium sulphite solution and blended using a heavy-duty blender. The homogenate mixture was then sieved using a 20 µm nylon mesh and washed with deionised water. The mixture was allowed to settle, the supernatant was discarded, and the crude extracted starch was washed repeatedly with tap water until the wash water was clear. The filter cake was then dried at 50 °C for 24 hrs and stored at room temperature.

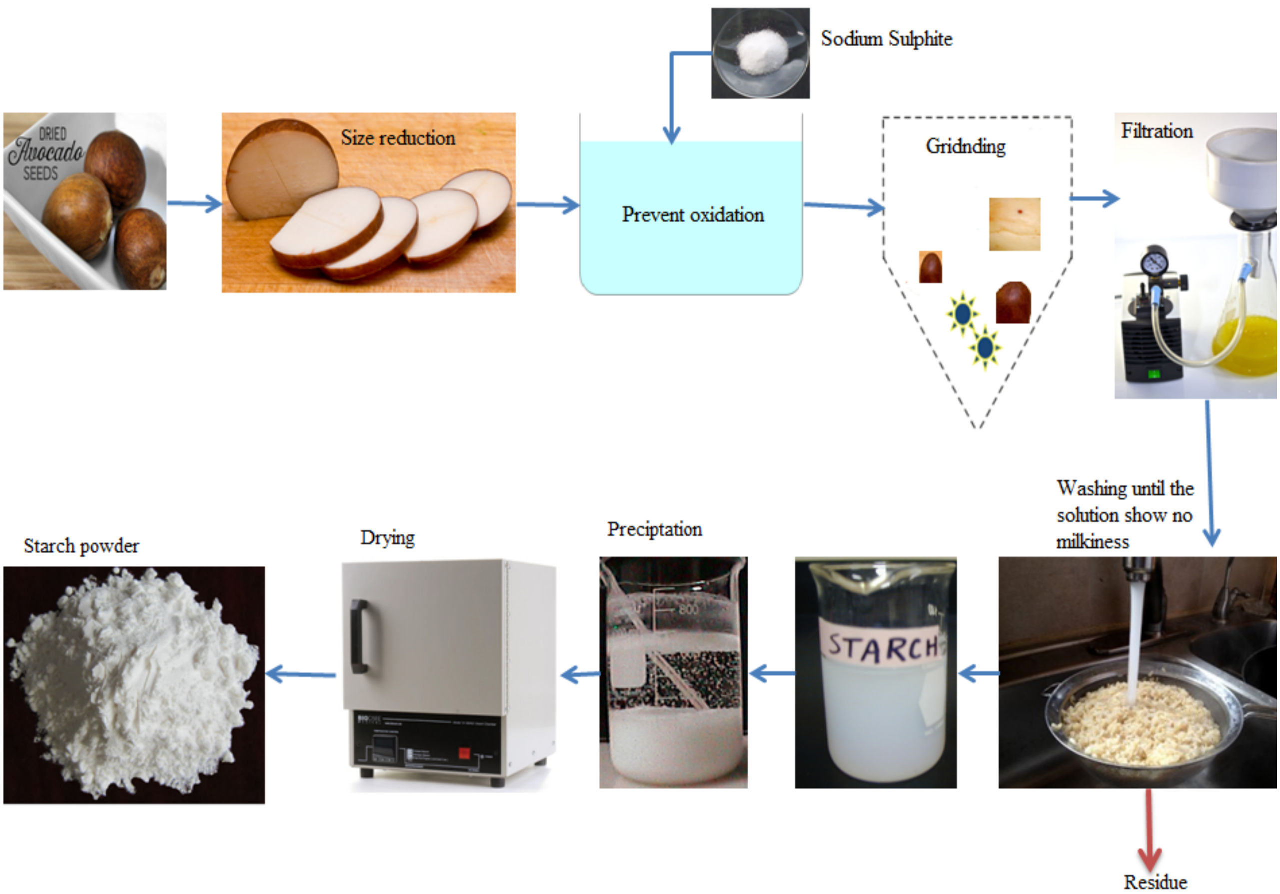

Figure 5.4.1. Process flow diagram for the starch extraction from waste avocado seeds.

Pre-treatment of chicken feathers

Figure 5.4.2 represents the process flow diagram for decontamination and pre-treatment of waste chicken feathers. Freshly plucked wet untreated chicken feathers were purified by washing with a 1 % of the weight of the chicken feathers SDS to remove the grease, other wastes and kill potential harmful pathogens. Untreated waste chicken feathers (10 g) feather samples were placed in a beaker to which was added the SDS solution at a liquid to solid ratio of 40:1. The sample was agitated at 500 rpm using a magnetic stirrer with the beaker on a hot plate maintained at 50 °C for 30 min. The treated feathers were further purified by rinsing in distilled water for 10 minutes and then laid on aluminium foil and dried to a constant mass at 100 °C in an air-forced dryer. Thereafter the sample was placed in plastic bag that was sealed and then stored in a controlled laboratory environment (20 °C, 65 % relative humidity). The decontaminated and treated feathers were then pulverised to 350 µm size using a heavy-duty milling machine before use to increase surface area.

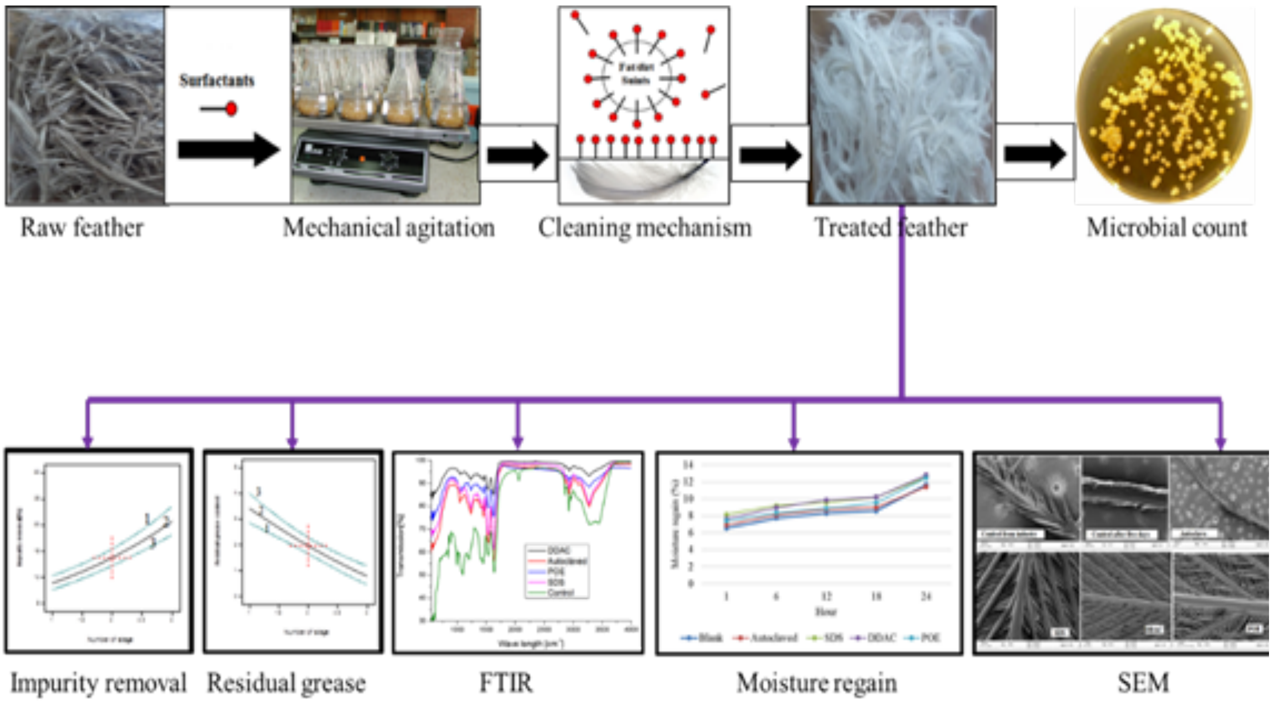

Figure 5.4.2. Process flow diagram for the decontamination and pre-treatment of waste chicken feathers.

Keratin extraction from chicken feathers

The extraction of keratin from feathers is illustrated in the schematic in Figure 5.4.3. In summary:

- Prepare an aqueous solution of 0.5 M $Ca(OH)_2$, 8 M urea, and 10 % wt of the feather SDS
- Add 10 g of chicken feather powder to 250 ml of the solution

- Extract keratin by heating the mixture at 70 °C for 30 min with constant stirring
- Filter the solution on 50 μm nylon mesh
- Adjust pH to neutral using 1 mol/L HCl acid solution
- Desalinate the mixture by dialysis with dialysis cellulose tubes (MWCO 6000-8000 Da) immersed in distilled water (changed 3 times a day) at room temperature for three days
- Freeze-dry the sample to obtain dried keratin
- Store keratin powder at 4 °C until ready for use

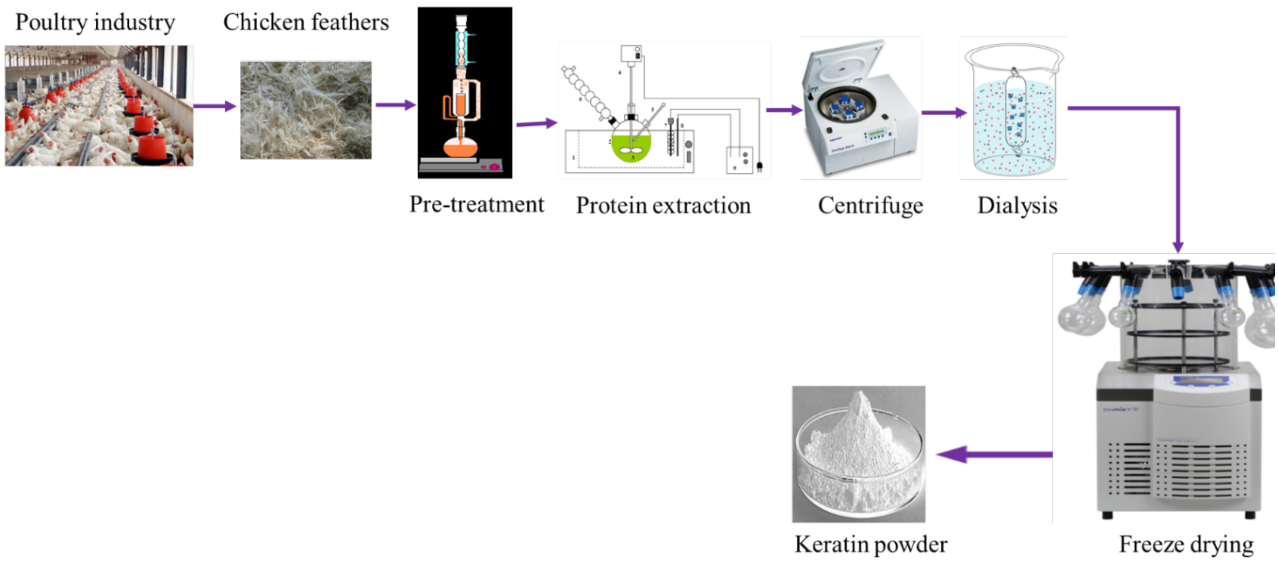

Figure 5.4.3. Process flow diagram for extraction of keratin extraction from chicken feathers.

Preparation of starch-keratin blended films

A process flow diagram for preparation of keratin/starch blend films is depicted in Figure 5.4.4. An aqueous starch solution was prepared by adding 5 g starch powder to 100 g deionized water (5 % v/w) under constant stirring, with a magnet, at 70 °C for 30 min. A 7 g sample of keratin powder was added to 100 ml of 0.1 M NaOH and then heated at 70 °C for 15 minutes with constant stirring with a magnetic bar. Then, various ratios of keratin/starch solutions and glycerol were mixed as shown in Table 5.4.1 below. Glycerol is a common plasticiser used in the preparation of bioplastic films. The mixtures were heated at 70 °C for 10 min with continuous magnetic stirring to prepare keratin/starch blend dispersions.

Table 5.4.1. Proportion of starch and keratin

Ratios of keratin/starch solutions	Glycerol (% solids, w/w)
10:90	40
30:70	40
50:50	40
70:30	40
90:10	40

The dispersions were sonicated for 5 min to remove bubbles to form homogenous dispersions that were poured into glass petri dishes (15 cm diameter) and dried in a vacuum oven at 60 ^{o}C for 24 h. After drying, the films were peeled from the petri dishes and conditioned at a relative humidity of 65±2 % and a temperature of 20±2 ^{o}C for 24 hours before analysis.

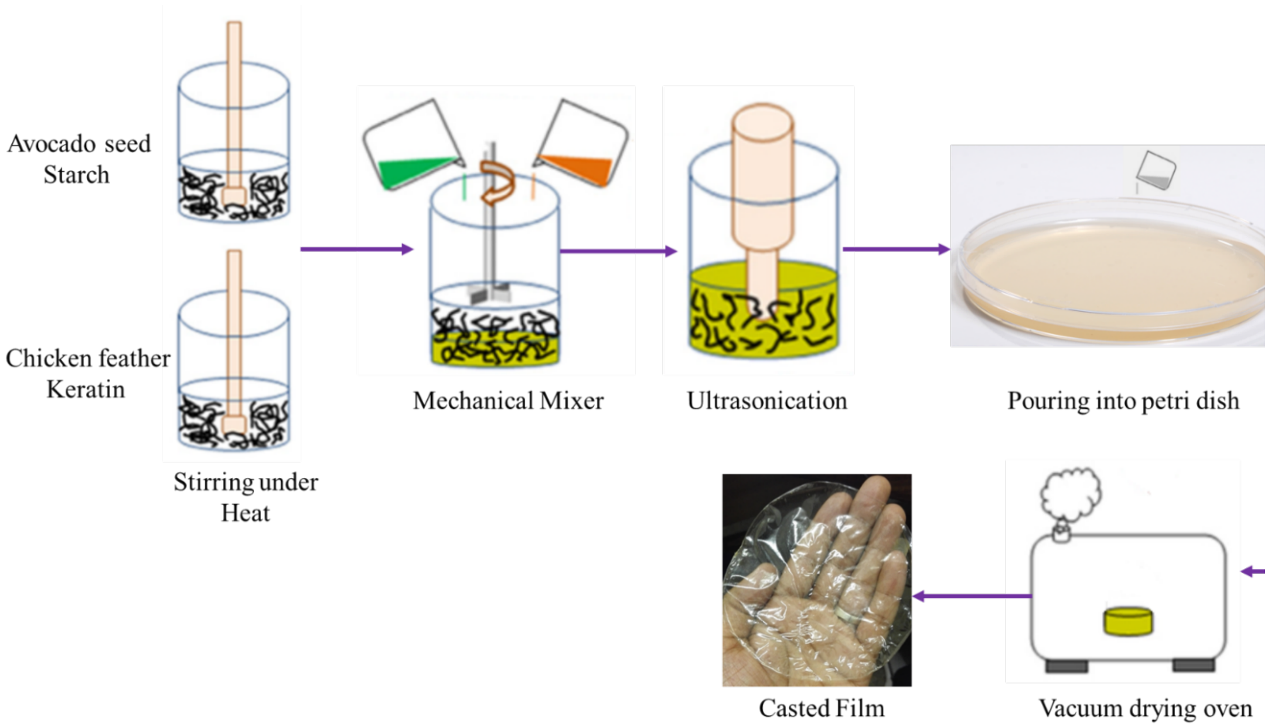

Figure 5.4.4. Process flow diagram for preparation of keratin/starch film productions.

FTIR spectroscopy

The functional groups present keratin/starch blend films were recorded using FTIR in the attenuated reflectance mode (Frontier Universal, PerkinElmer) and recoreded at a resolution of 4 cm^{-1} in the wave number range of 600 to 4000 cm^{-1} and each spectrum contained an average of 4 scans.

Morphological and fine detail analysis

The morphological structure of keratin/starch blend films were examined by scanning electron microscopy (SEM) at an acceleration voltage of 20 kV using a Carl Zeiss instrument (Oberkochen, Germany). Atomic Force Microscopy with a Solver P47H base with a SMENA head (NT-MDT) was also conducted to characterise the fine detail structure and roughness of the films.

X-ray diffraction (XRD)

X-ray diffraction/XRD analyses of keratin/starch blend films were performed using a multipurpose X-ray diffractometer (Bruker D8 Discover model diffractometer Bruker South Africa, Johannesburg), equipped with a diffracted beam monochromator, and a copper target X-ray tube operated at 40 kV and 30 mA. Crystallinity of the films was calculated using the empirical equation (Das, and Ramaswamy, 2006):

$$Crystallinity\ index = \frac{Maximum\ crystal\ latice\ diffraction\ with\ 2\theta\ at\ around\ 9°}{Minimum\ diffraction\ intensity\ with\ 2\theta\ at\ around\ 14°} \quad [1]$$

Solubility of films

Three circular films (2 cm diameter) from each keratin/starch blend films were dried at 105 ^{o}C for 24 hr and initial dry mass of each film was determined (W_1) after cooling for 10 min. The films were then immersed in 50 ml of deionised water and agitated periodically for 24 hr at room temperature after which undissolved portions of the films were removed and dried at 105 ^{o}C for 24h and weighed (W_2). The solubilities of keratin/starch blend films were calculated by equation 2:

$$Solubility\ [\%] = \frac{W_1 - W_2}{W_1} x100 \quad [2]$$

Moisture content of films

Film moisture contents were determined by drying samples in an oven at 105 ^{o}C for 24 h. Moisture content and moisture regain of the films were calculated using equations 3 and 4, respectively:

$$Moisture\ content\ [\%] = \frac{W_1 - W_2}{W_1} x100 \quad [3]$$

$$Moisture\ regain\ [\%] = \frac{W_1 - W_2}{W_2} x100 \quad [4]$$

where W_1 is the initial mass of the film and W_2 is the constant mass of the film after drying

Surface Density of films

5x5 cm^2 keratin/starch blend film were prepared and weighed to the nearest 0.001 g. The surface density of the films were calculated using equation 5:

$$Surface\ density = \frac{Avarage\ weight\ of\ the\ films}{Area\ of\ the\ film} \quad [5]$$

Tensile properties of films

The mechanical properties of keratin/starch blend films were measured using a Universal Instron Tensile testing machine (Model 3345) according to the ASTM standard D882 (ASTM, 1991).

Dissolution of films

A dissolution percentage of the keratin/starch films were performed in a 0.1 mM phosphate buffer saline solution (pH 7.4) at 37 °C for 7 days. The buffer was changed every 24 hrs and the extent of dissolution was calculated using equation 6 after drying at 50 °C for 24 hrs.

$$Dissolution\ (\%) = \frac{Initial\ weight\ of\ film - Final\ weight\ after\ dissolution}{Initial\ weight\ of\ film} x100 \quad [6]$$

5.4.3. Results and discussions

Thin, transparent, homogeneous, and flexible films were obtained from all keratin/starch blended films. Their colour varied from white to yellow. Increase in keratin content in the film resulted in increased yellowness of the films. Initial observations were that the keratin/starch blended films without plasticiser were brittle at low humidity and soft at high humidity. The mechanical properties of the films were improved. In order to improve the brittleness of keratin/starch blend film glycerol is incorporated in the blended solution. It was observed that the addition of glycerol increases the flexibility, homogeneity and transparency of the film by reducing the internal hydrogen bonding between polymer chains (Liu et al., 2009). Their surfaces appeared smooth without visible cracks or holes. These films show higher flexibility, whiter colour, homogeneous in surface appearance and sticky during peeling off the film from the plate due to the hygroscopic nature of starch, as the starch content increases.

5.4.3.1. FTIR spectroscopy of films

The infrared spectra of keratin/starch blended films are depicted in Figure 5.4.5: it is clearly evident that there were shifts in the spectra due to interaction between the amino acid functional groups of keratin molecules and hydroxyl groups in the starch molecules. The absorption peak at about 900-1000 cm^{-1} represents disulphide bonds in keratin and its intensity increases as keratin content in the films increases. The major absorption peaks are displayed in Table 5.4.2.

Table 5.4.2. Major functional groups identified in keratin/starch films.

Absorption peak, cm^{-1}	Functional group
800	Amide IV
900-1000	Disulphide bonds in keratin
1200	Amide III
1250	C-O stretching
1550	Amide II (NH bending)
1680	Amide I (C=O stretching)
1700	Carbonyl group
2900	C-H stretching
3100-3600	C-C
3000-3500	3000-3500 OH and/ or NH stretching

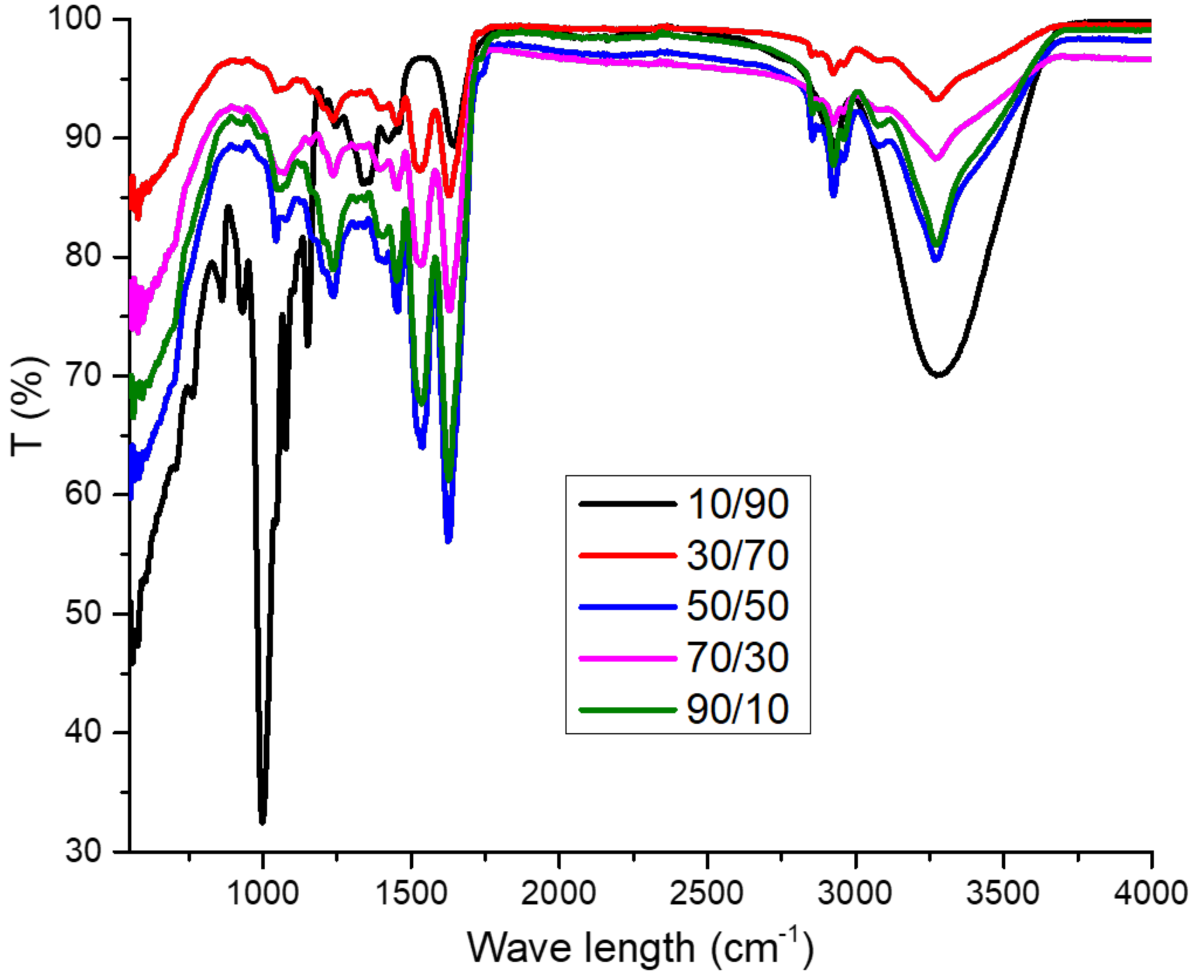

Figure 5.4.5. FTIR spectra profile of keratin/starch blend films

10/90 keratin/starch film showed absorption peaks at 900-1000 cm^{-1}, 1250 cm^{-1}, 1550 cm^{-1}, 1660 cm^{-1} and 3100-3600 cm^{-1} corresponding to saccharide, C-O stretching, N-H, C-C O-H or/and N-H stretch functional groups. The keratin/starch film showed the presence of absorption peaks about 800 cm^{-1}, 1200 cm^{-1}, 1550 cm^{-1} and 1680 cm^{-1} and these represents amide IV, III, II (NH bending) and I (C=O stretching) respectively. The presence of band about 1700 cm^{-1} in the keratin/starch suggested carbonyl group. Due to the interaction of hydroxyl groups (-OH) in the starch molecule and the amino groups (-NH_2) or carbonyl group (C=O) of the keratin protein, the keratin/starch blend films showed absorption peaks about 2900-3250 cm^{-1}. The peak near 2900 cm^{-1} suggested the presence of C-H stretching. The presence of broad band about 3000-3500 cm^{-1} was an indicator of OH and/or NH stretching.

5.4.3.2. Morphological and fine detail structures of films

Scanning electron microscopic (SEM)

The morphological structures of obtained keratin/starch film surfaces are presented in SEM images in Figure 5.4.6. It is evident that the morphological structures of keratin/starch films are affected by the chemical composition of the films. It could be also concluded that the surface morphology and texture of keratin/starch blend films were depended the ratios of keratin and starch used. It is observed that the roughness of the surface of keratin/starch blend films increases as the starch content increases and the structure of the film is porous like sponge texture. While as the keratin content increases the surface become smooth surface with non-homogeneous texture and granulates were embedded and merged, this could be due to the high range of molecular weight distribution of the keratin protein. All keratin/starch blend film except 90/10 keratin/starch blend comprises of high starch content, which are mainly similar monomer but high molecular weight difference with keratin and the surface of the film becomes rough with homogeneous texture. It was not possible to observe any significant morphological structure difference between 30/70 and 50/50 keratin/starch film and showed one more sponge cross-sectional structure which could be due to the functional group similarities of the films. The sponge like texture might be caused due to the evaporation of water molecules that reacted with various hydroxyl groups in the starch. All keratin/starch blend films have sponge texture and this could be due to the presence of hydroxyl group in the starch, and this group can interact with water through hydrogen bond during drying of the films.

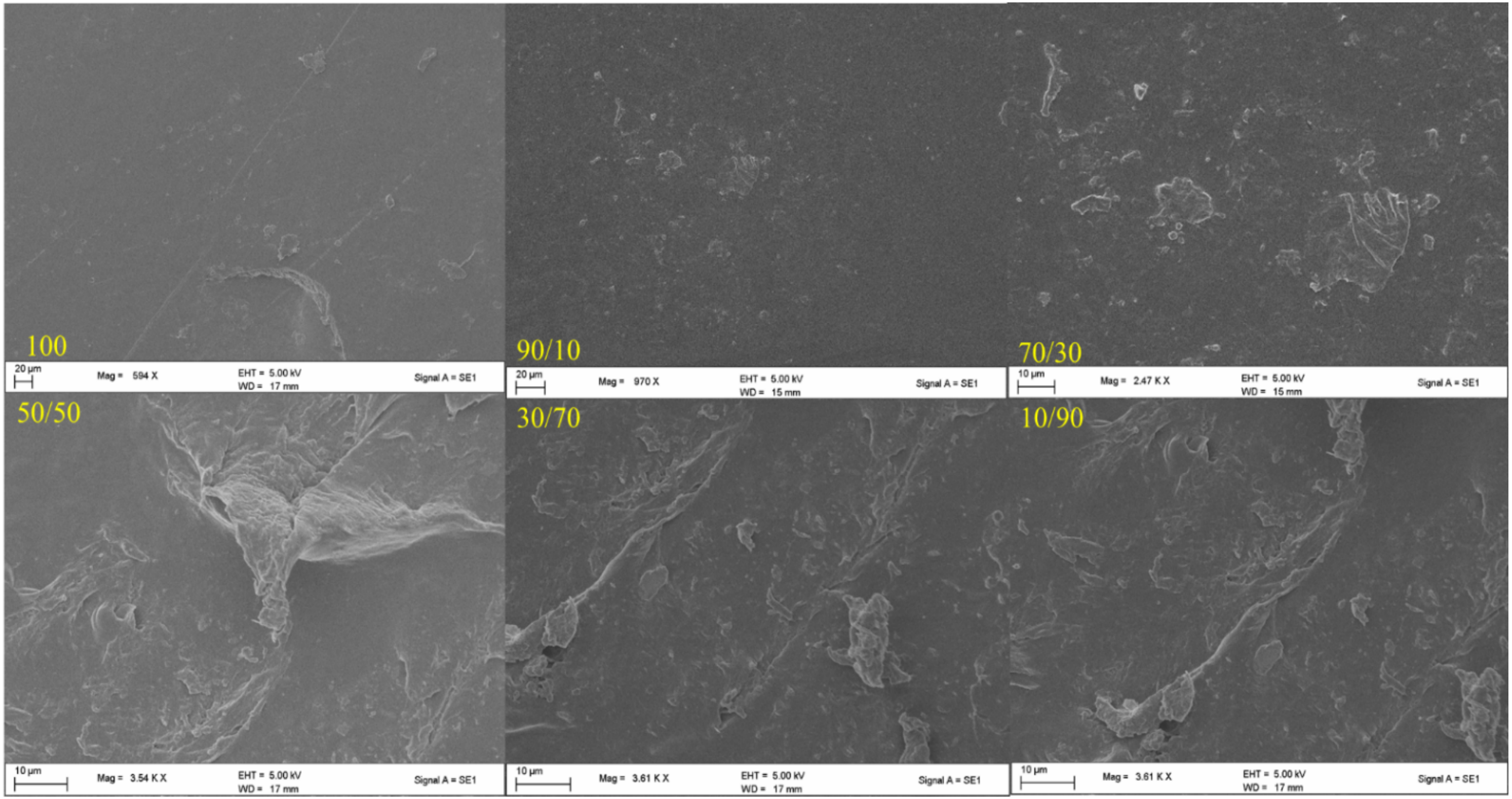

Figure 5.4.6. Morphological structures of keratin/starch blend films

Fine detail structure

To further clarify the surface roughness of the keratin/starch films the fine detail structures of the films were investigated using Atomic Force Microscopy (AFM). The AFM images of the keratin/starch blend films are shown in Figure 5.4.7. The 100 % keratin film exhibited a non-homogeneous, compact structure with aggregates embedded on the surface probably due to agglomeration of keratin proteins. Addition of increasing amounts of starch in the blends produces films with homogeneous and compact microstructures due to inter- and intra- molecular crosslinking of keratin proteins with starch molecules. The roughness of the blended film could be due to the difference in molecular weight distribution of keratin and starch molecules.

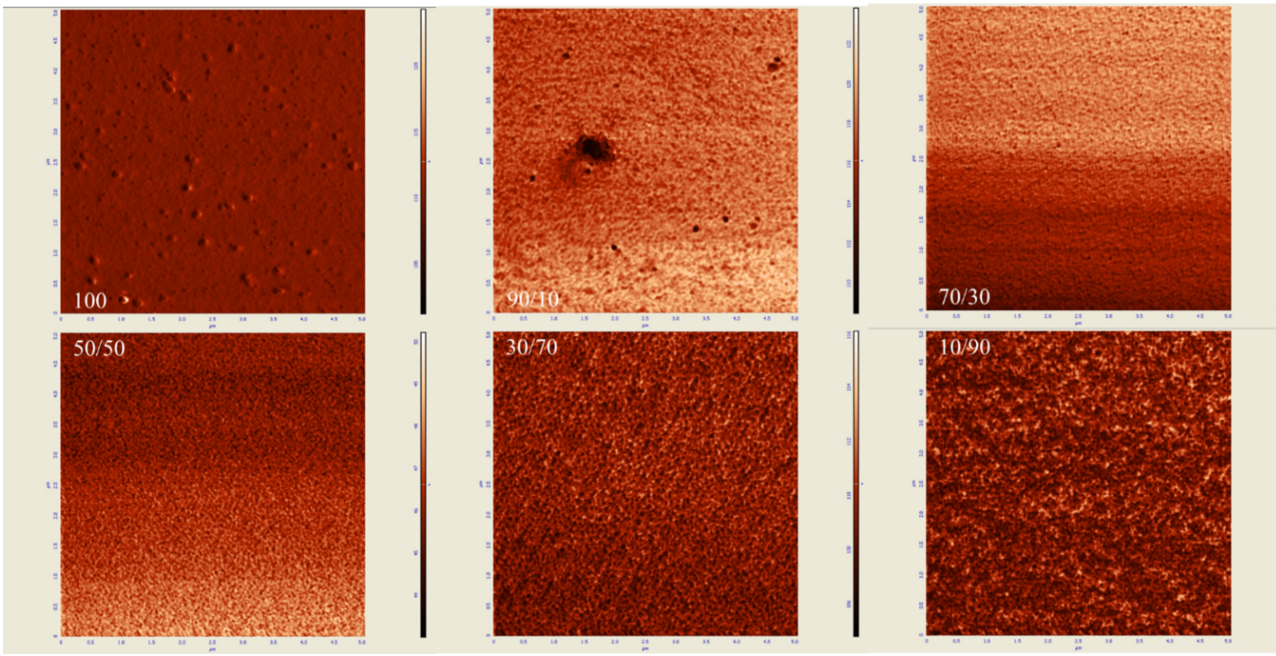

Figure 5.4.7. AFM images of keratin/starch blend films

5.4.3.3. X-ray diffraction (XRD) of films

To further clarify the effect of keratin/starch addition on the properties of the films, XRD analysis was investigated. XRD analysis was used to study crystallinity properties of the films. Diffraction peaks in the XRD pattern of the keratin/starch blended films are shown in Figure 5.4.8. They show broad diffraction peaks at 2θ values of ~9 and 20°, which are typical patterns of partially crystalline materials. The diffraction pattern intensity and peak width of higher starch content films is stronger than other samples indicating an increase in crystallinity behaviour. From the crystalline peaks, the crystallinity indexes were calculated based on equation 1 and the results all keratin/starch film were completely amorphous structure with crystallinity index of less than 20 %.

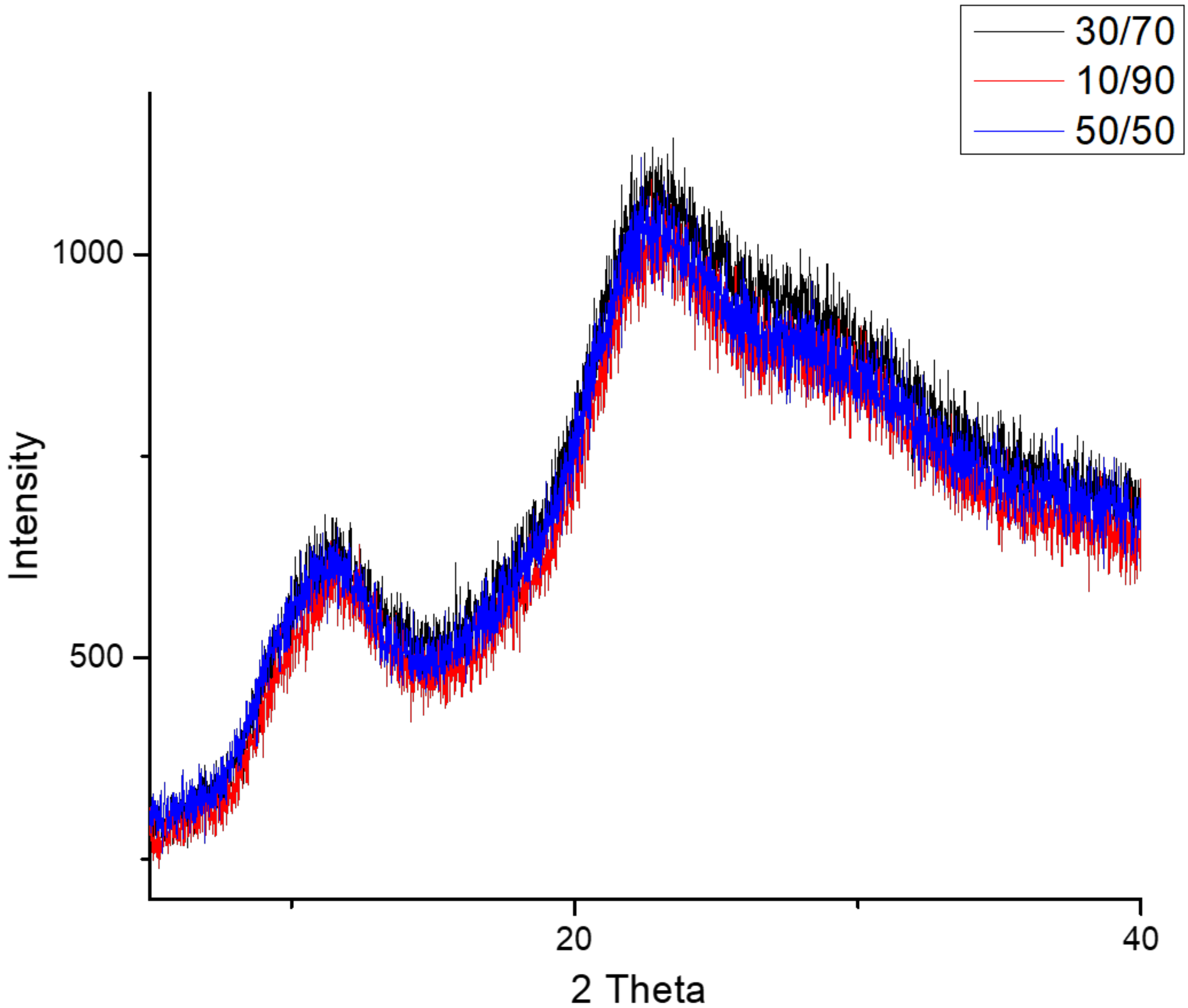

Figure 5.4.8. XRD profiles of keratin/starch blended films

5.4.3.4. Solubility test of films

The solubility profiles of keratin/starch blended films are shown in Figure 5.4.9: solubility of the films increased with increase in starch content in the films. This could be due to hydrophilicity of hydroxyl groups in the starch polymer starch – higher amounts of starch will lead to higher solubilities of the films in water. This seems to imply that higher starch content in the blends results in reduced cross-linking reactions between keratin and starch molecules thus facilitating solubilisation of the polymer films.

5.4.3.5. Moisture content and regain of films

The mechanical properties, water vapour barrier properties, dissolution, and drug delivery properties of polymer based materials are significantly influenced by the moisture content and moisture regain of the produced materials (Fang et al., 2002; Saul et al., 2011; Tanabe et al., 2004; Thonpho and Srihanam, 2016). Moisture content of the keratin/starch blended films was significantly affected by the amount of starch in the films and ranged between 10-16 %. Results shown in Figure 5.4.9 indicate that the increase in starch content increased the moisture content of the films: this could be due to the hydrophobic nature of keratin molecules and the crosslink network structure formed between keratin and starch molecules that could hinder exposure of the hydrophilic groups of keratin to water molecules. In contrast starch has good ability to bind with water. But in all cases the moisture content of the films is in the range of allowable moisture content (Gennadios and Weller, 1991; Saul et al., 2011; Tanabe et al., 2004; Thonpho and Srihanam, 2016). This indicates keratin/starch films could be stored for long periods at room temperature, with no concerns regarding fungal and microbial growths.

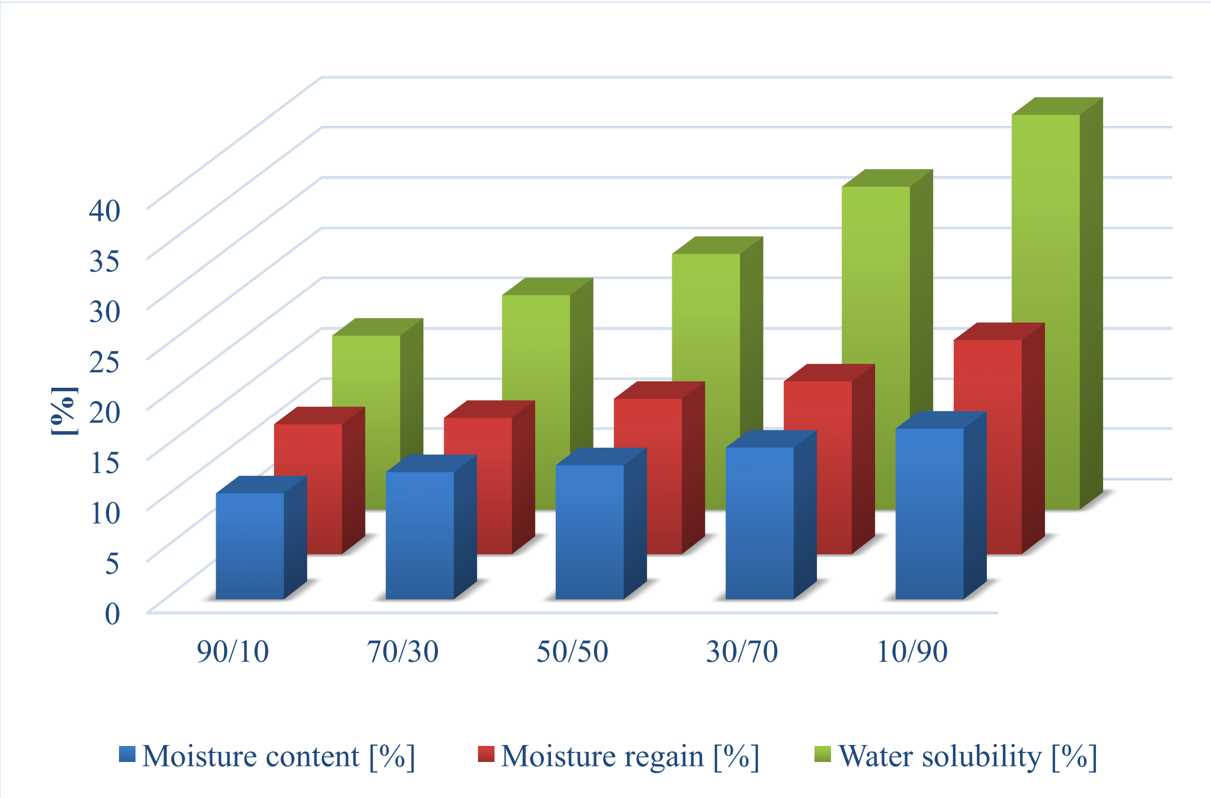

Figure 5.4.9. Moisture content, moisture regain and water solubility of keratin/starch blend films

Moisture regain data of keratin/starch blend films are displayed in Figure 5.4.9. Moisture regain of the films is an important property of the films that can be used in determining the measure of moisture sensitivity, water activity, and hydrophilicity of materials. It can also be used to assess the relative physical stability of materials when stored under humid conditions (Ohwoavworhu et al., 2004). Also, water regain properties of the films can be considered as an advantage for applications like wound healing, drug delivery system and hygiene. Moisture regain values of films in this study were 12-20 %. As can be seen in Figure 5.4.9, increasing starch content in films resulted in increase in moisture regain of the films possibly due to hydrogen bonding interactions and the hydrophilic nature of starch. As is well known higher quantities of hydrophilic group in materials lead to higher moisture content of the materials (Ohwoavworhu et al., 2004). The water adsorbed on keratin/starch blended films acts as a plasticiser for increasing chain mobility of starch and weakening inter-chain hydrogen bonding, by which starch chains are capable of slipping, thereby reducing internal stress and thus increasing film elongation. Chemical modification of the starch used in this study may be necessary so as to reduce its high moisture properties and enable production of bioplastic with good water barrier properties.

5.4.3.6. Surface density of the films

One requirement of current packaging materials is lightness. The surface density values of keratin and starch films are depicted in Figure 5.4.10: the values decrease with increasing keratin content in the films. This could be due to the higher density of starch compared to keratin protein.

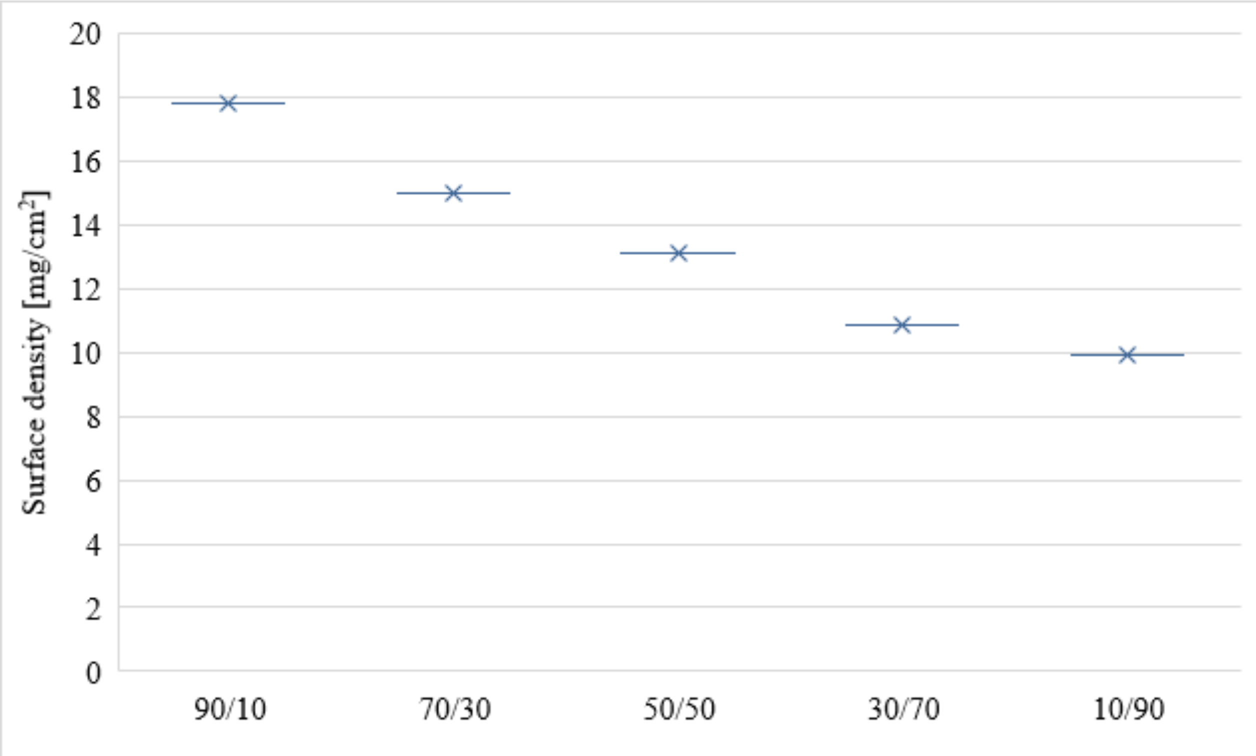

Figure 5.4.10. The surface density profile of starch/keratin film

5.4.3.7. Tensile properties of films

The effect of starch content on tensile strength and elongation of properties of keratin/starch blended films are shown in Figure 5.4.11. Increase in starch content caused significant differences in both tensile strength and elongation properties of the films: samples with lower starch content exhibited higher tensile strength and lower elongation properties than those with higher starch content. Figure 5.4.11 shows that films prepared with 10 % starch and 90 % keratin had higher tensile strength (15.91 MPa) and lower percent elongation at break/flexibility (9.10 %). Whereas films from 90 % starch and 10 % keratin showed a higher percent elongation at break (26.20 %) and lower tensile strength (7.34 MPa). The increase in avocado seed starch results in the decrement of tensile strength, low ductility of the protein matrix and increment of the elongation properties of the films. The increased tensile properties are due to formation of intermolecular hydrogen bonds between NH_4^+ of the keratin backbone and OH^- groups in the starch matrix.

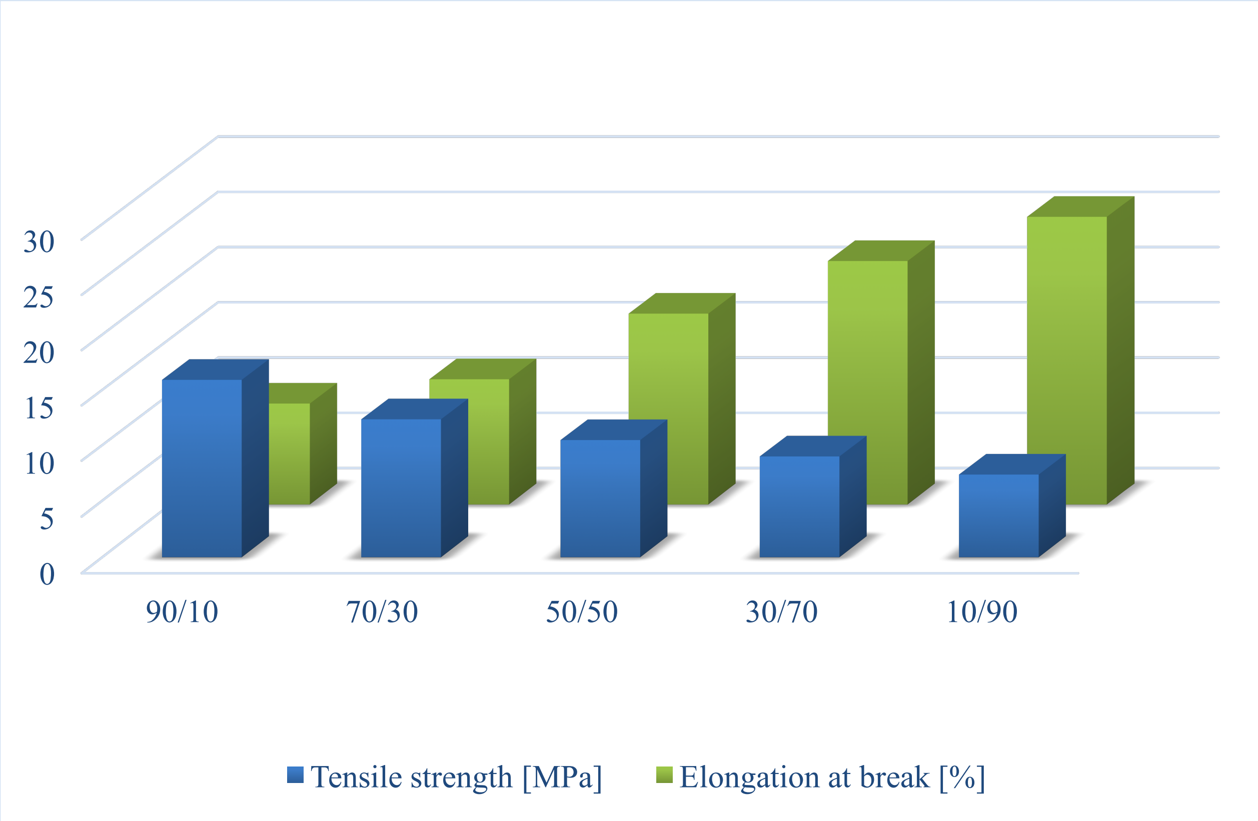

Figure 5.4.11. Tensile strength and elongation properties of keratin/starch films

Dissolution of films

The dissolution profiles of the keratin/starch blend films are depicted in Figure 5.4.12: dissolution decreases as the keratin content in the films increases. As shown in the Figure the highest percentage of dissolution was for film containing higher starch content, this might be affected by interaction force between keratin and starch. Moreover, the broad distribution of molecular sizes and molecular weights of starch and keratin should be affected on the bonding formation between two components and reflected on degradation pattern of the blended film.

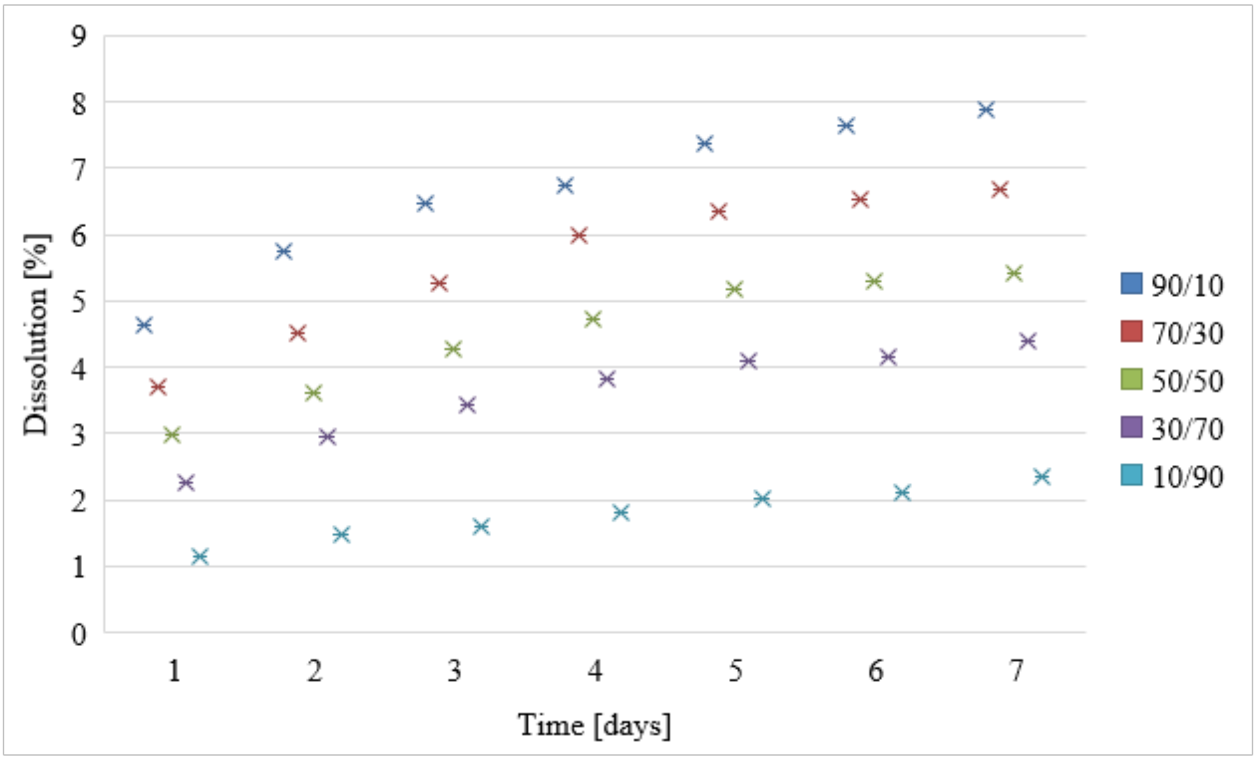

Figure 5.4.12. Dissolution profiles of starch/keratin films

The dissolution properties of the films can be used as indicators as to whether the materials could be used as drug release materials. The decrease in dissolution with increase in keratin content may be attributed to the high sulphur content from the amino acid cysteine in the keratin. The chicken feather keratin contains both hydrophobic and hydrophilic regions and the hydrophobic nature of keratin could influence the dissolution negatively. The sulphur-sulphur linkages (-S-S-) also affects the dissolution properties of the films (Chaosri et al., 2014; Thonpho and Srihanam, 2016; Sando et al., 2010). The starch matrix contains hydroxyl groups that should interact well and affect the release patterns of the films. As the starch content in the films increases, the texture of the keratin/starch blend films undergoes phase separation: consequently, water stability as well as the mechanical properties will be compromised.

5.4.4. Possible application areas of keratin/starch films

The films produced from renewable resources of waste chicken feathers and waste avocado seeds have potential for application and use in many applications as illustrated is in Figure 5.4.13. The results of the dissolution, water absorption, solubility, moisture content, mechanical properties and morphological structures of keratin/starch blended films imply that they could be used in a variety of applications such as:

- in the food packaging industry (as a cost-effective and environmental alternative source of raw material to the commonly used packaging materials, use and throw caps and edible food packaging);
- a raw material for different hygiene products, e.g., superabsorbent material for diaper products;
- use in tissue engineering (e.g., artificial heart, hip joints, heart valve, and finger joints);
- in wound dressing;
- fashion industry (as artificial lens and breast implants)
- artificial skin replacement;
- in the pharmaceutical industry (e.g., drug delivery and transdermal drug delivery systems).

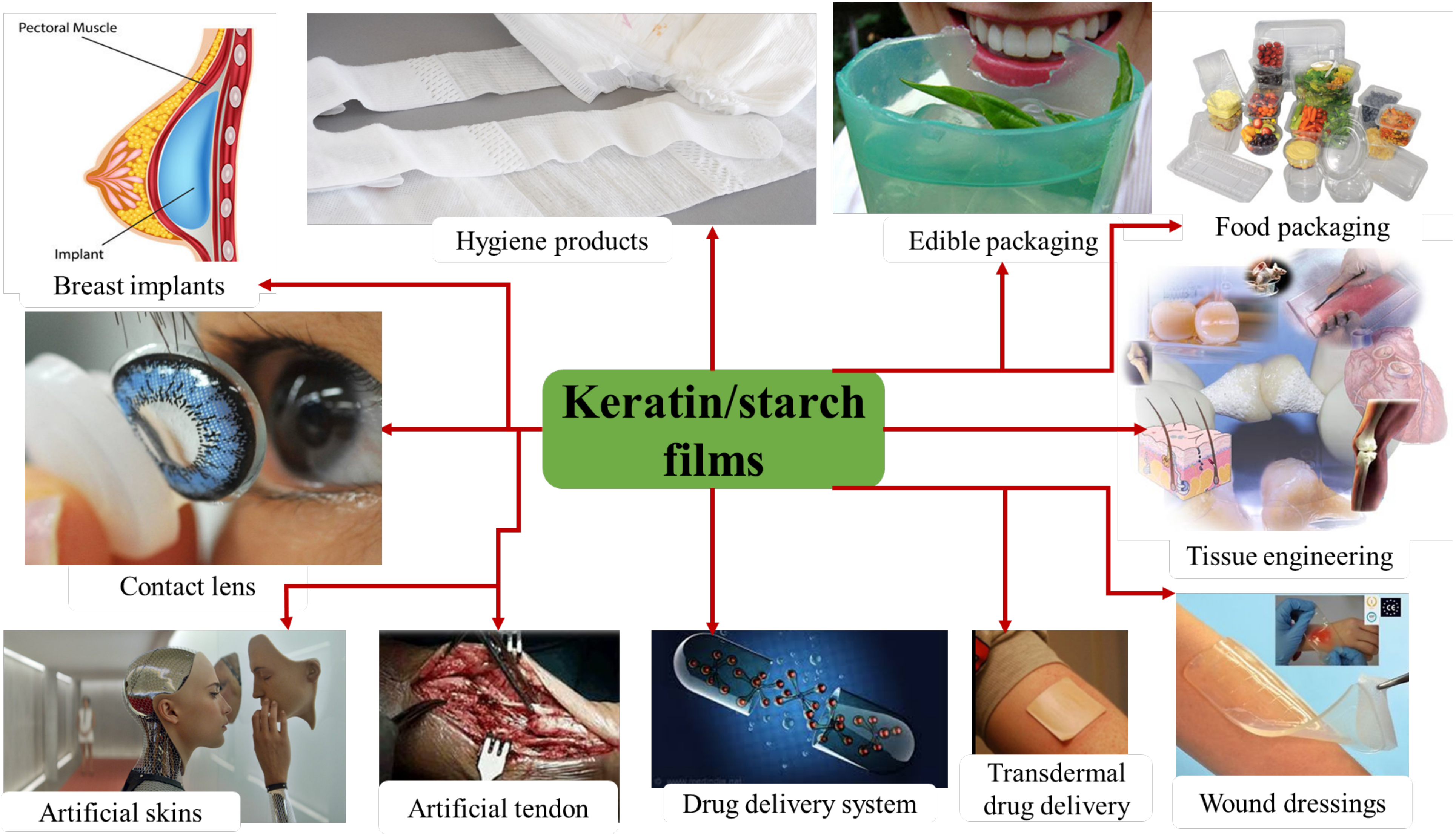

Figure 5.4.13. Possible valorisation routes of keratin/starch films

5.4.5. Conclusions

Biofilms were successfully produced from starch and keratin obtained from waste avocado seeds and waste chicken feathers. With increasing starch content, the flexibility, solubility, dissolution, moisture regain, and moisture content of the films increases, whereas the tensile strength property decreases. The results of the dissolution, water absorption, solubility, moisture content, mechanical properties and morphological structures of the films imply that they could be used: in the food packaging industry (as a cost-effective and environmental alternative source of raw material to the commonly used packaging materials; as a raw material for various hygiene products, e.g., superabsorbent materials for diaper products; in wound dressings; in the fashion industry (as artificial lens and breast implants); in biomedical applications, e.g., artificial skin replacement; and in the pharmaceutical industry (as drug delivery and transdermal drug delivery systems). Future studies will entail understanding the effect of chemical modifications of starch and keratins, different plasticizers, and extrusion/casting conditions on physiochemical and mechanical properties of the films. The possibility of the film for its drug release and other medical applications would be also analysed.

ACKNOWLEDGMENTS

The authors are highly grateful for the financial and technical support received from: the Thermodynamics Research Unit at the Discipline of Chemical Engineering, University of KwaZulu-Natal; the Institute of Technology for Textile and Fashion Design/EiTEX at Bahir Dar University, Ethiopia; the Department of Science and Technology, Waste Research Development and Innovation Roadmap and the Biorefinery Industry Development Facility, Natural Resources and Environment, Council for Scientific and Industrial Research (CSIR).

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5.5. VALORISATION OF WASTE CHICKEN FEATHERS: GREEN OIL SORBENT (BASED ON PAPER TEN)

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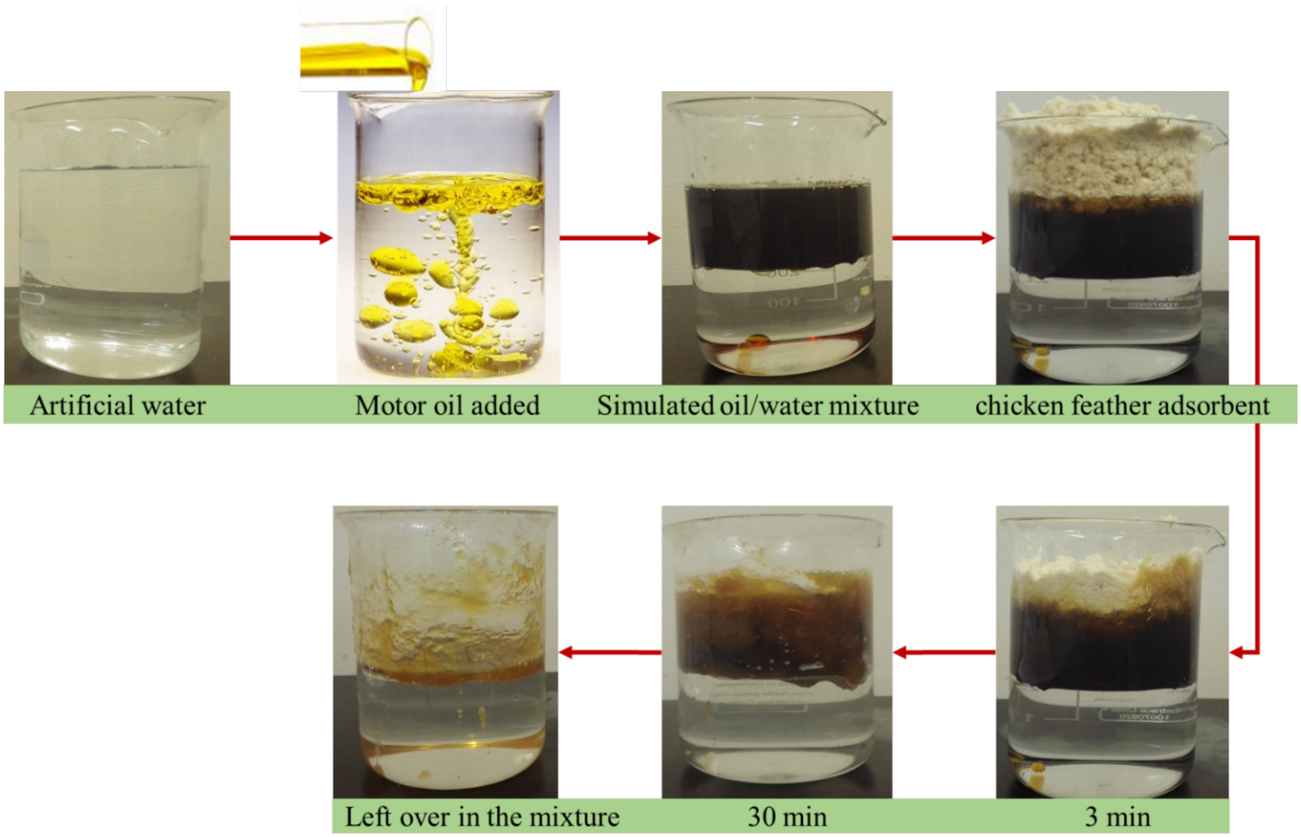
ABSTRACT

The threat of oil pollution increases with the development of large-scale off-shore petroleum industrial activities. Recently, reducing waste materials through reuse has contributed to sustainable manufacturing in many industries. With development of large-scale poultry farming industries, the disposal of large amounts of waste chicken feathers has become a huge problem. Thus sustainable methods for valorisation of this waste are needed. This paper examines beneficiation of waste chicken feathers via conversion into sorbents for clean-up of oil spills in water bodies to replace conventionally used synthetic adsorbents that are costly. Chicken feathers have a very high capacity for adsorption of liquid oils (up to 16.21 g of oil/g of chicken feather) at fast uptake time (10 min). The removal efficiency of oils in spills increases with increment in contact time with the sorbent. Untreated waste chicken feathers exhibited slow sorption rate for oil due to the presence of grease and other impurities on the surface of feathers. More than 85 % of the oil adsorbed by chicken feathers can be recovered. Thus, waste chicken feathers show very attractive and promising adsorption/absorption properties for oil spill clean-up applications to replace polymer based adsorbents due to their high oil absorption capacities. Both untreated and treated chicken feathers show promising potential for use as oil absorbents.

Keywords: chicken feathers, oil spill clean-up, sorption, oil recovery

Graphical abstract



5.5.1. Introduction

Oil pollution has become one of the most serious threats to the aquatic ecosystem during the last 30 years due to the development of large-scale off-shore petroleum industries, increase in runoff of oil, increase in accidental spills, discharges of fuel from land-based sources, oil drilling accidents, and increase in marine oil transportation (Goodbody-Gringley et al., 2013; Wahi et al., 2013; Wang et al., 2012; Zhu et al., 2011). Major sources of waste oil include petroleum refining, petrochemical plants, vehicle repair garages, metal and steel manufacturing industries, vegetable and animal oils in households wastes, and abbatoir wastes (Adebajo et al., 2003; Ahmad et al., 2005; Kabiri et al., 2014). Large quantities of oils discharged into the ecosystem can cause serious environmental problems, including adverse effects on water quality and aquatic biota, clogging of sewage treatment plants, increased chemical oxygen demand due to the large amount of bacteria necessary to decompose the oil, as well as increased biochemical oxygen demand (Adebajo et al., 2003; Ali et al., 2012; Brandão et al., 2010; Ceyla et al., 2009; Goodbody-Gringley et al., 2013; Wahi et al., 2013; Wang et al., 2012; Zhu et al., 2011). Treatment of oil spills in affected waters results in improved water quality, oil recovery, protection of aquatic biota, and environmental protection.

Several techniques are used for removal of oily contaminants from contaminated waters; they include *in-situ* burning, solidification of the oils, reverse osmosis, filtration, micro-filtration, ultra-filtration, air flotation, bioremediation, gravity separation, electrocoagulation, chemical coagulation, electroflotation, and physical techniques such as booms and skimmers (Almeda et al., 2013; Goodbody-Gringley et al., 2013; Rico-Martínez et al., 2013; Vasudevan and Rajaram, 2001; Wang et al., 2012; Wu et al., 2012). The methods can be categorised into three major groups, viz., chemical, biological and physical processes. Chemical methods are effective in oil removal from water but they are costly and can adversely affect zooplankton, a primary food source in the marine food chain. The treated oil cannot be recovered, and is thus hazardous to humans and animals (Almeda et al., 2013; Goodbody-Gringley et al., 2013). Bioremediation is effective in oil spill removal but it is time-consuming and its effectiveness is affected by oxygen level, temperature, and organic moieties in the oil (Atlas, 1991; Vasudevan and Rajaram, 2001).

Recently, physical sorbents have attracted attention for oil spill removal, owing to desirable characteritsics in some of them such as low environmental impact, low cost production, and low energy consumption. Physical sorbents cam be grouped into three classes: natural organic sorbents, inorganic sorbents, and synthetic organic sorbents. Synthetic adsorbents such as polyurethane (Wu et al., 2015), polyvinyl chloride (Zhu et al., 2011) and polyethene (Al-Obeidani et al., 2008) are costly and not environmental friendly. To overcome the environmental challenge, novel synthetic organic sorbents with high oil absorption capacities, high porosity, large surface area, and high degradability rate were developed, e.g., cellulose aerogels (Feng et al., 2015; Wu et al., 2012). Inorganic sorbents such as manganese oxide (Solisio et al., 2002), bentonite (Ahmad et al., 2005), vermiculite (Mysore et al., 2005), fly ash (Zainudin et al., 2005) and organoclay (Adebajo et al., 2003) have high oil absorption capacities. Natural organic sorbents such as peat and cotton grass fibre (Suni et al., 2004), rice husk and carbonised rice husk (Vlaev et al., 2011; Ali et al., 2012), butyl rubber (Ceylan et al., 2009), hydrophobic aquatic plants (Lim and Huang, 2006), activated carbon (Okiel et al., 2011), other carbon-based products (Kabiri et al., 2014), coconut husk (Khan et al., 2004), sawdust (Banerjee et al., 2006), Kapok fibre (Ali et al., 2012), sugar cane bagasse (Ali et al., 2012; Brandão et al., 2010; Said et al., 2009), chitosan (Ahmad et al., 2005) barley straw (Ibrahim et al., 2009) and other natural fibrous sorbent (Wahi et al., 2013) have also been used for removal of oils from contaminated waters.

This paper was designed to examine the utilisation of waste chicken feathers in the removal of oil spills from contaminated waters as a means of physical treatment to replace the conventional synthetic adsorbents that are currently used.

5.5.2. Materials and methods

5.5.2.1. Materials

Feathers: Chicken feathers were obtained from Rainbow Chicken Limited slaughterhouse in the province of KwaZulu-Natal, Durban, South Africa.

Cleaning agent: Sodium dodecyl sulphate (SDS) 99.0 % was purchased from Sigma-Aldrich.

Oil: High shear stable, multigrade engine oil formulated from crude oil (Havoline formula advanced motor oil, SAE 20W-50 was purchased from CALTEX, Durban, South Africa.

5.5.2.2. Methods

Treatment of chicken feathers

Experiments were conducted with treated and untreated feathers. Freshly plucked wet untreated chicken feathers were purified by washing with a 0.5 g/L aqueous solutions of SDS to remove the grease, other wastes and kill potential harmful pathogens. Untreated waste chicken feathers (10 g) feather samples were placed in a beaker to which was added the SDS solution at a liquid to solid ratio of 40:1. The sample was agitated at 500 rpm using a magnetic stirrer with the beaker on a hot plate maintained at 50 ^{o}C for 30 min. The treated feathers were further purified by rinsing in distilled water for 10 minutes and then laid on aluminium foil and dried to a constant mass at 100 ^{o}C in an air-forced dryer. Thereafter the sample was placed in plastic bag that was sealed and then stored in a controlled laboratory environment (20 °C, 65 % relative humidity). The different portions have different characteristics and properties as previously reported. Hence the different portions were separated (manually) for independent testing. Dried treated and untreated feathers were pulverised to 350 μm size using a heavy-duty milling machine before use to increase surface areas of the feathers.

Characterisation of chicken feather fractions: - Morphological, chemical and physical characteristics of feathers and fractions thereof have been described in a number of reports (Tesfaye, et al, 2017a, 2017b, 2017c).

Oil adsorption capacity of chicken feather fractions: - 30 g sodium chloride, 0.8 g potassium chloride, 6.6 g magnesium sulphate, 0.5 g of sodium hydrogen carbonate and 1.3 g calcium chloride were dissolved in 1000 ml of water to simulate artificial seawater. An oil spill was simulated by mixing 150 ml oil with 300 ml of the artificial seawater. 5 g each of untreated whole, untreated barb, untreated rachis, untreated whole powder (350 μm), treated whole, treated rachis, treated barb and whole chicken feather powder (350 μm) were dispersed in a beaker containing 300 ml simulated water and 150 ml oil using nylon mesh bag. The oil absorption experiments were carried out at 25±2 °C for 5, 10, 30 and 60 min. Then bags were then picked up with forceps and allowed to drain for 2 min until oil began to slowly stop dripping from the bags. The weight of the bags was recorded (Final weight) and the amount of oil absorbed per unit mass was calculated based on equation 1:

$$Oil\ adsorbed\ (g/g) = \frac{Initial\ weight - Final\ weight}{Initial\ weight} \qquad [1]$$

Oil desorption capacity of chicken feather fractions: - After adsorption, the chicken feather fractions were weighed (Initial weight) and then pressed (William Apparatus Co., Watertown, NY) for five minutes at 25±2 °C at YY newtons to squeeze out adsorbed oils. After pressing, the weight was noted (Final weight) and the amount of oil recovered per unit mass was calculated based on equation 2:

$$Oil\ recovered\ per\ unit\ mass\ of\ sorbent = Initial\ wight - Final\ weight\ of\ sorbent \quad [2]$$

5.5.3. Results and discussions

5.5.3.1. Characterisation of chicken feather fractions

Morphological structures of chicken feather fractions: - A closer look at a chicken feather reveals that it is comprised of three distinct units: the rachis, the central shaft of the feather that runs the entire length of the feather to which is attached the secondary branching structures; the barbs and tertiary smaller structures; and the barbules (Figure 5.5.1 b and c respectively). These morphological structures of chicken feathers were an indication of large surface areas. The rachis is composed of many individual fibres (Figure 5.5.1 d). As can be seen in Figure 5.5.1e, the feather barbs exhibit honeycomb shaped hollow cells in the cross-section direction. The voids inside chicken feathers may be very accessible to fluids or air. The presence of hollow honeycomb structures provides high resistance to compressibility and also imparts light-weightiness to barbs and rachis. The honeycomb structure in the cross-sectional view of the chicken feathers, as shown in Figure 5.5.1e, confirms the existence of extensive air pockets in the feathers. The images in Figure 5.5.1e confirm that the microstructure of feathers is nearly round; the medulla in coarse fibres are concentric and irregular in size. Any adsorbent material intended to remove oil from water surface should ideally float since oil tends to float on water. The presence of extensive air pockets (honeycomb structure) in the structure of waste chicken feathers imply that feathers can float on top of the water and could thus act as superabsorbent materials for oils present on water surface (Birbeck and Mercer, 1957; Das and Ramaswamy, 2006). The presence of hooks, hooklets, rough surface appearance, entangled pores and knots in the chicken feather structure enhance the oil retention properties (Tesfaye et al., 2017 (a)).

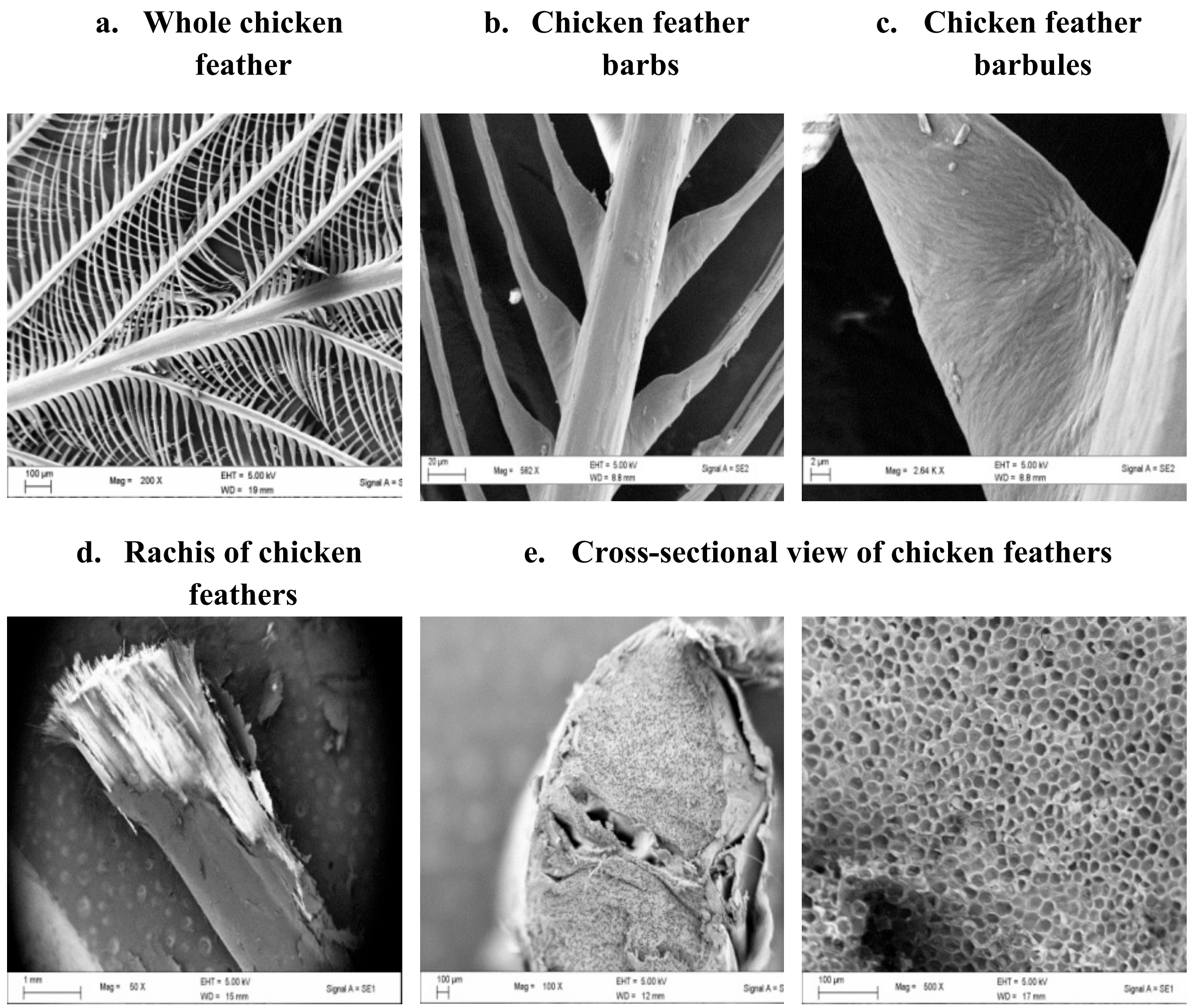


Figure 5.5.1. Morphological structures of chicken feathers (whole chicken feather, chicken barbs, chicken barbules, chicken rachis).

Density of chicken feather fractions: - The density values of various chicken feather fractions are shown in Figure 5.5.2**.** The density of whole feathers and feather fractions showed clear differences among them but that of the whole feather was very close to that of the barb density in almost all cases. The mean relative density of the barbs was 0.91 g/cm^3 with Cv 24.29 %, a relatively low variation indicative of sample homogeneity. The data in Figure 5.5.2 show that the mean recorded relative density of rachis was 0.44 g/cm^3 with Cv 28.99 %, a relatively low variation indicative of sample homogeneity (Tesfaye et al., 2017 (a)). The mean density of whole chicken feathers was 0.68 g/cm^3 with Cv 18.91 % again, the

Cv was relatively low and indicative of sample homogeneity. SEM micrographs of cross-sections of a rachis (Figure 5.5.1) show an open cell porous structure, which very probably, is responsible for the low-density value of the rachis. The mean wet density of rachis was 0.76 g/cm^3 with Cv 27.48 %, a relatively low variation indicative of sample homogeneity. The mean density of whole chicken feathers was 0.97 g/cm^3 (Cv 31.96 %) and barb was 1.31 g/cm^3 (Cv 30.26 %): again the Cv is relatively low and indicative of sample homogeneity ((Tesfaye et al., 2017 (a))). The result from Figure 2 shows that the density of chicken feather fractions after drying, indicating that a significant amount of moisture was present in the fractions. The density of chicken feathers and fractions thereof, were measured to be 0.44-0.91 g/cm^3: these values correlated well with literature values for protein and cellulosic fibre but were lower than those of animal and plant fibres such as wool (1.31 g/cm^3), silk (1.27 g/cm^3), jute (1.3 g/cm^3), coir (1.2 g/cm^3), and cotton (1.5-1.6 g/cm^3), etc. (Hearle, and Morton, 2008). As it seen clearly in the Figure no natural or commercially available synthetic fibres today have a density as low as that of chicken feathers. Considering that the density of chicken feather fractions they could float in water.

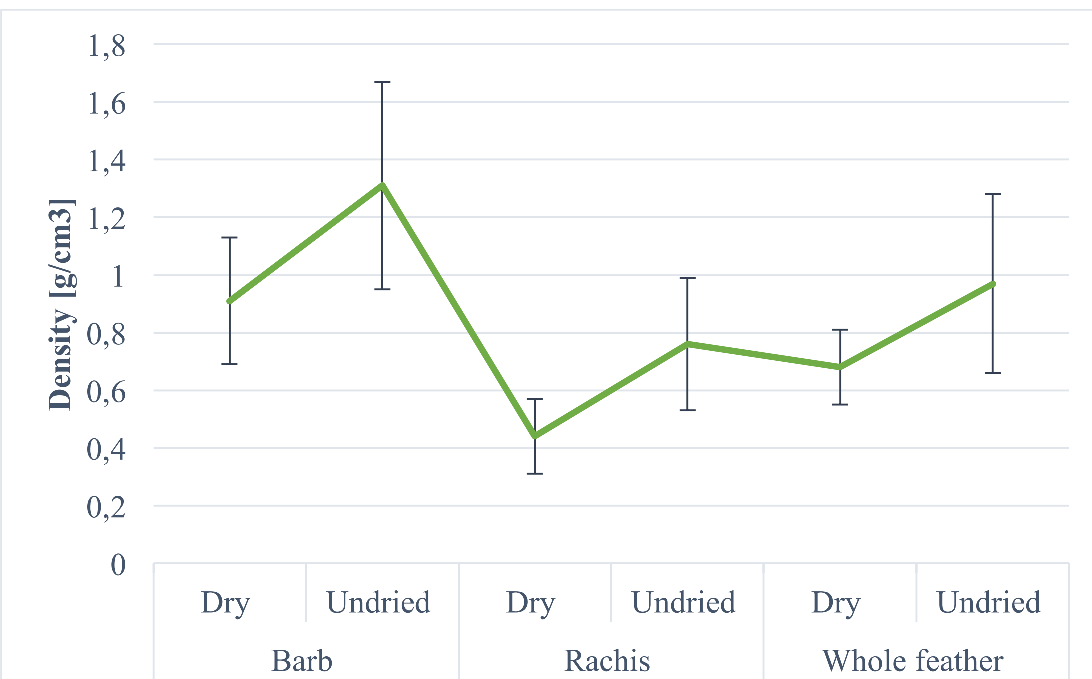


Figure 5.5.2. Density of chicken feather fractions

Hydrophobicity analysis of chicken feather fractions: - Chicken feathers contain approximately 91% protein (keratin), 1% lipids, and 8% water. The amino acid sequence of a chicken feather is precisely the same as that of keratin from reptilian claws (Saravanan and Dhurai, 2012). The amino acid sequence is mainly composed of cysteine, glutamine, proline and serine as shown in Table 5.5.1. Serine (16%) is the most abundant amino acid in chicken feathers (Saravanan and Dhurai, 2012). As can be seen clearly in the table the chicken feather fractions are therefore highly hydrophobic and partially hydrophilic (Table 5.5.1).

Table 5.5.1. Amino acid content in keratin fibre from chicken feathers (adapted from Saravanan and Dhurai, 2012).

Functional group	Amino acid	Percent content
Positively charged	Arginine	4.30
Negatively charged	Aspartic acid	6.00
	Glutamine	7.62
Hydrophobic	Tyrosine	1.00
	Leucine	2.62
	Isoleucine	3.32
	Valine	1.61
	Cysteine	8.85
	Alanine	3.44
	Phenylalanine	0.86
	Methionine	1.02
Hygroscopic	Threonine	4.00
	Serine	16.00
Special	Proline	12.00
	Asparagine	4.00

The majority of the amino acids present in chicken feathers are hydrophobic in nature (Saravanan, 2012). As shown in Figure 5.5.3, also it is evident that cotton and wood pulp were aggregate in the second layer (water layer) showing the complete wettability of the fibres. However, the chicken feather fractions (barb and rachis) aggregated in the interphase between the water and ethyl ether layers. This indicates poor wettability of chicken feather fractions compared with cotton fibre and wood pulp; these observations confirm the hydrophobic properties of chicken feather fractions (Tesfaye et al., 2017 (b)). Being hydrophobic in nature, the feathers will naturally be attracted and bind to the hydrocarbons in the oil until they are saturated. Thus chicken feathers are ideal materials for oil adsorption. A nonwoven or handsheet can be made from waste chicken feather to be used for oil removal from contaminated waters (Tesfaye et al., 2017; Tesfaye et al., 2017 (c)).

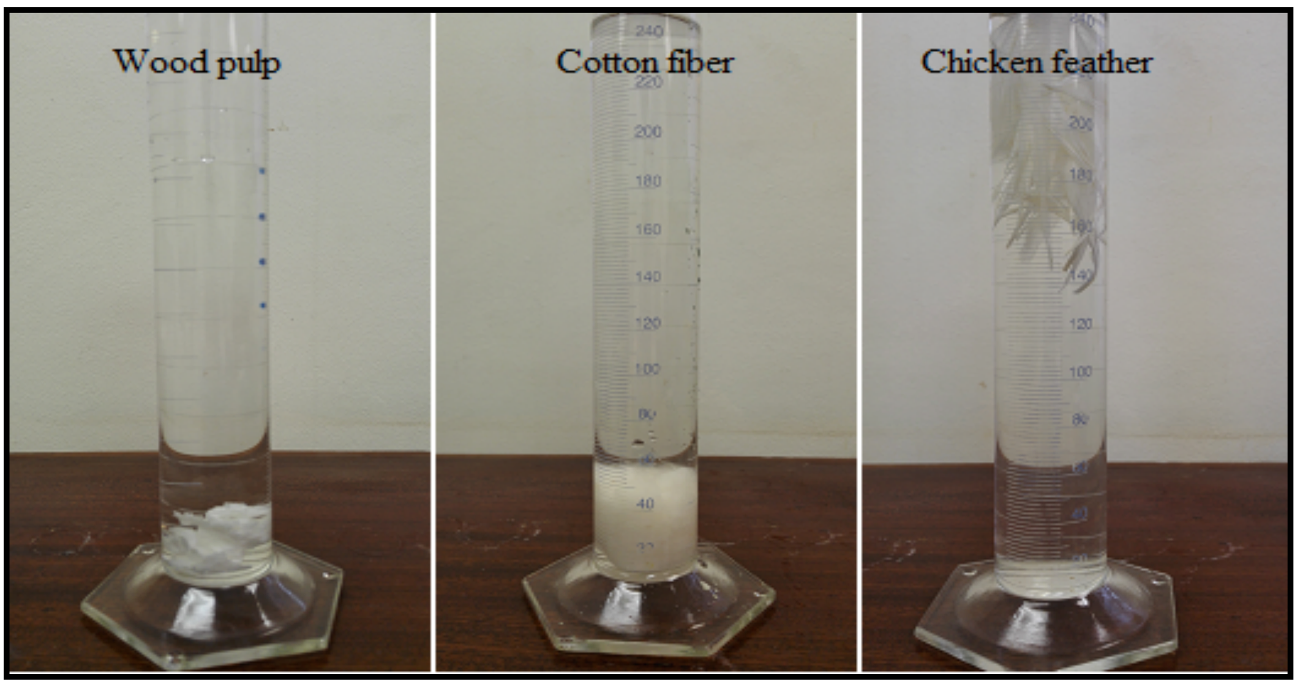


Figure 5.5.3. Hydrophobicity test on wood pulp, cotton fibre and chicken feathers (Tesfaye et al., 2017 (b))

BET analysis of chicken feather fractions: - As it is seen from Figure 5.5.4 and 5.5.5, the physiosorption property of the chicken feather fractions (barb and rachis) show significant differences in BET surface area. The difference in surface area of both samples may be due to the microstructural difference between the two samples as can be seen in the morphology characteristics (Figure 5.5.1). Since the pore size of both fractions falls in between 2-150 nm, it can be concluded that the chicken feather fractions were mesoporous and microporous material (Weber et al., 2010: Gil, and Montes, 1994). The surface area of the rachis was 1.25 m^2/g with a single point surface area at P/Po = 0.20:1.29 m^2/g. The pore volume of barb for single point adsorption total pore volume of pores less than 168.91 nm diameter at P/Po = 0.99 was 0.02 cm^3/g. The chicken feather rachis has a pore size of adsorption average pore width (4V/A by BET) 55.47 nm, BJH adsorption average pore diameter (4V/A):42.92 nm and BJH desorption average pore diameter (4V/A):28.78 nm. The surface area of the barb was 0.7845 m^2/g with a single point surface area at P/Po = 0.20:0.87 m^2/g (Tesfaye et al., 2017 (a)). The pore volume of barb for single point adsorption total pore volume of pores less than 139.39 nm diameter at P/Po = 0.99 was 0.01 cm^3/g. The chicken feather barb has a pore size of adsorption average pore width (4V/A by BET): 40.29 nm, BJH adsorption average pore diameter (4V/A):87.03 nm and BJH desorption average pore diameter (4V/A):25.81 nm (Tesfaye et al., 2017 (a)).

Figure 5.5.4 shows the BET specific surface area of chicken feather fractions. It can be seen that the rachis data were much more linear and the data is uniformly distributed compared to that of the chicken feather barbs. Figure 5.5.4 demonstrates that the amount of the adsorbed nitrogen is noticeably lower for barb compared to the rachis part. This region is representative of adsorption in micropores, which are the internal adsorption sites inside the chicken feather fractions (Tesfaye et al., 2017 (a)). These results showed that the material produced from rachis has very stable adsorption and desorption characteristics resulting in the higher surface area compared to material produced from chicken feather barbs.

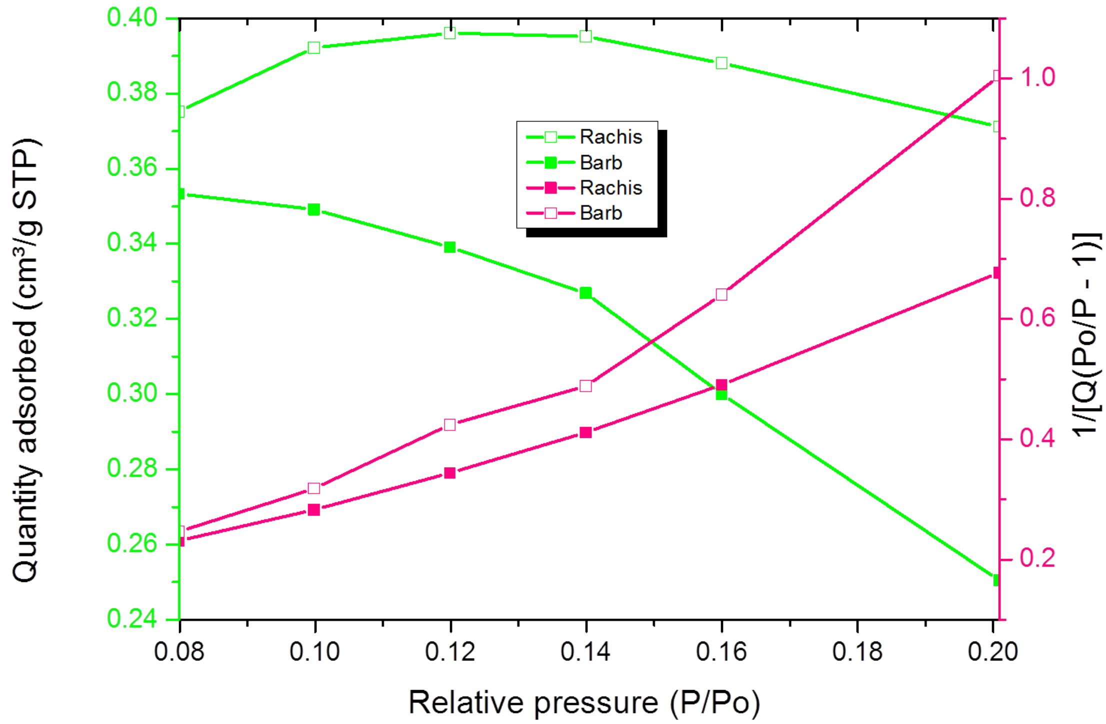


Figure 5.5.4. BET Specific surface area analysis of chicken feather fractions (Tesfaye et al., 2017 (a))

Nitrogen adsorption/desorption isotherms at 77 K of the barb and rachis of the chicken feather samples are shown in Figure 5.5.5. Both fractions exhibited the type-III isotherms and explain the formation of multilayers. Figure 5.5.5 shows considerable differences between the adsorption/desorption isotherms of barb and rachis of the chicken feather: the uptake amount at low pressure by rachis were much higher than barb this is the indication for the presence of more mesopores. The uptake of nitrogen at very low pressures is due to mesopore and micropores filling from the enhanced adsorbent–adsorbate interactions in the mesopores and is distinct from adsorption in macropores because adsorption in mesopores material is due to multilayer adsorption and capillary condensation (Weber et al., 2010; Gil and Montes, 1994).

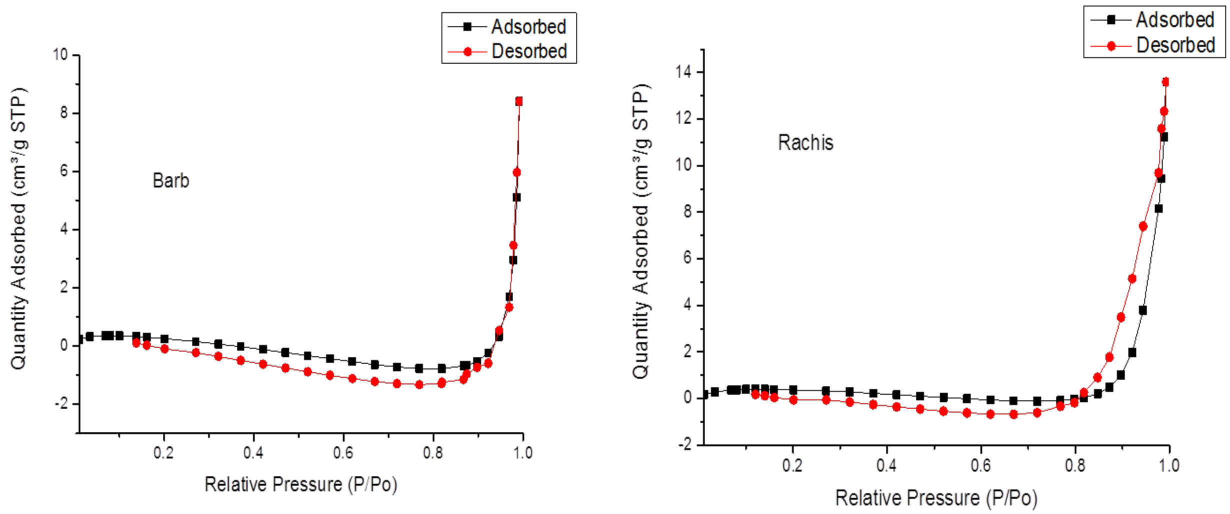


Figure 5.5.5. Adsorption/Desorption isotherm of chicken feather fraction (Tesfaye et al., 2017 (a))

Figure 5.5.6-5.5.7 shows the obtained pore size distribution of chicken feather fractions. The chicken feather fractions have both micropores and mesopores. The pore size distribution shows a maximum at the pore size of 11.8 nm for rachis and 2.89 nm for barb. There is a secondary maximum at a pore size of around 13.95 nm for rachis and 37.55 nm for barb and there are pores in the larger microporous and mesoporous regions, but all these pore distributions are much smaller than the primary maximum (Tesfaye et al., 2017 (a)).

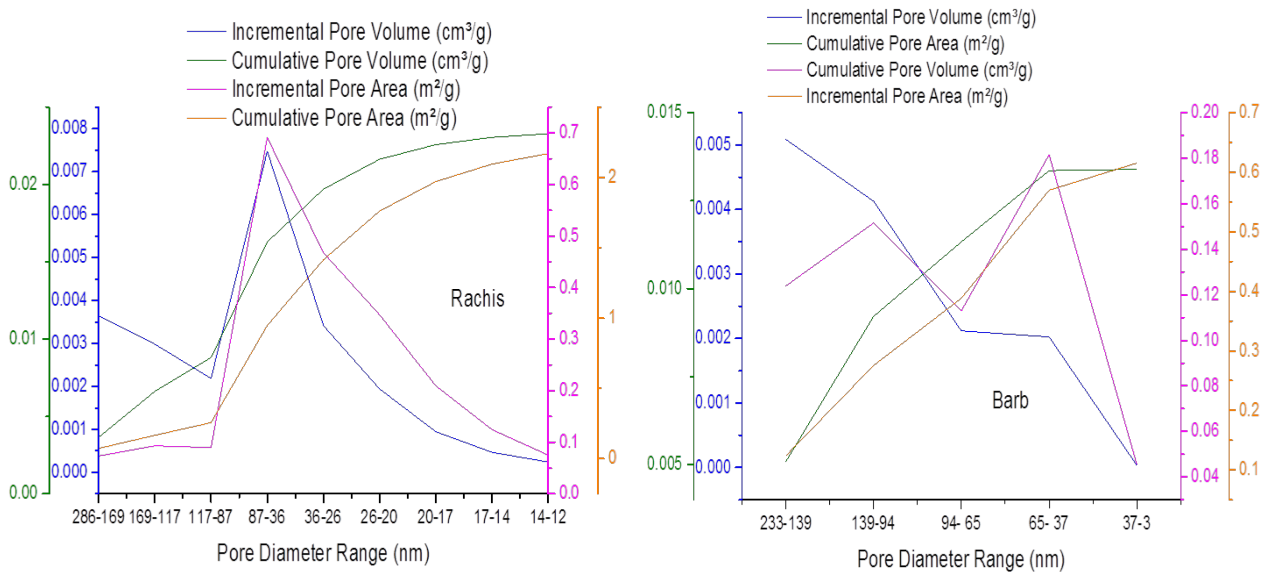


Figure 5.5.6. BJH adsorption pore distribution of chicken feather fractions (Tesfaye et al., 2017 (a))

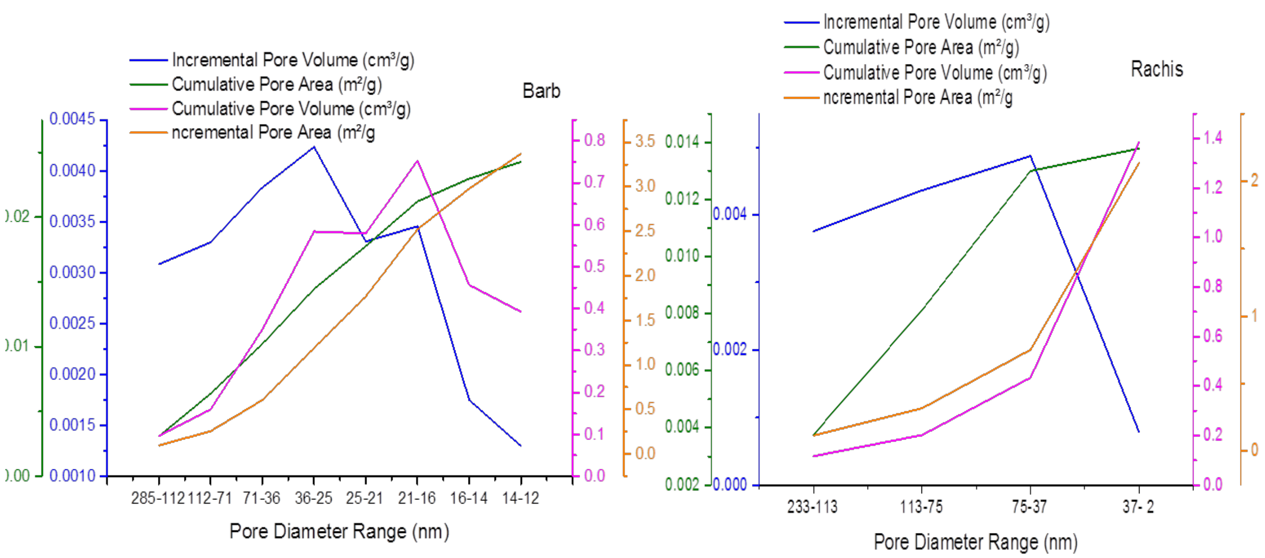


Figure 5.5.7. BJH desorption pore distribution of chicken feather fractions (Tesfaye et al., 2017 (a))

5.5.3.2. Experimental Data

Oil adsorption capacity of chicken feather fractions

Motor oil is immiscible with water; hence it floated on the surface of artificial seawater. In all sets of experiments the chicken feathers did not sink to the water layer but floated and interacted with the oil layer: this is possibly due hydrophobicity and oleophilicity of the feather fractions (Figure 5.5.8). These are important properties of chicken feathers and that are an indication that chicken feathers would interact with and adsorb oil at the surface rather than sink and mix with the water below the oil slick. This observation further confirmed that the surfaces of chicken feather fractions were hydrophobic in nature (Figure 5.5.8) and only absorbed oil selectively.

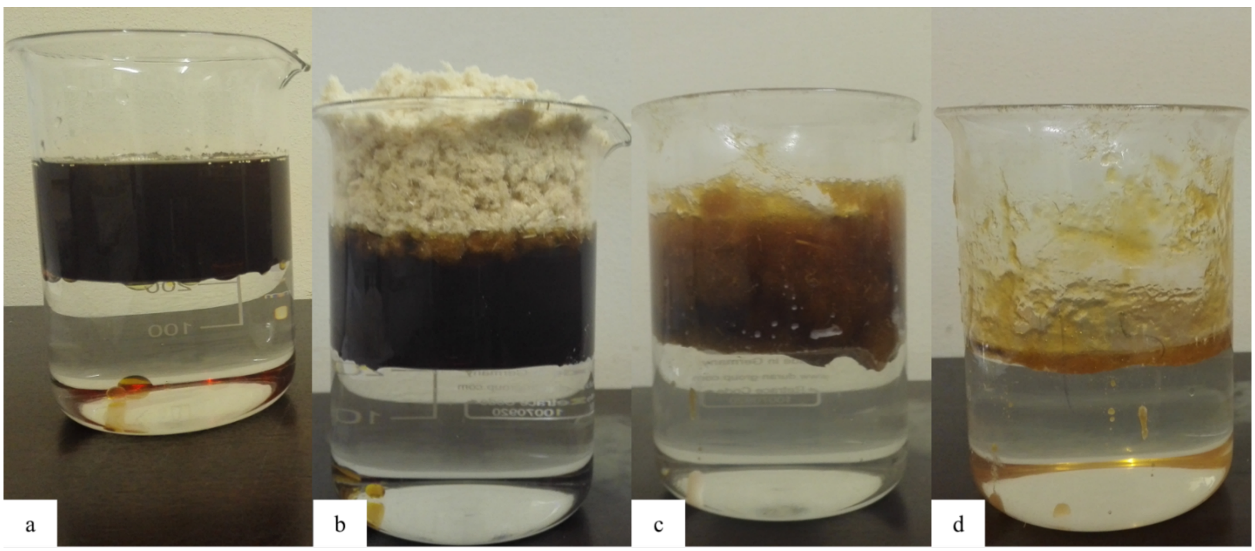


Figure 5.5.8. (a) Simulated oil spill; (b) chicken feather fraction floating on top of the oil layer; (c) chicken feathers saturated with adsorbed oil after 30 minute contact time; and (d) material remaining after removal of the feathers.

The oil adsorption capacities of the chicken feather fractions were evaluated and are depicted in Figure 5.5.9. It is evident that treated chicken feather fractions could absorb oil to about 16 times of its original weight. On the other hand, untreated waste chicken feathers only absorbed oil to about 6 times of its original weight. This is due to the presence of high grease content and other waste contaminants on the surfaces of raw untreated waste chicken feathers

(Figure 5.5.9). The treated chicken feather fractions absorbed oil rapidly as shown in Figure 5.5.9. The result from oil absorption experiment indicates that there was a statistical significant difference between the amount of absorbed oil by untreated and treated chicken feather this is due to the removal of greases and other waste materials from waste chicken feather that could hinder absorption. The high rate of sorption of the oils onto chicken feather fractions can be attributed to the hollow structures, hydrophobic characteristics, high keratin content and strong disulphide bonding in the materials.

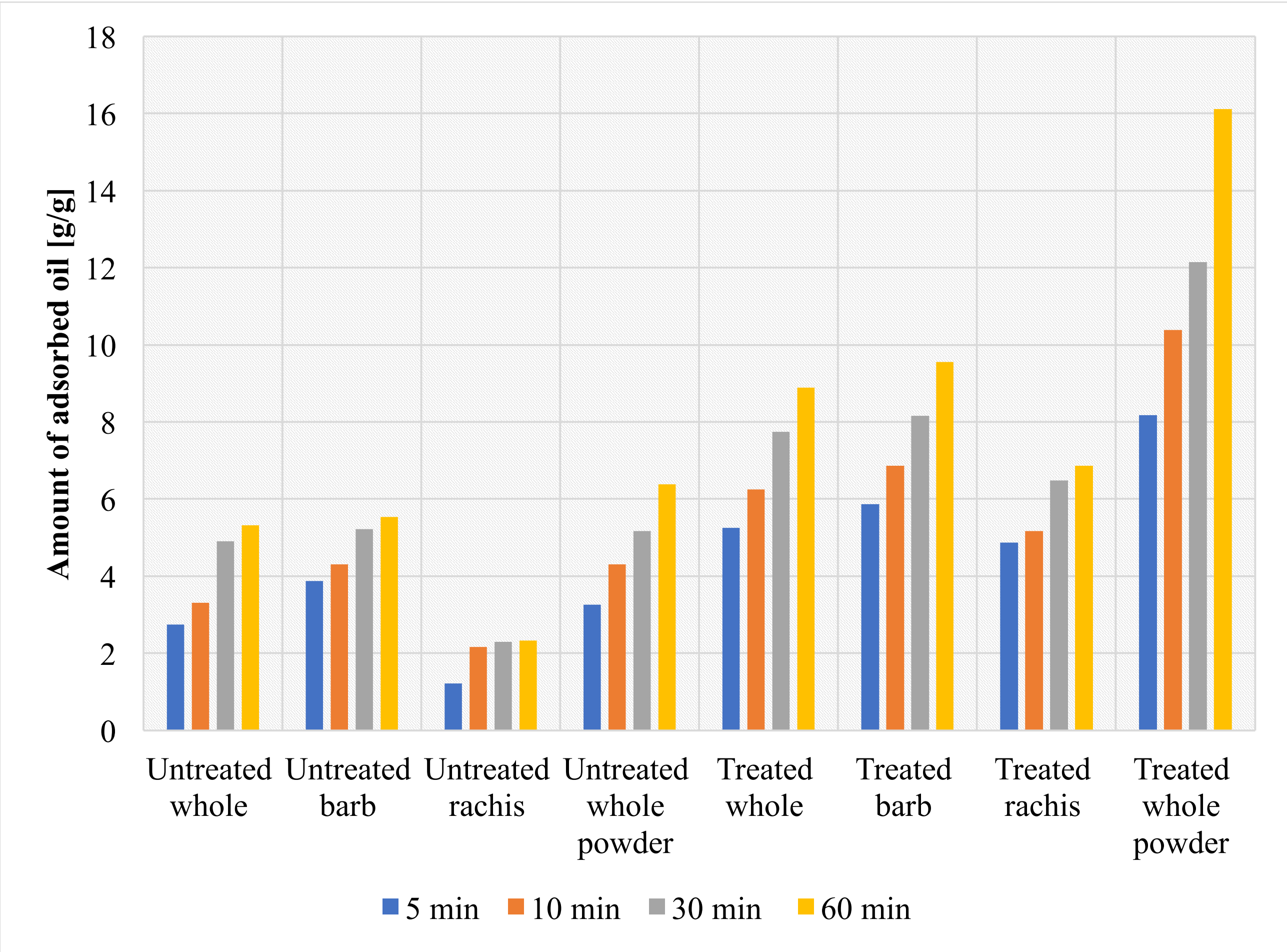


Figure 5.5.9. The amount of oil adsorbed by chicken feather fractions

The oil absorption capacity of chicken feather fractions as a function of time is shown in Figure 5.5.9. It is clear that as the adsorption time increases the amount of oil adsorbed by chicken feathers increases. There is an increase in oil absorption of about 35 % when the contact time is increased from 5 min to 30 min. It can be seen in Figure 5.5.9 that the rate of oil uptake in the adsorption process was rapid initially in the first 10 min and the weight of adsorbed liquid oil had reaching equilibrium in about 30 min, indicating that the chicken feather fractions were saturated. The observed initial rapid sorption may be due to the movement of oil molecules from the higher concentration regions to the surface of the adsorbent. The data indicate that 30 minute contact time would be ideal for oil spill cleanups.

The data also show that whole chicken feathers were more effective in oil removal than individual feather fractions. Thus there is no need to fractionate the feathers.

Oil desorption capacity of chicken feather fractions

The oil recovery efficiency of the chicken feather fractions adsorbent properties were evaluated by pressing using a Carver hydraulic press. Figure 5.5.10 shows that substantial amounts of the adsorbed oil (85-95 %) were recovered from the chicken feather fractions and the recovery was low for chicken feather powders. This could be due to the adsorption of oil on the surface is greater than its absorption in the void of chicken feathers and the oils are attracted and held to the chicken feather fractions surface, including internal fibre walls by physical bonds that becomes easily broken on pressing. The adsorbed sorbates on the surfaces are easily desorbed than the sorbates absorbed within the voids.

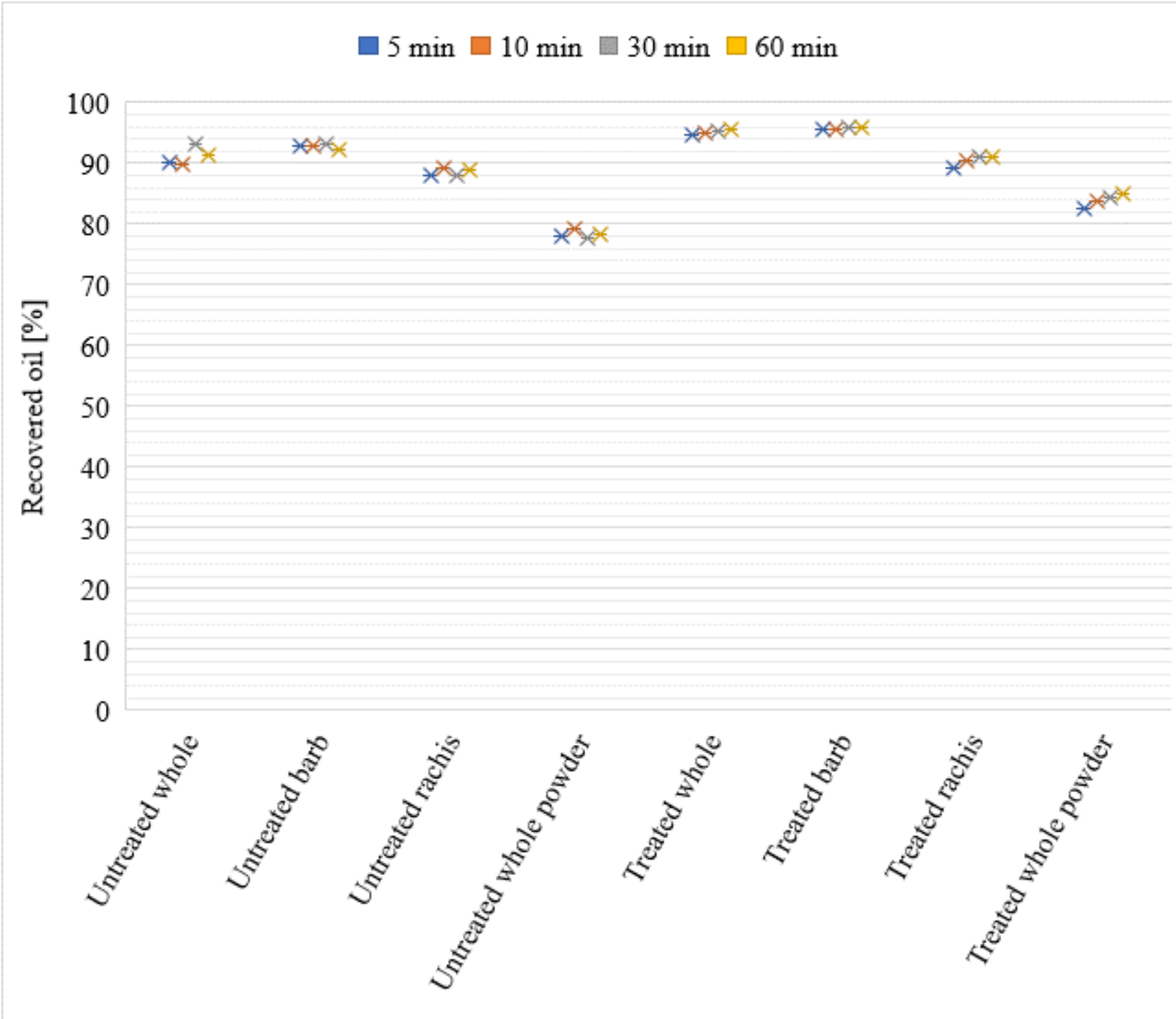


Figure 5.5.10. Amount of recovered oil from chicken feathers fractions and whole feathers

5.5.4. Conclusions

Both treated and untreated waste chicken feather fractions were evaluated for their potential beneficiation as oil spill sorbents from contaminated waters. Treated chicken feather fractions absorb oil up to about 16 times their weights whereas untreated waste chicken feathers only absorbed oil up to about 6 times of its original weight due to high grease content and other waste contaminants on its surfaces that impeded oil adsorption. Characteristics of feathers such as oleophilicity, hollow structure, high keratin content, pore size, and volume distribution, indicate that chicken feathers are ideal oil spill sorbents.

The only processing requirement on feathers for such application is pre-treatment to degrease and decontaminate the materials from microbial contamination. From the experimental results it can be concluded that the rate of oil uptake in the adsorption process was rapid initially in the first 10 min and then gradually increased with increase in contact time up to 30 minutes. Both untreated and treated chicken feathers show promising potential as oil absorbents as they are available abundantly and exhibit high oil absorption capacity. However, use of untreated feathers is not recommended due to the hazardous nature of the waste products. Thus the only processing requirement on feathers for such application is pre-treatment to degrease and decontaminate the materials from microbial contamination. The effects of contact time, the weight of adsorbents, viscosity of oil and the concentration of adsorbate and temperature on the oil adsorption will be studied and optimised in the future.

ACKNOWLEDGMENTS

The authors are highly grateful for the financial and technical support received from: the Institute of Technology for Textile and Fashion Design/EiTEX at Bahir Dar University, Ethiopia; the Thermodynamics Research Unit at the Discipline of Chemical Engineering, University of KwaZulu-Natal; the Biorefinery Industry Development Facility, Council for Scientific and Industrial Research (CSIR), and the Department of Science and Technology, Waste Research Development and Innovation Roadmap.

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CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1. SUMMARY

The general aims of the following work are to develop technically and economically viable technologies/methods for various forms of high-value material production from waste chicken feathers generated from poultry meat processing industries in South Africa.

This work comprises ten main areas

- Optimisation of the decontamination and pre-treatment of waste chicken feather aiming to reduce the microbial contamination.
- Investigating the effect of decontamination and pre-treatment physicochemical and mechanical properties of raw waste chicken feathers and treated feathers.
- Characterisation of waste chicken feather for its physical, mechanical, chemical, electrical thermal properties and morphological and fine detail structure in order to assess the possible valorisation route. Key physical properties, including length, diameter, dimensional analysis, moisture regain, moisture content, aspect ratio, density, BET, were determined. SEM and AFM were used to analyse\ the morphological and fine details structure of waste chicken feathers respectively. The major chemical properties that were in this study are proximate, ultimate analysis, CHNS, FTIR, chemical durability, EDX, hydrophobicity, swelling behaviour. TGA and DSC were used for thermal analysis while two probes technical is used for electrical characterisation. Key mechanical properties Instron and DMA analysis were determined.
- Investigating the presence of proteins using pyrolysis Gas chromatography-mass spectrometry.
- Examining the possibilities of waste chicken feather for the production of speciality paper and investigating the effect of processing conditions on the physicochemical and mechanical properties of handsheets.

- Investigating the use of waste chicken feather in yarn production and other technical textile applications based on the physical, chemical, thermal, mechanical and electrical characterisation.
- Investigating the possible valorisation avenue based on the chemical, physical, mechanical, electrical, thermal properties and morphological and fine detail structures.
- Production and characterisation of lightweight composite materials for construction industry using waste chicken feathers.
- Production and characterisation of bioplastics from waste chicken feather to be used for food packaging applications.
- Investigating the adsorbent properties of waste chicken feather aiming for oil cleaning from water streams.

6.2. CONCLUSIONS

The purpose of this work was to examine the potential of waste chicken feathers to be beneficiated into high value compounds and materials in order to develop environmentally sustainable technologies for disposal of the waste. Traditional disposal strategies of waste chicken feathers are expensive and difficult to implement. Hence they are limited to incineration, burial in landfills or recycling into low quality animal feed. These disposal methods are restricted, generate greenhouse gases or pose danger to the environment. This dissertation has demonstrated that waste chicken feathers can be beneficiated into high value materials and products thus solving the waste disposal problem. These high value products have potential to generate additional valuable income to the poultry industry. The research has resulted in the publication of 7 papers in peer-reviewed journals, one conference proceeding and 5 more that have been submitted or are in preparation. This researh is the first of its kind in South Africa. This chapter gives a summary of basic findings of the thesis. Below is a summary of the papers (1-10) that comprises the thesis.

6.2.1. Decontamination and pre-treatment (based on paper 1 and 2)

The results showed that bleaching agents were effective in decontamination of chicken feathers and the order of efficacy followed the order H_2O_2 > NaOCl > $Na_2S_2O_4$. In general decontamination of waste chicken feather using surfactant is better than bleaching agents in terms of removing the microbial counts. Althoug the decontamination process is water intensive process, the process of decontamination and pre-treatment is an essential process for future valorisation of waste feathers. A preliminary commercial feasibility analysis of the technologies indicates that using POE for decontamination of waste feathers was more cost-effective than using SDS and DDAC. And the production of high value materials from chicken feather not only reduces the levy cost of waste disposal but also have a positive economical effect for the poultry meat processing industries.

6.2.2. Characterisation (based on paper 3-5)

The data on analysis and characterisation of waste chicken feathers for their physical, thermal, mechanical, electrical and mechanical properties and morphological and fine detail structure provides a foundation knowledge and ideas for possible valorisation route. Paper 3 of the thesis comprehensively discusses physical properties and morphological structures of chicken feather fractions that indicate indicate that chicken feathers have unique features. The barb, unlike any other natural or synthetic fibre, is a protein fibre that has low density, high flexibility, good spinning length and a hollow honeycomb structure. The rachis has low density, low rigidity, and a hollow honeycomb structure. These characteristics indicate that chicken feather barbs can be utilised to manufacture textile products either on their own or by structural interaction with other fibres. The planar cross-section of barbules where they intersect with the barbs could give compression resistance for the fibre. This work shows that chicken feather rachis has a lower aspect ratio and flexibility than the barb. The density of the rachis fraction is less than that of the barb of chicken feather due to higher air voids. The characteristics of both the barb and the rachis, make them suitable for the manufacture of composite materials. Because of the presence of hollow honeycomb structures and a very low-density, chicken feather rachis and barbs could be used for applications that require excellent compressibility and resiliency, warmth retention, fluid absorption, lightweight composites and sound protection applications. Results of this study indicate that incorporation of chicken feathers can be beneficial in various industries including construction, automotive, aerospace and plastics to make products that are lightweight, improve sound attenuation, and offer insulate from heat loss.

Paper 4 of this thesis discussed the chemical properties of chicken feather fractions. The proximate analysis of chicken feathers revealed the following nutrients and anti-nutrients: crude lipid, crude fibre, crude protein, ash, NFE and moisture content whereas the ultimate analyses showed: carbon, nitrogen, oxygen, and sulphur. FTIR analysis revealed that the chicken feather fractions contain amide and carboxylic groups indicative of proteinaceous functional groups; XRD showed a crystallinity index of 22. Durability and burning tests confirmed that feathers behaved similarly to animal proteins. The results confirm that chicken feathers contain animal fibres. Close similarities in thermal properties between barb and rachis fractions indicate that the fibre fractions do not need to be separated for beneficiation into products that take advantage of these propertiesThe results from electrical properties indicated that chicken feather fractions have low conductivity, high resistivity, and dielctric constant lower conventional semi-conductor insulator materials. Overall, the results indicate that chicken feathers have potential to be used in a variety of applications such as electrical insulator materials, yarn production for use in textiles, nonwoven fabric production, filler for winter clothing, geotextile and construction materials. Such beneficiation of waste chicken feathers would open up new industries and job opportunities, and make the poultry industry more competitive.

The chemical functional groups, physical properties, thermal stability, chemical properties, microstructure, and the mechanical properties of chicken feather barbs were determined as reported in Papers paper 3, 4 and 5. The structure and properties of chicken feather barb are similar to the two most common natural proteinous fibres, viz., wool and silk. The unique properties of chicken feather barbs such as low density, high slenderness ratio, good pliability, moderate strength, spinnability, fineness and length, durability, and high moisture regain provide unique properties that make barbs suitable for use in textile applications.

The levy paid by poultry processing industries for waste disposal has a negative economic influence on the abattoirs. Due to the environmental and health risk of the rendered poultry by-products the disposal process becomes expensive that drives up the cost of poultry meat and due to price competitiveness, the local poultry production growth rate has slowed significantly and imports of poultry meat into the country have increased. Reducing the cost related to waste disposal and adding value to the waste creates new avenue for the poultry processing industries that could help them to be competitive in the local and global poultry market.

The South African waste sector provides an opportunity to recover valuable materials to return them back into the local manufacturing economy as high value products (strengthening the local economy), create new jobs in an emerging secondary resources economy, create job opportunities for low skilled, unemployed citizens, through low barriers to entry, establish new enterprises, including co-operatives and SMMEs, to stimulate a local Green Economy. The results from this thesis demonstrate that it is possible to produce a large variety of products from waste chicken feathers. Ascertaining economic viability of the developed processes was beyond the scope of this thesis.

CHAPTER 7

RECOMMENDATION FOR FUTURE RESEARCH

The results of the present study suggested a number of new avenues for research in future. Some recommendations for future areas of research include;

- The work can be extended to study other possible valorisation areas such as composite for automobile interiors, filling properties of waste chicken feather in winter clothing, nonwoven fabric production for apparel and technical applications, yarn production, geotextile materials, production of multilayer and hybrid composite and energy storage materials.
- This work can be further extended to production of nanostructured materials for different sectors.
- Optimisation of the production of lightweight composite to be used in future housing
- Optimisation of binder synthesis for forest products application
- Production of superabsorbent materials to be used in diaper production
- Future studies will entail studies on the effect of starch modification, keratin modification, different plasticizers, concentration of plasticiser, and extrusion/casting condition on physiochemical and mechanical properties of the keratin/starch film. The possibility of the film for its drug release and other medical applications would be also analysed.
- The effects of contact time, the weight of adsorbents, viscosity of oil and the concentration of adsorbate and temperature on the oil adsorption will be studied in the future.
- The performance of chicken feathers in making paper for mainstream applications will be studied further by varying process parameters (e.g., refining conditions, bleaching conditions, beating condition and change in freeness values) to improve performance characteristics of the papers.

- Optimisation the process of utilisation waste chicken feather in paper production and techno-economic feasibility analysis could be studied in order to assess the conversion of the technology into SMMEs.
- The techno-economical analysis of keratin extraction, composite production and bioplastic production could be studied in order to assess the conversion of the technology to SMMEs and cooperatives.

APPENDICES

APPENDIX A

PUBLICATIONS

PUBLICATION TWO

ARTICLE IN PRESS

Waste Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Optimisation of surfactant decontamination and pre-treatment of waste chicken feathers by using response surface methodology

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ARTICLE INFO

Article history:
Received 28 April 2017
Revised 16 October 2017
Accepted 5 November 2017
Available online xxxx

Keywords:
Microbial count
Chicken feather
Grease content
Whiteness
Surfactant

ABSTRACT

Commercially processed, untreated chicken feathers are biologically hazardous due to the presence of blood-borne pathogens. Prior to valorisation, it is crucial that they are decontaminated to remove the microbial contamination. The present study focuses on evaluating the best technologies to decontaminate and pre-treat chicken feathers in order to make them suitable for valorisation. Waste chicken feathers were washed with three surfactants (sodium dodecyl sulphate) dimethyl dioctadecyl ammonium chloride, and polyoxyethylene (40) stearate) using statistically designed experiments. Process conditions were optimised using response surface methodology with a Box-Behnken experimental design. The data were compared with decontamination using an autoclave. Under optimised conditions, the microbial counts of the decontaminated and pre-treated chicken feathers were significantly reduced making them safe for handling and use for valorisation applications.

1. Introduction

With the development of large-scale poultry farming, the disposal of large amounts of waste chicken feathers is a long-standing problem. On a world scale, it is estimated that approximately 40×10^9 kg of chicken feathers are produced from the slaughter of more than 58×10^9 chickens (Compassion in world farming, 2013). In 2013, the South African poultry farming activity generated more than 528×10^6 kg of feathers (DAFF, 2014). Chicken feathers constitute 5–10% of the weight of the chicken and comprise a significant portion of the poultry wastes (Tseng, 2011; Pourjavaheri et al., 2014). Poultry waste is divided into solid waste (feathers, viscera, heads, feet, carcases, skin and bones), and liquid waste (blood and liquid effluents) (EL Boushy et al., 2000). The disposal of this waste gives rise to environmental and health concerns, and are guided by legal requirements and contemporary best practices, such as the Zero Waste Initiative in South Africa (Karani and Jewasikiewitz, 2007). Common disposal techniques such as incineration, landfilling and composting are not environmentally sustainable in that they are energy intensive, and/or take up valuable landfill space, as well as contribute to the emission of greenhouse gases (Sudalaiyandi, 2012; Coward et al., 2006; Tseng, 2011; Pourjavaheri et al., 2014). Hence valorisation of chicken feathers by conversion into valuable materials is a desirable route for dealing with the waste. For example, it has been reported that waste chicken feathers can potentially be converted into high value materials and products such as automotive products (side trims, door inner panels and body panels), medical products (drug delivery carriers, scaffolding and tissue engineering), cosmetics (for skin and hair), bioplastics, paper additives, nonwoven textiles, superabsorbent materials, biodiesel, energy storage, electrical insulators, and composites for use as reinforcements in construction and furniture industries (Tesfaye et al., 2017a, 2017b, 2017c, 2017d).

It has also been reported that chicken feathers can be used in preparation of microbial peptones (Taskin and Kurbanoglu, 2011), protein hydrolysates for use as a nutritional substrate for microbial production of valuable substances, such as carotenoid (Taskin et al., 2011), polysaccharide (Taskin et al., 2012), glutathion (Taskin 2013), and lactic acid (Taskin et al., 2013). Other studies have demonstrated that waste feathers could be used as plant fertilizer (Paul et al., 2013; Jie et al., 2008; Hadas and Kautsky, 1994) and low-grade animal feed (Davis et al., 1961; EL-Boushy et al., 1990; Grazziotin et al. (2006)) immobilization supports for enzymes or chemicals (Chauhan et al., 2016), in paper production (Tesfaye et al., 2017a, 2017b, 2017d), for biogas production

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https://doi.org/10.1016/j.wasman.2017.11.013
0956-053X/

Please cite this article in press as: Tesfaye, T., et al. Optimisation of surfactant decontamination and pre-treatment of waste chicken feathers by using response surface methodology. Waste Management (2017), https://doi.org/10.1016/j.wasman.2017.11.013

(Patinvoh et al., 2016), and for preparation of carbon nanotubes (Gao et al., 2014).

As mentioned in the preceding paragraphs, waste chicken feathers are biological waste that is loaded with microbial contamination from bacteria in the intestinal tracts of the harvested chickens. Consequently, disinfection of waste feathers is an important prerequisite for valorisation of this waste biomass. Mesophilic or psychotropic organisms can grow on all parts of chicken feathers considering that chickens are warm-blooded mammals (Rajchard, 2010). In poultry processing plants, feathers are plucked from the chickens and they generally lie in heaps, containing smaller amounts of various foreign materials such as offal, dilute blood, biological organisms, grease, skin, faeces, flesh, and water. Due to the contamination with blood, intestinal contents, offal fat, fatty acids, debris and preen oil fresh chicken feathers can be a suitable habitat for many microorganisms (Cunningham, 2012; Gill, 1998). In general, as a by-product of poultry processing, unprocessed raw feathers appear straw-like (the barbs get stuck to the rachis); they have a greasy texture, a brown colour, and are spattered with blood, emitting an obnoxious odour (Tesfaye et al., 2017a, 2017b, 2017c).

There are a variety of reasons for the appearance and texture of plucked feathers. A preen gland secretes lipids to uphold the feather's properties (e.g., waterproofing), giving rise to the greasy texture (Jones, 2005). Free fatty acids from lipid decomposition and pigment cells, called melanocytes, are responsible for microbial growth and the dull yellow colour of feathers after slaughter. The growth of microorganisms on chicken feathers will cause them to decompose and could impart potentially fatal biological hazards for humans. Table 1 shows bacterial control points in a typical waste chicken feather biomass. It is evident that chicken feathers contain different types of hazardous microorganisms and the major ones are enterococci, coliforms, and sulphate reducing bacteria. Indeed, chicken feathers contain the highest total microbial counts (69,457 Cfu/cm^2/cm^3) (Table 1) compared to other control points in poultry slaughtering industries. Consequently, waste chicken feathers need to be adequately disinfected before handling and processing for valorisation purposes. Since the objective is to valorise feathers, it is important to develop technologies for decontamination and pre-treatment of chicken feathers that will render the feathers safe for handling but without negatively impacting the composition and structure of the feathers.

Chicken feathers could be a fatal hazard for humans if they are not processed or disposed of properly. Technologies need to be developed and customised for commercial pre-treatment and decontamination of feathers to a standard that is appropriate for their further use. Most importantly, raw chicken feathers require decontamination and pre-treatment to remove pathogens and impurities that cause objectionable odours, discoloration and to ensure process hygiene. Technologies for cleaning feathers can be adapted from those used for decontamination and pre-treatment of natural fibres used in the textile industry, e.g., washing with organic or inorganic solvents, or washing with surfactants (Augurt and Van Asten, 2000; Falbe, 2012; Sudalaiyandi, 2012; Tseng, 2011; Pourjavaheri et al., 2014). Decontamination is the removal or reduction of microbial count whereas pre-treatment refers to cleaning activities mainly for the removal of grease, fat, sand etc. Cleaning of contaminants from the feather material can be done by dissolution of the contaminants in suitable solvents, mechanical detachment, evaporation, and chemical treatment.

In this study, decontamination by washing with surfactants was selected and the efficacies of the procedures were compared with decontamination by high heat using an autoclave unit. The efficacy of the decontamination was evaluated by monitoring the microbial content of the treated and untreated samples as well as by monitoring grease content of the samples. The use of surfactants for decontamination was selected as this would be more cost effective than using high energy intensive autoclaving technology. Surfactants are commonly used in decontamination and pre-treatment of materials; they are surface-active detergents that provide remarkable benefits in dispersing, chemical or dye absorption, heat transfer, wetting, softening, emulsification, dye fixation, melting, vaporisation, sublimation, foaming and defoaming in the textile industry (EL Boushy et al., 2000; Pletnev, 2001). The surface activity and disinfecting/bactericidal performance of a surfactant is dependent on various factors such as concentration, pH, solid to liquid ratio, the number of treatment cycles, temperature, and contact time (Mandavi et al., 2008). Their bactericidal activity has not been extensively investigated, but it is claimed that they do have strong bactericidal activity (Pletnev, 2001; Tadros, 2006).

2. Materials and methods

2.1. Materials

Waste chicken feathers were supplied by a slaughterhouse in the province of KwaZulu-Natal, South Africa. The surfactants evaluated for use as combined pre-treatment and decontamination agents were: sodium dodecyl sulphate (SDS) – (anionic chemistry); dimethyl dioctadecyl ammonium chloride (DDAC) – (cationic surfactant); and polyoxyethylene (40) stearate (POE) – (non-ionic chemistry), and all were obtained from Sigma–Aldrich. Hexane (Sigma–Aldrich) was used for grease content analysis. Peptone (Merck) and yeast extract agar (Merck) were used for the bacteriological analyses.

2.2. Decontamination and pre-treatment

Pre-treatment was done by removal of materials that were not feathers: these included offal, dilute blood, grease, sand, faeces, and waste water. Decontamination was done to remove blood borne pathogens during slaughtering and microorganisms present in chickens. In this study the materials and contaminants were removed by one pot treatment using various surfactants.

2.2.1. Sampling

The act of obtaining samples from a bulk system is subject to errors that can neither be detected not compensated due to the

Table 1
Bacterial contamination control points in the poultry industry (). adapted from Jones, 2005

Control points	Total viable counts (Cfu/cm^2/cm^3)	Enterococci (cfu/cm^2/cm^3)	Coliforms bacteria (Cfu/cm^2/cm^3)	Sulphate reducing bacteria (Cfu/cm^2/cm^3)
Feathers	69457.0	184.5	0.9	179.1
Bleeding knife	7269.0	227.0	19.6	8.4
Scalding water	6421.0	5.3	0.9	55.2
Pluckers' rubber finger	2362.5	73.1	1.6	21.6
Carcass surface	6984.0	197.1	15.3	4.8
Plucking finishing table	55444.0	793.35	1483.6	225.0

Cfu = colony forming units.

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bulk system being non- homogeneous and the sample therefore possibly not being exactly representative. Since waste chicken feathers fall under this category, maximum representative samples were prepared by placing raw feathers in a mixing vessel and thoroughly mixed to form an aggregate sample from which the final sample was obtained using the sample division system.

2.2.2. Decontamination and pre-treatment procedures

Statistically designed experiments on decontamination and pre-treatment of waste feathers were used to ascertain optimum conditions for decontamination and pre-treatment of waste feathers. For factor screening analysis, 5 g raw chicken feathers were processed by Soxhlet extraction under different conditions that were: surfactant concentrations, contact time, temperature, number of stages, feather to liquid ratio, pH, and stirring speed as listed in Table 2. After screening the most significant factors using a Plackett-Burman design, the optimisation process was carried out using a Box-Behnken design (Table 3). For the optimisation process the following combinations were used; surfactant concentrations (0.15–1.00% w/v), number of stages, (1 –3), time (5–60 min), and temperature (25–100 °C). After decontamination and pre-treatment, the liquid was filtered using a 0.5 mm mesh filter and the treated chicken feathers were rinsed with tap water until the washing solution was free of surfactants (no foaming). The treated chicken feathers were laid on aluminium foils and dried to constant mass at 70 °C in an air-forced dryer after which they were stored in sealed plastic bags, in a controlled laboratory environment (20 °C, 65% relative humidity) for further characterisation (Fig. 1). In addition to these methods, the chicken feathers were decontaminated by autoclaved in a sterilisation process (vertical type steam steriliser, HL-340, Already Enterprise Inc. Taipei, Taiwan) with saturated steam at 132 °C for 20 min at 4 kg/cm^2. This was used as a comparison with the raw and treated chicken feathers.

2.3. Determination of microbial content

Treated, untreated, and autoclaved chicken feather samples were conditioned to ambient temperature for 1 h prior to testing for microbial content using standard methods (Pourjavaheri et al., 2015). A 0.1 g sample was mixed with 9.9 ml of sterile peptone water (8.5 g NaCl and l g peptone (Merck) per litre) to restore microbial cells to enable a good estimate of microbial counts. The sample was then shaken at 120 rpm for 30 min to ensure proper mixing and homogenisation. 1.0 ml of the homogenised mixture was pour plated onto yeast agar (Merck) and incubated at 30 °C for 24–48 h, after which the microbial colonies were counted on a digital plate reader. A schematic of the process is summarised in Fig. 2.

2.4. The effect of decontamination and pre-treatment on physicochemical and mechanical properties of chicken feathers

2.4.1. Removal of impurities

Impurity removal is a measure of mass lost from the raw chicken feather during pre-treatment and decontamination, represented as a percentage of the weight loss and calculated using Eq. (1):

$$\text{Impurity removal}\ (\%) = \frac{M_1 - M_2}{M1} * 100 \quad (1)$$

where M_1 is a dry raw chicken feather and M_2 is a dry decontaminated and pretreated feather in grams.

2.4.2. Residual grease content

Residual grease is the grease content of chicken feathers after pre-treatment and decontamination. The residual grease content of treated chicken feather was determined by extracting the washed samples with hexane using a Soxhlet apparatus according to ASTM D1574 (ASTM D1574, 2013). Three replicate samples were measured for each of the decontaminating and pre-treatment techniques.

2.4.3. Fourier transform infrared (FTIR) spectroscopy

FTIR spectroscopy (Frontier Universal ATR-FTIR, from PerkinElmer) was used to ascertain if the decontamination and pre-treatment procedures affected the functional groups of the feathers. A universal attenuated total reflectance (ATR) module was used for all spectra in a wave number range between 400 cm^{-1} and 4000 cm^{-1}.

2.4.4. Whiteness and yellowness indices

The pre-treated and decontaminated feathers were monitored for their colour using a spectrocolorimeter, which was standardised with Hunter lab colour standards. The colour of the chicken feathers in terms of L*, a*, and b* values were measured with a Hunter lab Colorimeter (Greta Macbeth Colour Eye 3100). The whiteness value was obtained according to Eq. (2):

$$\text{Whiteness}\ \% = 100 - [(100 - L)^2 + a^2 + b^2]^{\frac{1}{2}} \quad (2)$$

2.4.5. Fibre density

The density of the chicken feather fractions was measured using a liquid pycnometer (Rude et al., 2000). Five replicates were performed for each sample type.

Table 2
Placket-Burman design for screening the significant factors.

Run	Variables							Response
	Concentration of surfactant, %w/v	Temperature, °C	Time, min	Feather to liquid ratio	Number of stage	pH	Stirring speed, RPM	Bacteria content, Cfu/g
1	0.15	100	5	1:50	1	3	500	988
2	0.15	100	5	1:50	3	10	0	597
3	0.15	25	5	1:10	1	3	0	1097
4	1	25	5	1:50	1	10	0	507
5	0.15	25	60	1:10	1	10	500	684
6	1	100	60	1:10	1	10	0	338
7	1	25	60	1:50	1	10	0	449
8	1	100	60	1:50	3	10	500	0
9	1	100	5	1:10	3	10	500	97.3
10	1	25	5	1:10	1	3	500	367
11	0.15	25	60	1:50	3	10	500	233
12	0.15	100	60	1:10	3	3	0	127

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Table 3
Coded values of variables used in Box-Behnken design.

Coded value	Independent variables	Level		
		−1	0	1
X_1	Concentration (% w/v)	0.15	0.58	1.00
X_2	Temperature (°C)	25.00	62.50	100.00
X_3	Time (min)	5.00	32.50	60.00
X_4	Number of stage	1.00	2.00	3.00

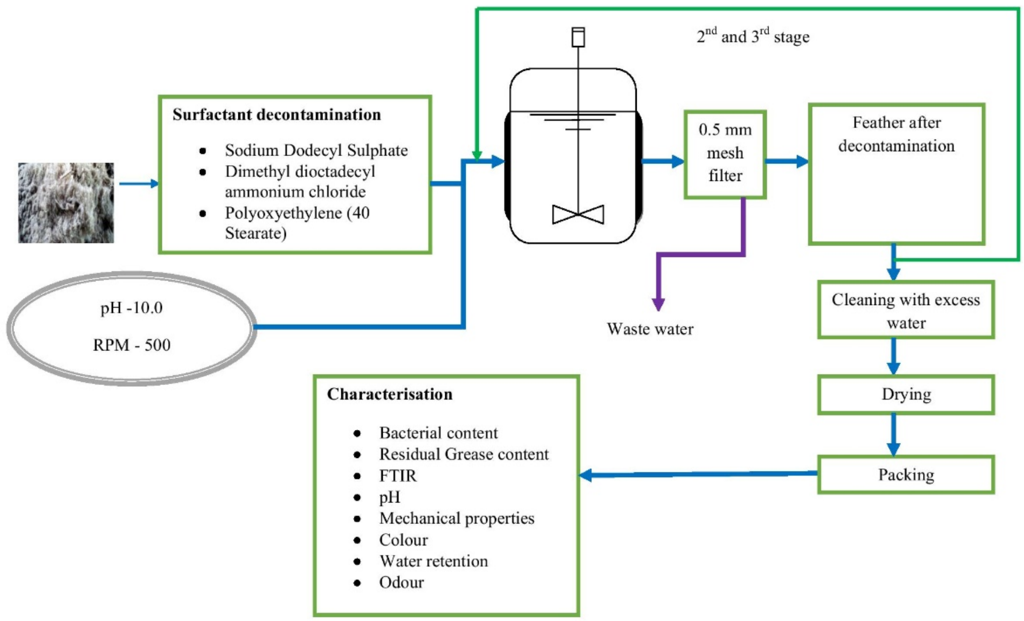

Fig. 1. Decontamination and pre-treatment block diagram.

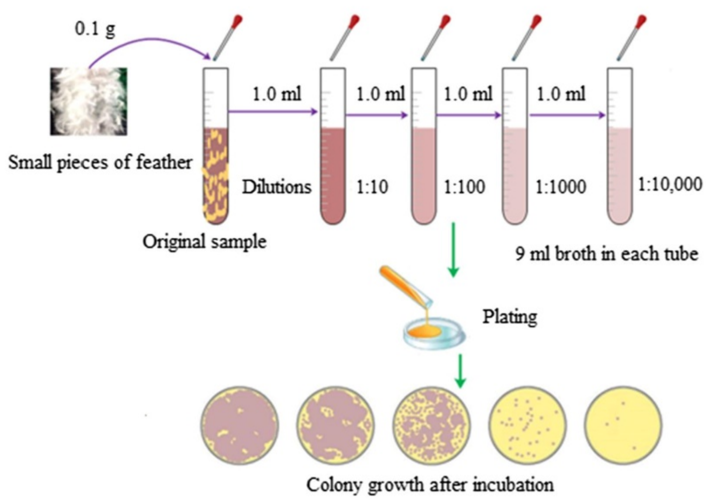

Fig. 2. Pour plate technique for microbial test on treated and untreated chicken feathers.

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2.4.6. Water retention and moisture regain

Decontaminated and untreated chicken feather samples were dried at 105 °C for over 4 h and weighed (W_1) before soaking in distilled water at different temperatures for 5 min. The wet chicken feathers were removed and centrifuged for 5 min at 9000 rpm and weighed again (W_2). Water retention (%) was calculated according to equation 3 and the average of three tests was taken:

$$Water\ retention\ (\%) = \frac{W_2 - W_1}{W_1} * 100 \quad (3)$$

2.4.7. Morphological and elemental profile analysis

The impact of the decontamination and pre-treatment techniques on the morphology and elemental composition of the feathers was investigated using low-resolution scanning electron microscopy and energy dispersive spectroscopy (EDS). Chicken feathers from experiments that showed superior bactericidal efficacy were further analysed using high-resolution scanning electron microscope (SEM) analysis as well as elemental profile analysis using energy dispersive spectroscopy (EDX) using a Field Emission Gun Scanning Electron Microscope with EDX capability (Carl Zeiss, Oberkochen, Germany).

2.4.8. Mechanical properties

The feather samples were dried and conditioned at a relative humidity of 65 ± 2% and a temperature of 22 ± 2 °C and then used to measure their bundle strength tenacity, length, and single feather strength. The feathers were carefully combed with a fine comb, and then 11.8 mm long feathers were prepared. The bundle tensile test was carried out on an Instron Tensile Tester (Model 3345) at 0 mm gauge length.

2.4.9. Thermogravimetric analysis

The thermal properties of untreated and treated samples were measured using a Perkin-Elmer TGA thermogravimetric analyser, under temperatures that ranged between 25 °C and 550 °C, at a heating rate of 20 °C min^{-1} under nitrogen gas purge.

2.5. Statistical optimisation

The conventional method of experimental design, i.e., changing one factor at a time, is laborious and often ignores the interactive effects of each independent variable (Montgomery, 2008). With this in mind, a Plackett-Burman factorial, design-and-response was used wherein the surface methodology was used for screening and optimisation of the parameters under study. The objective was to evaluate various surfactant pre-treatment and decontamination strategies to purify chicken feathers prior to valorisation. The resultant data can be used to target decontamination applications and to develop financial analysis informed by an understanding of necessary processing costs and potential financial benefits. The heterogeneous properties of chicken feather had to be considered in all decontamination and characterisation processes.

2.5.1. Screening using Plackett-Burman factorial design

A selection of major factors required for the minimum microbial count was performed using a Plackett-Burman design. The effects of seven factors, namely surfactant concentration, the number of treatment stages, time, temperature, pH, feather to liquid ratio, and stirring speed, were investigated at two levels (minimum and maximum). Statistica 13.2 and JMP 13.0 software (Stat-Ease, Minneapolis, USA) were used to generate 12 sets of the experiments (Table 2). The effect of each factor on microbial count was determined using the calculated p-value of each factor.

2.5.2. Optimisation using response surface methodology (RSM)

The four major factors and their interactions selected by the Plackett-Burman design were analysed and optimised by means of a Box-Behnken design. A Box-Behnken design with four factors (surfactant concentration (0.15–1% w/v), the number of treatment stages (1–3), treatment time (1–60 min), and temperature (25–100 °C) with a total number of 27 experimental runs was employed for each type of pre-treatment and decontaminating agent. The coded values of the variables at various levels are given in Table 3. Microbial count, residual grease content, and impurity removal were determined by the coefficient of determination, analysis of variance, and contour plots. Using multiple regression analysis, the data obtained was fitted into a second-order polynomial Eq. (4).

$$Y = \beta_0 + \beta_i X_i + \beta_{ij} X_i X_j + \beta_{ii} X_i^2 \quad (4)$$

where Y is the predicted response variable; β_0, β_i, β_{ii}, β_{ij} are constant regression coefficients of the model; and Xi, X_j ($i = 1, 3$; $j = 1, 3$; $i \neq j$) represent the independent variables in the form of coded values.

2.6. Feasibility analysis of the pre-treatment and decontamination procedures

A preliminary technoeconomic analysis of the procedures was evaluated considering their efficiency in terms of cost of chemicals, the number of treatment steps, the temperature of treatment, and the treatment time required. The comparison of costs of chemicals for decontamination and pre-treatment of 5 g chicken feather was based on the price of reagent grade surfactants. Further requirements for additional costs were noted (e.g., number of treatment stages, treatment time, and temperature).

3. Results and discussions

Experiments were conducted to achieve the objectives of the decontamination and pre-treatment of chicken feather studies. Further aims included determining the optimum washing conditions based on minimum bacterial count and the effect of pre-treatment on physicochemical and mechanical properties of the chicken feathers.

3.1. Effect of surfactant treatment on appearance and odour of chicken feathers

Visual inspection of the samples showed that the barbs of raw chicken feathers were tangled and stuck to the rachis. When left at room temperature, the raw wet feathers turned dark brown after two days and had a distinct putrid smell – the raw chicken feathers turned dark brown from bacterial decomposition. After washing with water, their barbs opened and appeared white, however the odour remained. The untreated feathers contained blood, which looked pink upon collection but turned brown after drying. This allowed the bacteria to excrete waste material that caused the feathers to darken (Tseng, 2011; Pourjavaheri et al., 2014). The treated feathers exhibited weight loss compared to the raw and autoclaved samples. This indicates that there was a large amount of impurities in the initial sample. The surfactant treatment imparted a soap smell to the feathers and changed their colour from brown to white. Decontamination and pre-treatment require frequent changes of the washing solution to prevent resorption of the contaminants as a result of rapid saturation of the solution with contaminants. The repeated deposition of contaminants can also be caused by the destruction of solvate membranes from molecules of the surfactants as a result of intensive mechanical action (Tadros, 2006; Tseng, 2011). During the final washing stage,

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the residual surfactant present in the treated feathers had to be completely removed by adequate rinsing with tap water since any residual surfactants would cause chemical degradation of the feathers (Tseng, 2011; Pourjavaheri et al., 2014). The effects of treatment of feathers with surfactants on the visual appearances of the feathers are illustrated in Fig. 3.

3.2. Screening of factors using the Placket-Burman design

Using the Placket-Burman design, seven independent variables (i.e., concentration, time, temperature, feather to liquid ratio, the number of stages, pH and steering speed) were screened with regard to their effects on bacterial content and residual grease. The 12 experimental runs generated using the software and corresponding responses (microbial count) are shown in Table 2. An ANOVA analysis of the Placket-Burman design results is presented in Table 4. The parameters with p-values of less than 0.05 were considered to have a significant effect on the microbial count. As shown in Table 4, concentration, time, temperature, and number of stages were the most significant factors ($p < .05$). Out of the significant variables screened using the Placket-Burman design, concentration, time and number of stages exerted a positive effect on bacterial content, whereas temperature exerted a negative effect.

3.3. Microbial counts

As expected the untreated chicken feathers had the highest microbial counts (1.48E + 07 ± 6.72E05 Cfu/g) (Table 5) and decontamination by autoclaving reduced the microbial count by a thousand-fold to 2.81E + 06 ± 5.62E04 Cfu/g. Results for microbial counts after treatment of feathers with surfactants are shown in Figs. 4–6. The results show that the surfactants were effective in removing microorganisms from the feathers. The lower standard microbial counts in the treated samples could be due to the microorganisms being washed away in the surfactant decontamination and pre-treatment processes. Additionally, the lowering of microbial content is due to bactericidal properties of surfactants (Davis, 1960; Huffman, 2002; Kronberg et al., 2014). Decontamination with SDS was the most effective in reducing microbial counts. As shown in Figs. 4–6, the order for microbial reduction was according to the order POE > DDAC > SDS. This was the same trend observed for corresponding critical micelle concentration and surface tension values of the surfactants (Mandavi et al., 2008). The lower standard microbial counts indicate higher bactericidal removal.

The data in Figs. 4–6 shows that the microbial counts of the treated chicken feathers were significantly dependent on the number of treatment stages and concentration of surfactant used, followed by time, and temperature. The first treatment stage did not reduce the microbial loads as effectively as the 2nd and 3rd decontamination cycles. However, a single decontamination cycle with all types of surfactants may provide sufficient disinfection if the treated feathers were to be used for the production of composites.

All the decontamination and pre-treatment procedures with all the surfactants studied showed significant decreases in microbial counts (Figs. 4–6). This is in agreement with literature data that indicate that surface active agents are capable of eliminating a broad range of microorganisms (Mandavi et al., 2008).

3.4. Optimisation by Box-Behnken design

The microbial count decreased more than a thousand-fold after decontamination and pre-treatment (Table 5). Four signal factors obtained in Placket-Burman design were further optimised using the Box-Behnken design. Twenty-seven experimental runs were conducted for each surfactant type. In this model, the effect of individual, or a combination/interaction of independent variables on microbial count were assessed. The processed data from the experimental design enabled calculation of the coefficients of the regression equation – which characterise the dependency of microbial count on the independent variables. After the exclusion of insignificant coefficients of the regression equation, a multiple mathematical model regression analysis of the observed responses can be predicted by the quadratic model below (Eqs. (5)–(7)):

$$(\mathbf{MC}(\mathbf{SSD}))^{0.35} = +2.682 - 0.973 * X_1 - 0.089 * X_2 - 0.003 * X_3 - 0.003 * X_4 - 0.922 * X_1 * X_2 + 0.005 * X_1 * X_3 - 0.002 * X_1 * X_4 + 7.2e - 005 * X_2 * X_3 - 0.0003 * X_2 * X_4 - 4.4e - 005 * X_3 * X_4 \quad (5)$$

$$(\mathbf{MC}(\mathbf{POE}))^{0.26} = +24.609 - 6.441 * X_1 - 5.79176 * X_2 - 0.021 * X_3 - 4.179e - 003 * X_4 \quad (6)$$

$$(\mathbf{MC}(\mathbf{DDAC}))^{0.13} = +4.210 - 0.925 * X_1 - 0.723 * X_2 - 2.689e - 003 * X_3 - 2.668e - 003 * X_4 \quad (7)$$

Analysis of the equation of regression allows us to draw a conclusion that the criterion of optimisation (microbial count) in the selected factor space is influenced by four factors – the concentration of surfactant (X_1), time (X_2), temperature (X_3) and number of stage (X_4). The negative values of coefficients of the regression equation confirm that an increase in the value of any of the factors will lead to a decrease in the value of microbial count. The mathematical

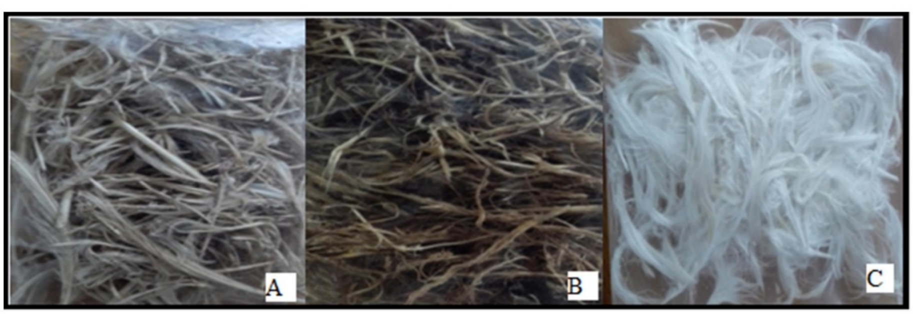

Fig. 3. Chicken feathers upon sampling (A), after storage for 3 days at room temperature (B) and after decontamination and pre-treatment with surfactants (C).

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Table 4
ANOVA analysis of Placket-Burman design.

Code	Term	Estimate	t Ratio	Prob > |t|	Remark
	Intercept	426.475	11.71	<0.0001*	
X_1	Concentration	−194.525	−5.34	0.0011*	Significant
X_2	Temperature	25.049		0.0316*	Significant
X_3	Time	−107.4971	−2.96	0.0212*	Significant
X_4	Feather to liquid ratio	43.6		0.0769	Non-significant
X_5	Number of stages	−224.7338	−6.09	0.0005*	Significant
X_6	pH	23.98		0.3569	Non-significant
X_7	Stirring speed	−19.597		0.6547	Non-significant
$X_5 * X_1$	Interaction effect	41.433824	1.12	0.2986	Non-Significant
$X_5 * X_3$		42.997			Significant

Table 5
The characteristics of chicken feather before and after treatment.

Pre-treatment	Microbial count
Control	1.48E + 07 ± 6.72E05 Cfu/g
Autoclave	2.81E + 06 ± 5.62E04 Cfu/g

model (Eqs. (5)–(7)) of the decontamination and pre-treatment of chicken feather attests that the desired value of microbial count is within the limits of the tested factor space. The statistical significance of the model Eqs. (5)–(7) and the model terms were evaluated by the F-test for analysis of variance (ANOVA), which indicated that the regressions were statistically significant.

3.4.1. Sodium dodecyl sulphate

The model F-value of 180.53 implies the model is significant, and there is only a 0.01% chance that a model F-value this large could occur due to noise. From Table 6, it can be observed that concentration, number of stage and time of the model were significant to the response, indicating that low microbial count depends on the interactions between these four factors. The "Lack of Fit F-value" of 0.99 implies the Lack of Fit is not significant relative to the pure error. There is a 61.76% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good for process optimisation to fit the model. The fit of the model was checked by the coefficient of determination R^2, which was 0.9704, indicating that 97.04% of the variability in the response could be explained by the model. A high R^2 coefficient (0.9704), as a measure of a number of reductions in the variability of the response, obtained using the independent factors within the model confirms a satisfactory adjustment of the proposed model to the experimental data. The "Predicted R-Squared" of 0.9558 is in reasonable agreement with the "Adjusted R-Squared" of 0.9651; i.e., the difference is less than 0.2. "Adequate Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. In this case, the ratio of 48.052 indicates an adequate signal so this model can be used to navigate the design space. The optimised process parameter for SDS treatment is a concentration of 0.5, number of stage 2, time of treatment 30 min and temperature of 80 °C.

3.4.2. Polyoxyethylene (40) Stearate)

The Model F-value of 137.01 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. According to the p-values of the model term (Table 6), number of stage, concentration and time were significant model terms. The "Lack of Fit F-value" of 2.08 implies the Lack of Fit is not significant relative to the pure error. There is a 37.43% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good for process optimisation to fit the model. The coefficients of determination (R^2) of the model was 0.9614, which further indicates that the model was suitable for adequate representation of the real relationships among the variables. The "Predicted R-Squared" of 0.9409 is in reasonable agreement with the "Adjusted R-Squared" of 0.9544; i.e., the difference is less than 0.2. The optimised process parameter for PEE treatment is a concentration of 0.75, number of stage 2, time of treatment 40 min and temperature of 80 °C.

3.4.3. Dimethyl dioctadecyl ammonium chloride

The model F-value of 27.17 implies that the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. From Table 6, it can be observed that concentration and number of stage of the model were significant to the response, indicating that low microbial count depends on the interactions between these four factors. The "Lack of Fit F-value" of 190.25 implies the Lack of Fit is significant relative to the pure error. There is only a 0.52% chance that a "Lack of Fit F-value" this large could occur due to noise. Significant lack of fit is bad for process optimisation to fit the model. The fit of the model was checked by the coefficient of determination R^2, which was 0.8316, indicating that 83.16% of the variability in the response could be explained by the model. The "Predicted R-Squared" of 0.7345 is in reasonable agreement with the "Adjusted R-Squared" of 0.8010; i.e., the difference is less than 0.2. "Adequate Precision" measures the signal to noise ratio. In this case, the ratio of 18.892 indicates an adequate signal so this model can be used to navigate the design space. The optimised process parameter for DDAC treatment is a concentration of 0.5, number of stage 2, time of treatment 50 min and temperature of 90 °C.

3.5. Coefficient of variation

The coefficient of variation (Cv) indicates the ratio of the standard error of the estimate to the mean value of the observed response. Generally, a model can be considered reasonably reproducible if the Cv is not greater than 15% (Montgomery, 2008). Here, the Cv value was 11.05% (SDS), 12.03% (DDAC), and 10.31% (POE) indicating a high degree of precision in the experiment. From Table 7 the negative sign for the coefficients of factors in the fitted models for microbial count indicated that the level of microbial count decreased with increasing levels of factors. Also, the greatest coefficients of factor, number of stage, revealed the high sensitivities of the response to this factor. Adequate precision is a measure of the range in predicted response relative to its associated error, which provides a measure of the "signal-to-noise ratio". In the present study, the ratio of 11.05% (SDS), 12.03% (DDAC), and 10.31% (POE) indicates an adequate signal, so this model can be used to navigate the design space. Simultaneously, low values of the coefficient of variation (Cv) (11.37%) indicated good precision, reproducibility and reliability of the experiments.

The three-dimensional response surfaces illustrate the interactions between two variables by keeping another variable constant (Figs. 4–6). It has been reported that elliptical contours mean perfect interactions between the independent variables (Haji et el.,

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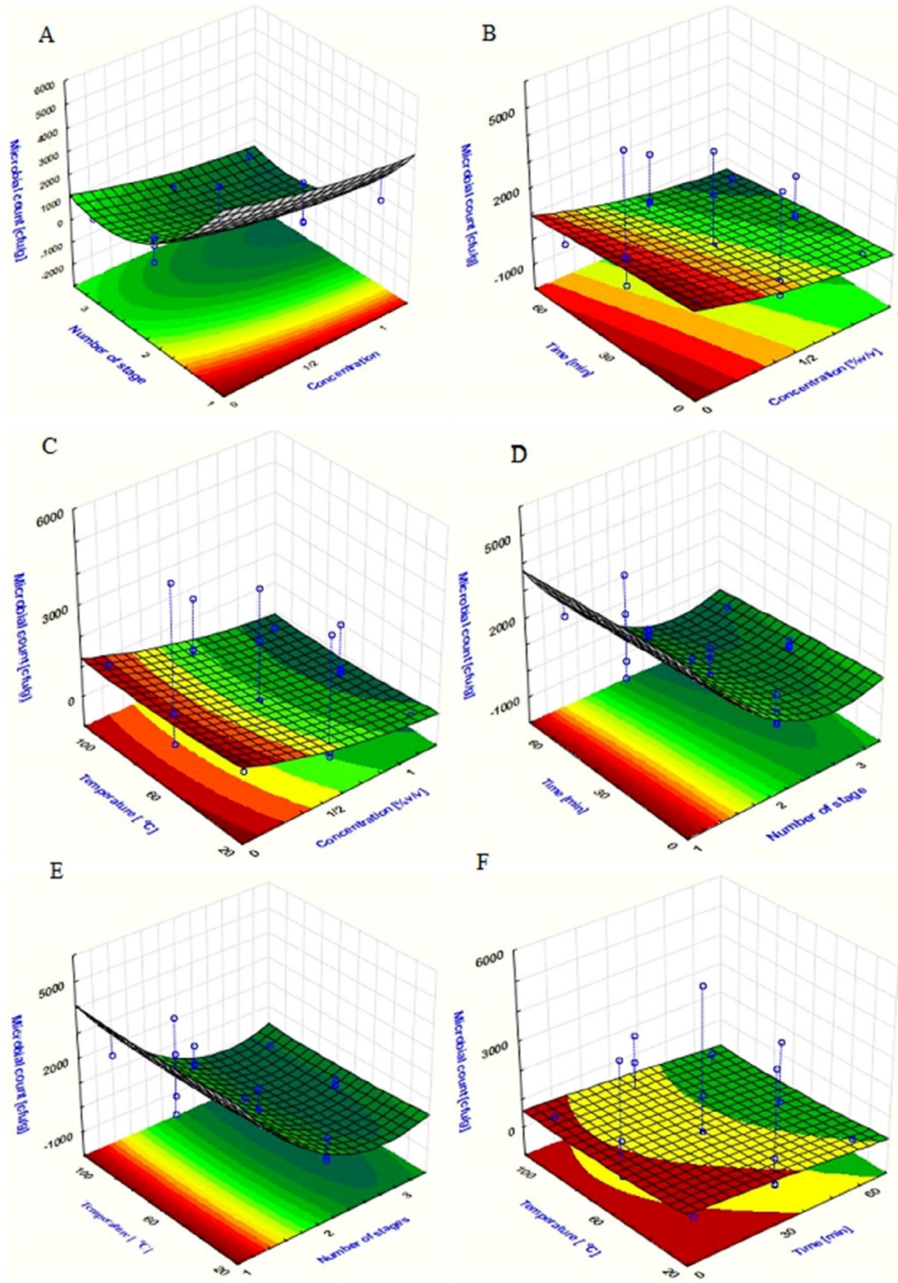

Fig. 4. Three-dimensional plots of the effect of four variables on the microbial count (SDS). Interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) Number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

2014). As shown in Fig. 4, the shapes of the contour plots are all elliptical except for Fig. 4C and F, indicating that the mutual interactions between every two variables were significant. As shown in Fig. 5, the shapes of the contour plots are all elliptical except for Fig. 5C and F, indicating that the mutual interactions between every two variables were significant. As shown in Fig. 6, the shapes of the contour plots are all elliptical, indicating that the mutual interactions between every two variables were significant.

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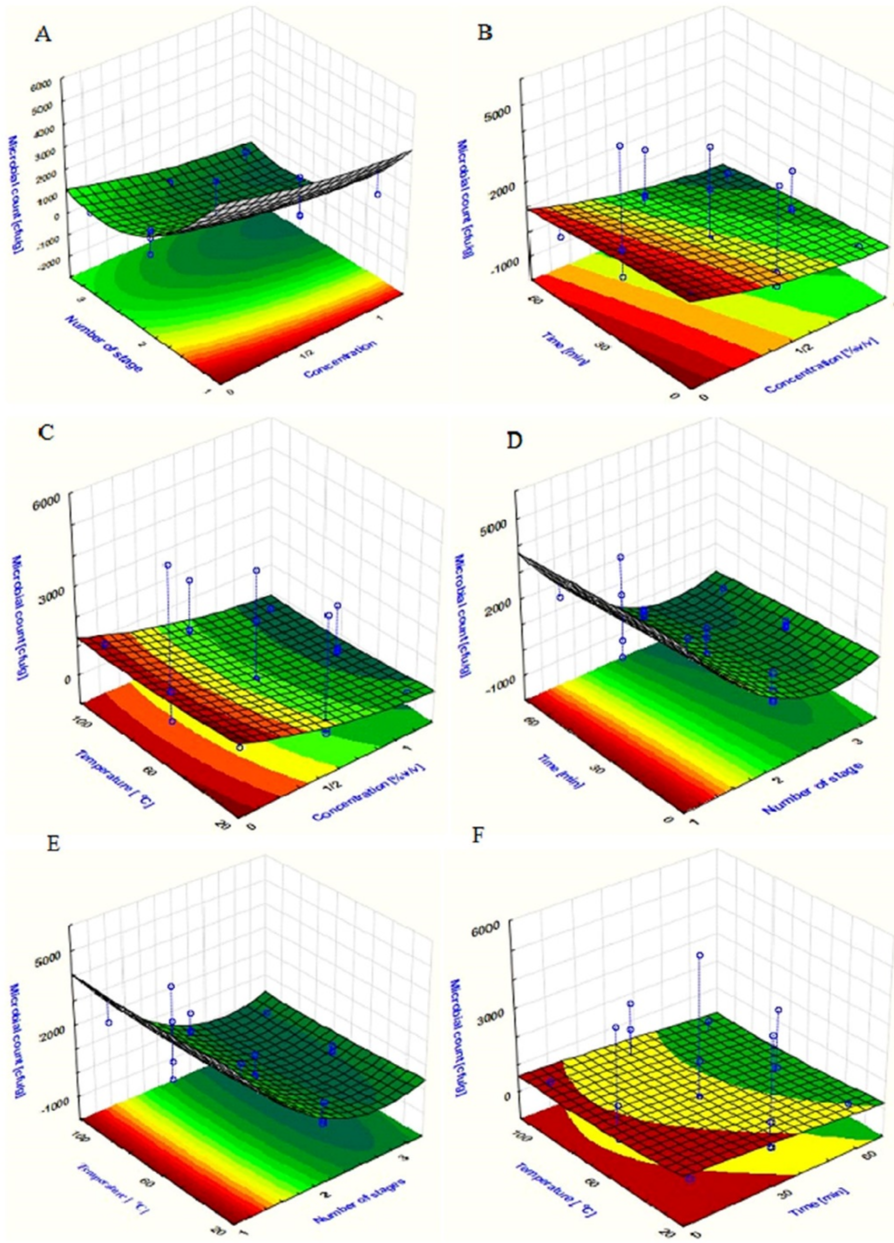

Fig. 5. Three-dimensional plots of the effect of four variables on the microbial count (POE). Interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) Number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

3.6. The effect of decontamination and pre-treatment on physicochemical and mechanical properties of chicken feathers

3.6.1. Evaluation of impurities

The removal of impurities in decontaminated and pre-treated chicken feathers was plotted against concentration, number of stages, time, and temperature as shown in Fig. 7. The impurity removal after washing was about 8–25%. This impurity removal is due to the washing out of short fibres and foreign materials such as vegetation, suints, blood, dust and some other contaminants from the poultry industry and proves that the impurity removal has direct dependency on the cleaning agents. From Fig. 7 it can

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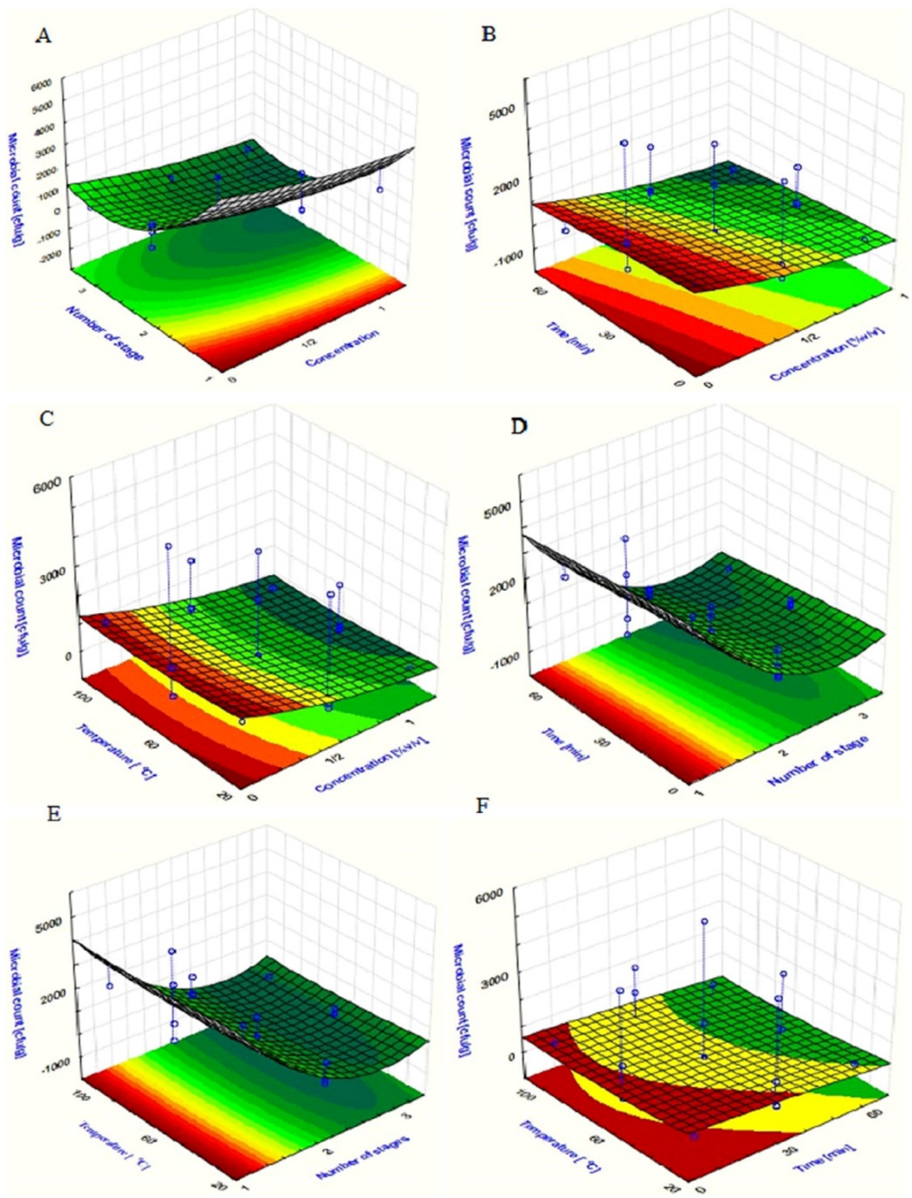

Fig. 6. Three-dimensional plots of the effect of four variables on the microbial count (DDAC). The interaction between (A) concentration and number of stage; (B) concentration and time; (C) concentration and temperature (D) Number of stage and time; (E) number of stage and temperature; and (F) time and number of stage.

be seen that there is a significant reduction in impurity content compared to the untreated chicken feather. The result in Fig. 7 would suggest that a single stage would be insufficient in reducing impurities to an acceptable level, so it requires more than one stage of cleaning. From the figure, it can be seen that using all of the surfactant cleaning methods at a concentration from 0.1 to 0.57% was ineffective at reducing all the impurities. But increasing the concentration to 1% improves the removal of impurities.

3.6.2. Residual grease content

Fig. 8 shows the residual grease content after hexane extraction of the decontaminated and pre-treated chicken feathers at 60 °C. The anionic surfactant SDS had the best outcome since it was effective at removing oily dirt and stains in pure water at the three lower detergent concentrations. DDAC surfactant was the next most effective, followed by POE. As can be seen from Fig. 8 the increase in concentration and number of stages significantly

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Table 6
Analysis of variance (ANOVA) for the fitted linear model for optimisation of microbial count.

Type of surfactant	Source	Sum of Squares	Degree of freedom	Mean Square	F Value	p-value Prob > F	
SDS	Model	506.67	4	126.67	180.53	< 0.0001	Significant
	Concentration (%v/v)	97.86	1	97.86	139.46	< 0.0001	
	Number of stage	404.38	1	404.38	576.31	< 0.0001	
	Time (min)	4.40	1	4.40	6.28	0.0201	
	Temperature (°C)	0.037	1	0.037	0.053	0.8201	
	Residual	15.44	22	0.70			
	Lack of Fit	14.02	20	0.70	0.99	0.6176	Not significant
	Pure Error	1.41	2	0.71			
	Corrected Total	522.11	26				
	R^2 = 0.970, Adjusted R^2 = 0.965, Predicted R^2 = 0.955, Adequate Precision = 48.052; CV = 11.05%						
POE	Model	496.84	4	124.21	137.01	< 0.0001	Significant
	Concentration (%v/v)	89.93	1	89.93	99.20	< 0.0001	
	Number of stage	402.53	1	402.53	444.01	< 0.0001	
	Time (min)	4.08	1	4.08	4.50	0.0455	
	Temperature (°C)	0.29	1	0.29	0.33	0.5743	
	Residual	19.94	22	0.91			
	Lack of Fit	19.03	20	0.95	2.08	0.3743	Not significant
	Pure Error	0.91	2	0.46			
	Corrected Total	516.78	26				
	R^2 = 0.961, Adjusted R^2 = 0.954, Predicted R^2 = 0.941, Adequate Precision = 41.633; CV = 11.37%						
DDAC	Model	8.19	4	2.05	27.17	< 0.0001	Significant
	Concentration (%v/v)	1.85	1	1.85	24.62	< 0.0001	
	Number of stage	6.27	1	6.27	83.16	< 0.0001	
	Time (min)	0.066	1	0.066	0.87	0.3606	
	Temperature (°C)	1.2E−003	1	1.2E−003	0.016	0.9007	
	Residual	1.66	22	0.075			
	Lack of Fit	1.66	20	0.083	190.25	0.0052	Significant
	Pure Error	8.7E−004	2	4.4E−004			
	Corrected Total	9.84	26				
	R^2 = 0.832, Adjusted R^2 = 0.801, Predicted R^2 = 0.735, Adequate Precision = 18.892; CV = 12.89%						

Table 7
Coefficient of estimate for the fitted linear model for optimisation of microbial count.

Type of surfactant	Factor	Coefficient estimate	Degree of freedom	Standard error	95% CI Low	95% CI High
SDS	Intercept	7.86	1	0.41	7.00	8.72
	Concentration (%v/v)	−2.74	1	0.27	−3.31	−2.17
	Number of stage	−5.79	1	0.27	−6.36	−5.22
	Time (min)	−0.79	1	0.37	−1.57	−0.017
	Temperature (°C)	−0.11	1	0.20	−0.53	0.30
POE	Intercept	7.86	1	0.41	7.00	8.72
	Concentration (%v/v)	−2.74	1	0.27	−3.31	−2.17
	Number of stage	−5.79	1	0.27	−6.36	−5.22
	Time (min)	−0.79	1	0.37	−1.57	−0.017
	Temperature (°C)	−0.11	1	0.20	−0.53	0.30
DDAC	Intercept	2.06	1	0.12	1.81	2.30
	Concentration (%v/v)	−0.39	1	0.079	−0.56	−0.23
	Number of stage	−0.72	1	0.079	−0.89	−0.56
	Time (min)	−0.10	1	0.11	−0.32	0.12
	Temperature (°C)	−7.33E−003	1	0.058	−0.13	0.11

reduces the residual grease content of the treated chicken feathers. The higher number of stages improves emulsification and removes the grease more effectively. This is evident even at the lower treatment concentrations. The greatest scouring ability of all surfactants significantly depends on the number of stages and concentration. This eliminates more than 90% of the grease content of the chicken feathers. The residual grease content of a chicken feather needs to be below 2% to make processing easier during further valorisation activities (Bateup, 1986; Bateup and Warner, 1986). The second and third stage decontamination and pretreatment cycles, especially at higher surfactant concentrations, produced feathers with low residual grease content. As can be seen from Fig. 8, the reduction of decontamination and pretreatment time and temperature affects the level of residual grease on the feather. However, the effect of time and temperature is not as significant as the number of stage and concentration.

3.6.3. Ash Content

Fig. 9 shows the effect of surfactant decontamination and pretreatment on the ash content of chicken feathers. From the results, it was observed that the ash content of decontaminated and pretreated samples were higher than those of untreated samples (12.15% vs 1.25%). This is due to removal of non-ash impurities from waste chicken feathers in the treatment processes (in effect the ash content becomes higher due to the lower amounts of non- ash impurities in the samples). This is also an indication of the efficiency of the treatment process. The effect of treatment of feathers on ash content has also been reported in the literature where it was reported that higher concentration of treatment chemicals aided the removal or reduction of the proportion of the ash content of the fibres whereas lower concentrations of the alkaline treatment improved the development of ash content in the fibres (Anderson and Christoe, 1984; Oladele, 2016).

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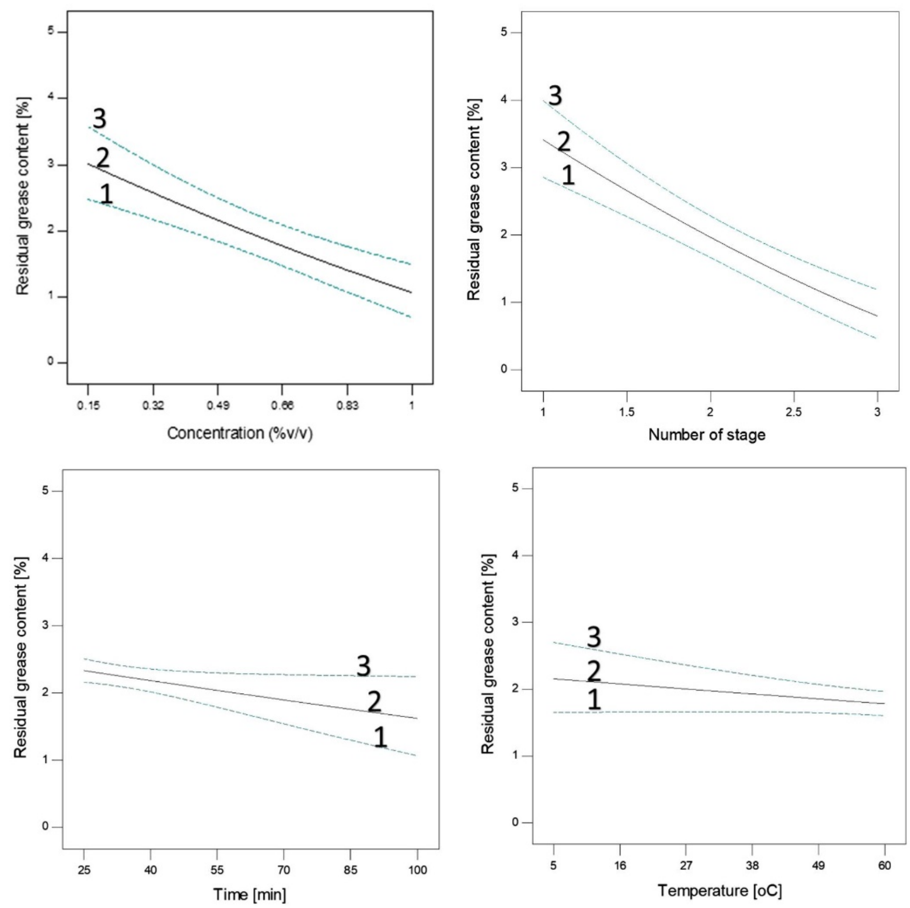

Fig. 7. The effect of independent variables on residual grease content [%] (1 = SDS; 2 = DDAC; 3 = POE treated feather).

3.6.4. FTIR spectroscopy

In order to examine the effects of decontamination and pre-treatment processes on chicken feathers, FTIR spectra of untreated and decontaminated and pre-treated chicken feathers were obtained (Fig. 10). There were no significant differences in the chemical composition and structure of surfactant decontaminated and pre-treated chicken feathers, except for the autoclaved sample. However, the autoclaved technique did not significantly remove adhered waste materials and fats as the FTIR spectrum of the autoclaved sample was the same as that of the untreated feathers.

3.6.5. Water retention and moisture regain

The water retention properties of the chicken feather barbs are presented in Table 8. There were no significant differences found for all samples regardless of the type of decontamination, pre-treatment methods and water temperature. The amount of water retained by a chicken feather barb increases with an increase in the hydrophilic tendency of the fibre.

Fig. 11 illustrates the interaction of a surfactant compound with a chicken feather surface showing an intact lipid. Hydrophobic interactions exist between the chicken feather surface lipid and hydrophobic tail of the surfactant. Fig. 11 illustrates that the outermost surfaces of surfactant-chicken feather interface by creating a more hydrophilic surface.

In this study, the surfactant either forms a continuous layer or hemimicelles on the chicken feather surface. Due to the hydrophobicity of chicken feathers, electrostatic and hydrophobic interactions are also found between the surfactant and chicken feathers (Brack et al., 1999; Kronberg et al., 2014). After the lipid is removed, the surfactant molecules are orientated in such a manner that the polar region forms the outermost surface. The wettability of chicken feather barbs can increase due to this phenomenon.

Removal of grease, dirt, suints, burrs and woody fragments and mineral matter from chicken feathers can also result in moisture regain change due to surface modification of treated chicken feathers (Freeland et al., 1985; Tseng, 2011). Pre-treated and decontaminated chicken feathers absorbed water from the atmosphere quickly whereas the saturation values after 24 h were not as large as that for untreated feathers (Fig. 12). The reduction of the polar groups after pre-treatment and decontamination reduced regain saturation values. As can be seen in Fig. 12, the moisture is attracted to the polar groups present in the treated chicken feathers. A practical implication of this observation is that increase in moisture regain will cause reduction in the electrical resistance

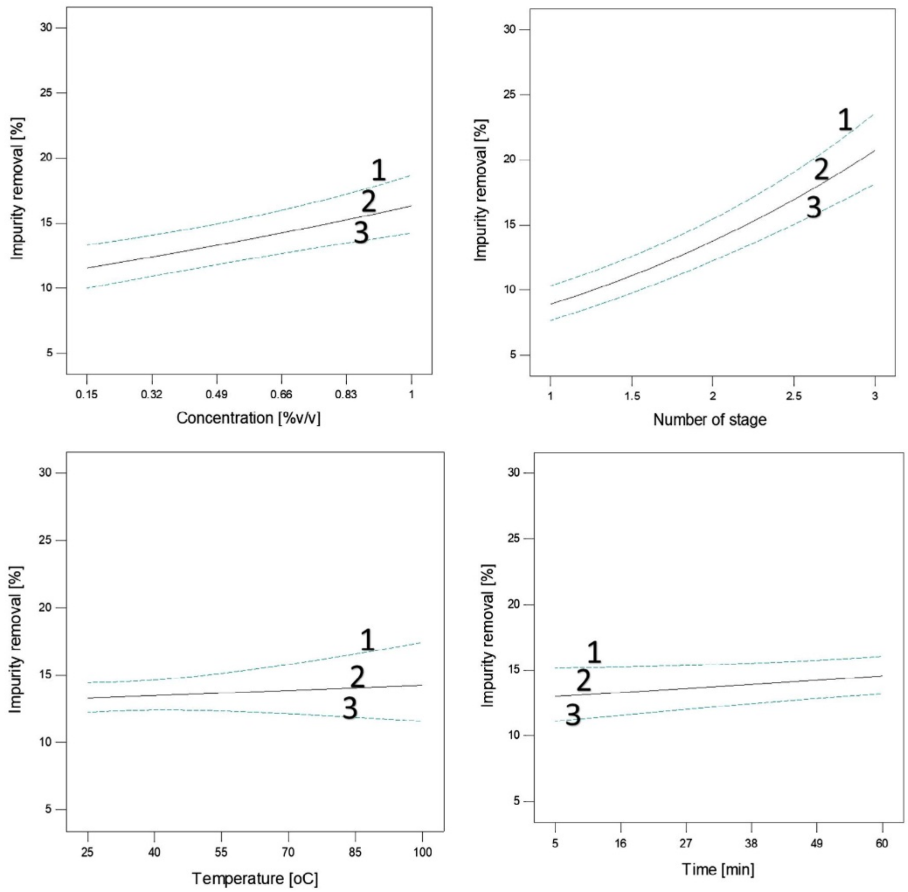

Fig. 8. The effect of independent variables on impurity removal [%] (1 = SDS; 2 = DDAC; 3 = POE).

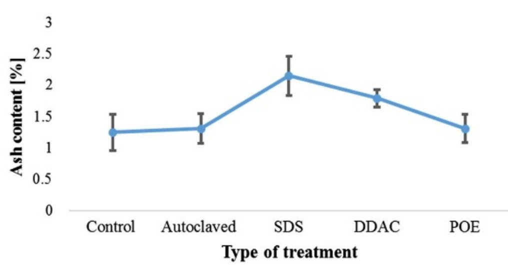

Fig. 9. Effect of decontamination and pretreatment on the ash content of chicken feathers.

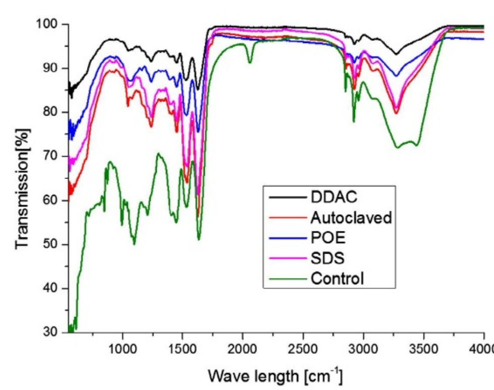

Fig. 10. FTIR spectra of treated and untreated chicken feathers.

of chicken feathers resulting – this, in turn, will induce static electricity on the feathers (Hearle and Morton, 2008).

3.6.6. Whiteness and yellowness indices

The colour of feathers varies not only in terms of the type of pretreatment used but also in terms of the variation in age of the chicken, individual nature of the poultry, and the slaughtering processes used (Sheffield and Doyle, 2005). Varying amounts of preen, particulates from dust bathing, faecal matter, and type of feed, all

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Table 8
pH and water retention of treated and untreated chicken feathers.

	Untreated	Autoclaved	SDS	DDAC	POE
pH	5.36	5.26	5.50	4.72	4.41
Water retention	46.63	51.24	61.28	56.81	58.75

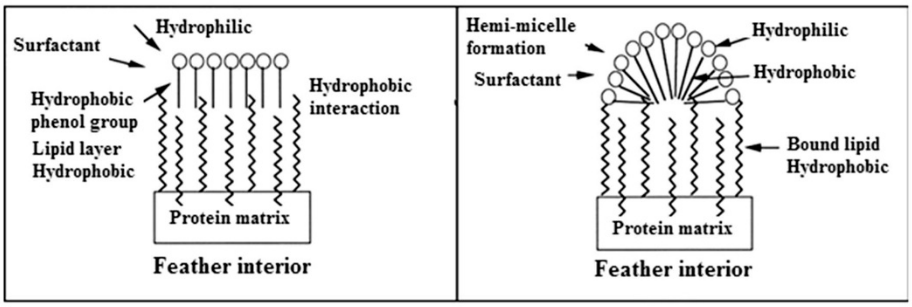

Fig. 11. Illustrations of the hydrophobic/hydrophilic interaction between surfactants and the feather surface showing the formation of hemimicelles (). adapted from Kronberg et al., 2014

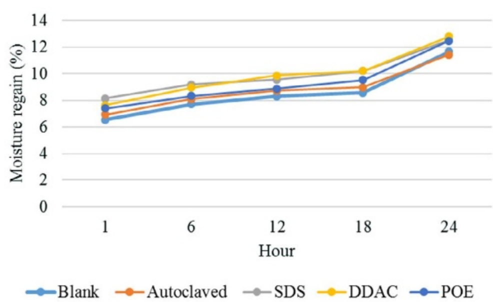

Fig. 12. Moisture regain differences between treated and untreated feathers.

contribute to variation in colour of chicken feathers. Since raw chicken feathers contain blood and may have been collected several hours before decontamination, their colour becomes dark brown due to bacterial development. The whiteness index and yellowness index for both untreated and treated chicken feathers as a result of different decontamination and pre-treatment methods were measured. Table 9 illustrates the colour variations that were obtained. There were no significant differences in the whiteness indices of the feather treatment methods using surfactants (Table 9). SDS produced the whitest feathers. The improvement of the whiteness and yellowness indices in treated and untreated samples depended on the concentration of surfactant, number of treatment stages, and time of treatment (Bateup, 1985). It was noticed that the increase in each factor led to an increase of whiteness index and a decrease in yellowness index.

3.6.7. Density

Density measurements of whole chicken feathers and fractions (rachis and barb) showed clear differences, almost twofold, between barb and rachis fractions for treated and untreated chicken feathers. The density of whole feathers was closer to that of the barb fraction in almost all cases whereas values for untreated chicken feathers showed noticeably higher dispersions due to inhomogeneity of the sample. On the contrary, there were no significant differences in densities of the treatment samples, irrespective of the treatment method used (Fig. 13). The density of chicken feathers was lower than 1 g/cm^3 with the exception of the untreated and autoclaved sample. This value is a lower value than the density of cellulosic and other protein fibres such as wool. Generally, the density values for chicken feathers were in

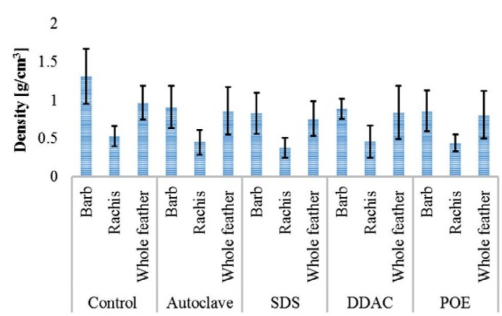

Fig. 13. Density measurement for untreated and treated chicken feathers.

Table 9
CIE tristimulus values, whiteness index and colour differences (ΔE) for treated and untreated chicken feathers.

Type of feather	L^*	a^*	b^*	ΔE	WI CIE	YI E313
Control	75.36	2.81	19.59	77.91	−57.75	43.18
Autoclaved	81.49	1.89	18.29	6.13	−34.36	37.70
SDS	94.85	0.07	4.36	24.89	67.49	8.28
DDAC	92.35	0.06	4.25	23.03	61.60	10.56
POE	94.48	−0.01	4.32	24.64	65.00	9.31

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Table 10
Tensile properties of treated and untreated chicken feathers.

	Maximum load [cN]	Tenacity at maximum load [cN/tex]	Tensile extension [%]	Tensile strain at maximum load [%]	Tensile stress at maximum load [MPa]
Untreated	375.79	8.39	2.45	2708.53	0.38
Autoclaved	485.06	10.25	2.54	2797.33	0.49
SDS	1000.77	12.40	6.09	6744.38	1.00
POE	662.75	12.58	3.36	3703.99	0.66
DDAC	488.37	11.42	4.45	4908.01	0.49

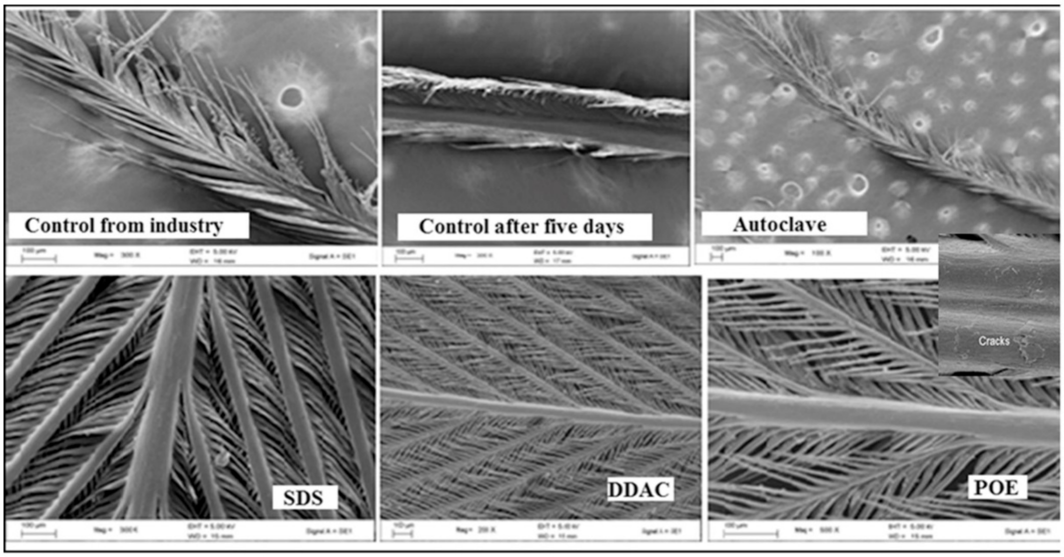

Fig. 14. The SEM structure of treated and untreated chicken feather (at 100 μm scale).

agreement with those reported in the literature (0.8–0.89 g/cm^3) (Pourjavaheri et al., 2014).

3.6.8. Mechanical properties

Chicken feathers suffer reversible loss of tensile strength when wet (Wang et al., 2003). This could be due to the hydrogen bonds which are dissociated in aqueous conditions resulting in reduction of disulphide bonds in the feathers. In aqueous media, protein chains can be ionised and attract charged molecules – hence chicken feathers are susceptible to chemical damage (strong alkali and strong acids) in aqueous media (Tesfaye et al., 2017a, 2017c). The alkaline nature of suint is critical for setting the conditions for pre-treatment. Prolonged treatment time and high temperatures will lead to strength loss and yellowing. The effect of bacteria removal from chicken feathers was evaluated after decontamination and pre-treatment of the feathers.

The analyses of the mechanical properties of treated and untreated chicken feather barbs are shown in Table 10. In some cases, decontamination of feathers results in minimal fibre damage whereas treatments with surfactants enhanced the tensile strength of barbs. From the results, SDS treatment best influenced the improvement of tensile stress at maximum load. This indicates that the chemical treatment can enhance the tensile properties of animal fibres (Feughelman, 2002). The enhanced strength observed in treated samples may be due to increase in protein content of the treated samples due to the removal of other impurities. This is in agreement with literature results where the presence of a high amount of protein content led to enhancement of tensile properties (Pourjavaheri et al., 2014). From Table 10, it is clear that enhancement of strain ability of treated samples has been achieved compared to untreated feathers. This suggests that treated feathers can withstand more strain thus delaying failure of materials made from them. Consequently, potentially chicken feather barbs could be used as materials for reinforcement in natural fibre composites.

3.6.9. Scanning electron microscopy, energy dispersive spectroscopy, SEM/EDX

The morphology and elemental profile analyses of the feathers were studied by SEM/EDX in order to ascertain if the decontamination and pre-treatment procedures had any effects on the feathers. The images in Fig. 14 reveal that the detergents used washed the chicken feathers cleanly, leaving them free from dust with their naturally smooth surfaces. This is probably due to the removal of dirt and lipid layer that coated the chicken feather as a result of the detergency action. The bulk of the decontaminated and pre-treated chicken feather became white and fluffy. The tangled and curled chicken feathers started to unfurl after decontamination and pre-treatment. Feather whiteness and unfolding of the barb from the rachis increased as the number of pre-treatment stages increased. The autoclave treated samples remain folded due to lipid residues whereas the untreated chicken feathers had an abundant amount of contaminants, lipids, and closely linked barbules on the surface. These observations are similar to those reported

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for pre-treatment of alpaca and hair fibres (Mendes and Piackeski, 2003; Wang et al., 2003).

All surfactant treatments show a good level of contaminant removal. However, Fig. 14 shows that there was cracking on the surface of the feathers. The feather microstructure was not damaged after decontamination and pre-treatment and barbules were found intact. The texture of the treated chicken feathers had a hard texture. The feathers treated using the autoclave technique had the same appearance and texture as the unwashed feathers. However, the surfactant solution softened the texture in the rachis parts and made them more brittle. The level of feather entanglement and fibre length are also important factors if the feather fractions are to be used for textile applications.

Fig. 15 shows the SEM-EDX images and the elemental analysis of the samples. The relative proportions of the sulphur element decreased where the carbon content increased in all the treated samples. This may be due to the removal of dirt and decontaminates (blood, skin and other dirt) from the surface of the chicken feather.

3.6.10. Thermogravimetric analysis

Although the mass loss profiles for treated and untreated chicken feathers were very similar a closer examination of the derivative diagram shows significant differences in the profiles (Fig. 16). The first mass loss observed in the temperature range of 25–235 °C can be attributed to water release. The second and third mass loss stages (around 235–350 °C and 350–550 °C respectively) are related to denaturation of chicken feathers. The complete degradation of the chicken feather carbonic chain takes places in the temperature range of 350–550 °C (Fig. 16A). Fig. 16 A shows rapid decomposition in the temperature range between 235 and 550 °C.

In Fig. 16B the denaturation temperature increases after decontamination and pre-treatment. Decontamination and pre-treatment of chicken feathers promote stability of the structure and shifts the denaturation temperatures higher by increasing the ionic interactions (Monteiro et al., 2005). Disinfecting and pre-treatment of chicken feathers shows a large degradation of the cystine disulphide bonds inside and between the chains (Pourjavaheri et al., 2014), and therefore exhibits higher denaturation temperatures, compared to the control chicken feathers. It is apparent that more energy is spent to disorganise the structure of untreated chicken feathers than in the treated chicken feathers. This fact is supported by the increase of the denaturation temperature and the decrease in the denaturation enthalpy of chicken feather (Monteiro et al., 2005) (Fig. 16B).

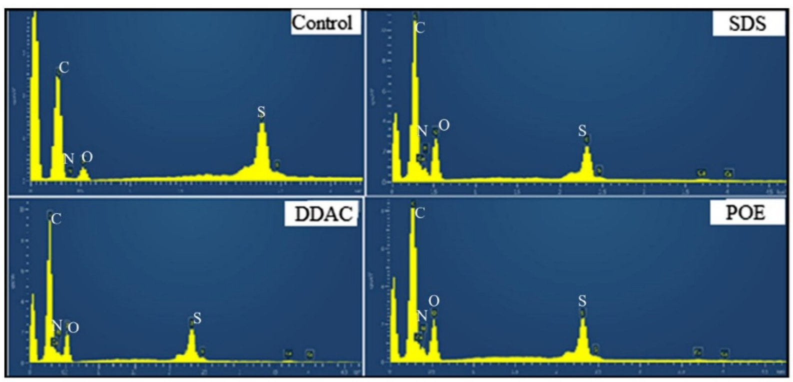

Fig. 15. SEM-EDX and elemental data drived from treated and untreated chicken feathers.

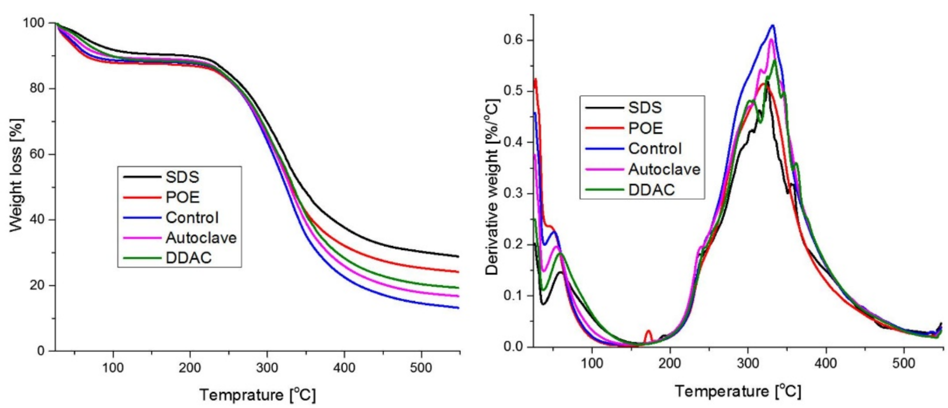

Fig. 16. Thermogravimetric (A) and derivative curves (B) for treated and untreated chicken feather.

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Table 11
Economic comparison.

Method	Price[a]	Time	Steps	Temprature[b]	Scale[c]
SDS	2	1	2	RT	++
POE	1	1	2	RT	+++
DDAC	3	2	2	RT	+

[a] Relative cost of chemicals on a 5 g of chicken feather basis.
[b] Required temperature in °C.
[c] Feasibility of scaling up the method, (+++ means most feasible, +means least feasible).

3.7. Commercial feasibility analysis

For bench scale application, all of the decontamination and pre-treatment methods are practical, in terms of energy input, the cost of materials, and time at the laboratory scale. Table 11 shows the differences between each type of treatment to scale the method up to the pilot plant industry. For this study, the filtration, final wash and drying steps that are common to all methods have been ignored. The DDAC decontamination and pre-treatment methods have the highest costs in terms of chemical and energy input. The lowest input costs are for POE methods where chemical prices, therefore this method is recommended for the bactericidal effect of the surfactant in the biomedical application area.

4. Conclusions

This study has investigated the effectiveness of surfactants for removal of contaminants and microbial content of waste chicken feathers from a poultry processing facility. Treatment of feathers with surfactants was effective in removing lipid matter from the feathers. Although not as effective as combined pot surfactant treatments, autoclaving was also effective in removing microbial matter from the feathers to levels that rendered the feathers safe to handle and use. The physicochemical properties of the chicken feathers were not adversely affected by the treatments. A preliminary commercial feasibility analysis of the technologies indicates that using POE for decontamination of waste feathers was more cost effective than using SDS and DDAC.

Acknowledgments

The authors are highly grateful to the Thermodynamics Research Unit and the Biorefinery Industry Development Facility/CSIR for providing funding and necessary laboratory facilities and technical support to complete this work. The Department of Science and Technology's Waste Roadmap (South Africa) and Ethiopian Institute of Textile and Fashion Technology is also acknowledged for financial support.

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Please cite this article in press as: Tesfaye, T., et al. Optimisation of surfactant decontamination and pre-treatment of waste chicken feathers by using response surface methodology. Waste Management (2017), https://doi.org/10.1016/j.wasman.2017.11.013

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PUBLICATION THREE

Journal of Cleaner Production 149 (2017) 349–365

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Valorisation of chicken feathers: Characterisation of physical properties and morphological structure

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ARTICLE INFO

Article history:
Received 17 October 2016
Received in revised form
14 February 2017
Accepted 14 February 2017
Available online 20 February 2017

Keywords:
Barbs
Characterisation
Chicken feathers
Morphology
Protein fibres
Rachis
Whole feathers

ABSTRACT

The physical properties and morphological structure of chicken feathers were examined in order to identify possible avenues for the valorisation of waste chicken feathers. The physical properties ascertained were fibre length, fineness, diameter, colour, ash content, moisture content, moisture regain, density, aspect ratio and dimensional measurement. The morphologies of the whole feather and its fractions (barb and rachis) were characterised by scanning electron microscopy. The results indicate that a chicken feather has unique features. The barb, unlike any other natural or synthetic fibre, is a protein fibre that has low density, high flexibility, good spinning length and a hollow honeycomb structure. The rachis has low density, low rigidity, and a hollow honeycomb structure. These characteristics indicate that chicken feather barbs can be utilised to manufacture textile products either on their own or by structural interaction with other fibres. The characteristics of both the barb and the rachis, make them suitable for the manufacture of composite materials. These results illustrate the possibilities of chicken feathers as a valuable raw material. The collection and processing of the chicken feathers from poultry can be a new source of employment and provide income generation opportunities.

1. Introduction

The disposal of waste in an economically and environmentally acceptable manner is a critical issue facing most modern industries. This is mainly due to increased difficulties in locating disposal works and complying with stringent environmental quality requirements imposed by waste management and disposal legislations. Worldwide, the poultry–processing industry generates large quantities of feather by-products that amount to 40×10^9 kg annually (Compassion in World Farming, 2013). According to some available figures of the USA Foreign Agricultural Service post reports, the total domestic per capita consumption of chickens is 59 kg in the United States; 48.0 kg in the Saudi Arabia, 67.1 kg in Hong Kong, 69.7 kg in Israel, and 35.4 kg in Canada (USDA Foreign Agricultural Service, 2014) – in South Africa the consumption rate in 2011 was 36.27 kg (DAFF, 2014). Considering that feathers represent 5–7% of the total weight of mature chickens (Rahayu and Bata, 2015), it is evident that the industry generates a large amount of feathers as a waste product, e.g., more than 258×10^6 kg of chicken feathers are produced in the Republic of South Africa alone (DAFF, 2014) (Fig. 1). This large consumption of chicken results in generation of huge amounts of chicken feathers.

The feathers are considered wastes and different approaches have been used for disposing of waste feathers, including landfilling and incineration (Veerabadran et al., 2012; Stingone and Wing, 2011). However, improper disposal of these biological wastes by landfilling contributes to environmental damage and transmission of diseases (Tronina and Bube, 2008). Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. Burning poultry wastes may actually produce as much or more toxic air emissions than coal plants. For example, analysis conducted by the North Carolina Department of Environment and Natural Resources found that a 57 MW poultry waste combustion plant emitted levels of carbon monoxide, particulate matter, nitrogen oxides, and carbon dioxide per unit of power generated that were higher than

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http://dx.doi.org/10.1016/j.jclepro.2017.02.112

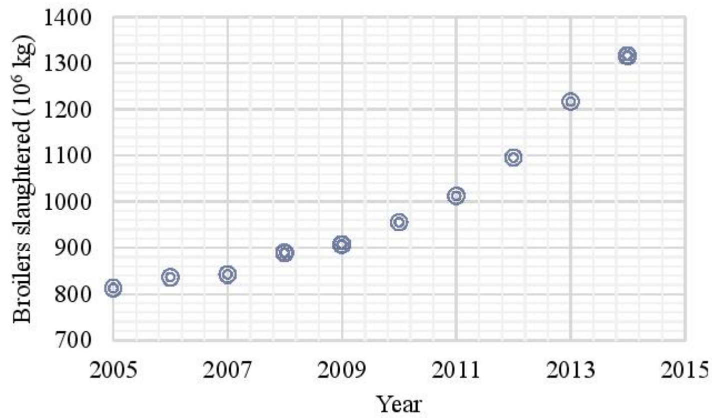


Fig. 1. Annual slaughter of broilers in South Africa (adapted from DAFF, 2014).

those for new coal plants (Stingone and Wing, 2011). An alternative to reduce these environmentally unfavourable disposal options is the utilisation of feather constituents as animal feed. Traditional methods to degrade feathers for subsequent use as animal feed include alkali hydrolysis and cooking under steam pressure. For example, the feathers may be hydrolysed, dried and ground to a powder to be used as a feed supplement for a variety of livestock, primarily pigs (Park et al., 2000). This is a fairly expensive process, however, and results in a protein product of low quality for which the demand is low (Veerabadran et al., 2012). These methods are not ideal in that they not only destroy the amino acids in the feathers but also consume large amounts of energy.

The world poultry industry has struggled with this question: what to do with more than 40×10^9 of poultry feather waste their business generates each year? A closer look at a chicken feather reveals that it is comprised of the rachis or quill, its primary structure, the barbs, its secondary structure, and the barbules, the tertiary structure (Fig. 2).

Can these features and properties of these structures allow for valorisation of chicken feathers? The applications mentioned in the preceding paragraphs utilise only a small portion of waste feathers generated by the poultry processing industry. Therefore, there is need to find or develop valorisation technologies for the waste.

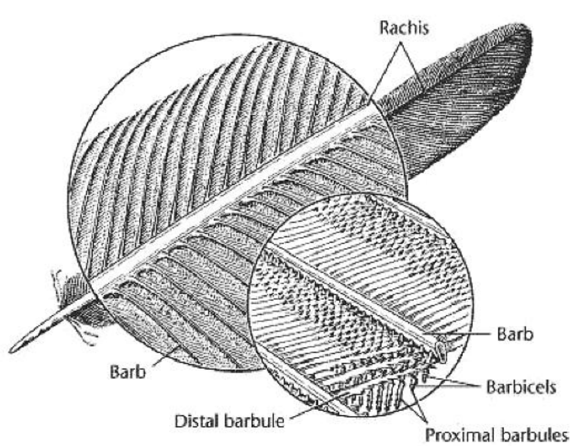


Fig. 2. Structures of a chicken feather (adapted from Bartels, 2003).

Characterisation and analysis of chicken feathers fraction to assess their suitability for valorisation as a source of protein fibre for high-value applications and the textile market is the first step for valorisation. In order to determine their suitability for these applications, it is important to understand the physical properties and the morphological structure of chicken feathers. Studies have been done in this topic, however, the studies were focused on specific applications upfront, e.g., textile applications (Reddy and Yang, 2005; Paul et al., 2014; Reddy et al., 2014), composite building applications (Jeffrey, 2006), biobased plastic resins containing chicken feather fibres (Roh et al., 2012), removal of heavy metals from wastewater (Al-Asheh and Banat, 2003), and a general description of feathers in domesticated birds (Bartels, 2003) none have focused on comprehensive evaluation of physical and morphological properties of feathers to help ascertain their possible valorisation. In this research, results of such comprehensive studies are reported: the morphological structure and physical properties of the whole chicken feather and of the component parts of the feather (barbules, barbs and rachis) were used to evaluate the possibilities for beneficiation of waste chicken feathers.

2. Materials and methods

2.1. Sample collection

Chicken feathers were obtained from a slaughterhouse in the province of KwaZulu-Natal, South Africa.

2.2. Sample preparation

The feathers were dried and conditioned at a relative of humidity 65 ± 2% and a temperature of 20 ± 2 °C. The barbs were separated from the rachis manually by cutting with scissors. The cutting of fibres was performed near the rachis so as not to lose length and the natural properties due to the format of the fibre along the extension. For all samples prepared, their characterisations were conducted in a lab environment (temperature of 20 ± 2 °C and a relative humidity of 65 ± 2%).

2.3. Measurement of physical properties

The chicken feathers were characterised for their physical properties and morphological structures. The methods used for the physical characterisation were adapted from those used for fibre characterisation of wool and other textile fibres. The parameters studied were fibre length, fineness, diameter, colour, ash content, moisture content, moisture regain, density, aspect ratio and dimensional properties.

2.4. Fibre length

Fibre length was determined by the "Oiled plate method" (ASTM, 2012) adapted from ASTM D5103-07. This is an individual fibre method that is used to measure the length distribution of short staple fibres. The requirements for the measurement of individual fibres makes this method the most accurate available. A sheet glass sheet was smeared with liquid paraffin, and some fibres were placed on its far-left corner. The fibres were then drawn out one at a time manually and straightened out and smoothed out over a centimetre scale etched on the underside of the glass sheet. The paraffin served to prevent the fibres from being blown away and assisted in keeping the fibres flat and straight for measurement. The lengths of 100 individual samples were noted.

2.5. Fibre diameter

The diameter of the feather fractions were measured at three different points along each fraction using an optical microscope (Nikon H600L). The average diameter of each fraction was calculated and was considered as the fibre diameter.

2.6. Fibre dimensions

For each chicken feather 25 samples were randomly chosen for measurement and the mean was calculated. Wall thickness and medulla width were measured using a light microscope. The following derived values were calculated from the data:

$$Slenderness\ ratio = \frac{Length\ of\ sample}{Diameter\ of\ sample} \quad (1)$$

$$Flexibility\ ratio = \frac{Lumen\ width\ of\ sample}{Diameter\ \ of\ sample} \quad (2)$$

2.7. Linear density of the barbs

The conditioned feathers were carefully combed with a fine comb, and 11.8 mm long bundles were cut with scissors. The bundles were weighed and the linear density was calculated.

2.8. Fibre density

Whole chicken feathers and feather fractions were prepared as blends of carbon tetrachloride (1.592 g/cc) and xylene (0.866 g/cc) density gradient. The samples were placed in a liquid pycnometer column for measurement of density. The density of the column increased linearly from top to bottom. A sample placed within the column comes to rest in a position which corresponds to its density. Five replicates were performed for each sample type.

2.9. Moisture content and moisture regain

A hot air oven was used to determine the moisture content of the samples. Two-gram samples were processed according to ASTM D1576-90 using the formula (ASTM, 2001):

$$Moisture\ content = \frac{W_1 - W_2}{W_1} * 100 \quad (3)$$

$$Moisture\ Regain = \frac{W_1 - W_2}{W_2} * 100 \quad (4)$$

W_1 = Original mass of sample (g), and W_2 = Oven dry mass of sample (g).

2.10. Longitudinal and cross-sectional areas

The longitudinal and cross-sectional areas of the feather barbs and rachis were measured using a Hitachi TM1000 scanning electron microscope (Hitachi High Technologies, Japan). The samples were cut to about 0.5–1 mm using a blade and the cut flat ends were used to measure the cross-sectional area, fine structure, appearance, microstructure and longitudinal views of the samples.

2.11. Surface area analysis

Surface areas of the samples were determined via Brunauer-Emmett-Teller/BET analyser. The BET surface area and micropore volume are determined using the nitrogen adsorption/desorption isotherms collected at liquid nitrogen temperature (77 K) using a Micromeritics TriStar II surface area and porosity analyser (USA). Prior to analysis, the samples are degassed at desired temperature for a particular time under a vacuum of more than 2 μm He with a nitrogen gas flow to ensure absence of moisture in the sample. The desorption branch of the isotherm is used to determine the Barret-Joyner-Halenda (BJH) pore size distributions of the material.

2.12. Atomic force microscopy (AFM)

Atomic Force Microscopy was performed with a Solver P47H base with a SMENA head, manufactured by NT-MDT. The cantilever of choice was a SuperSharpSilicon™ SPM-Sensor (SSS-NCLR, Nanosensors™) with a resonance frequency of 146–236 kHz; Force constant of 21–98 N/m; Tip radius 2 nm (typical), the scan rate ranged from 0.6 to 1.6 Hz. Scans were taken in both height mode, in which the deflection of the cantilever was directly used to measure the z position (Height image) and in phase mode, where the phase lag of the cantilever was used to determine the differences in material stiffness (Phase image). All scans were conducted in air (climate controlled) at 256 × 256 pixels.

2.13. Colour

The colour of the samples was determined by using a Konica Minolta CR-410 Chroma instrument. The metre was calibrated with a white plate. Absolute colour readings were recorded in L*, a* and b* space (ASTM, 1998). The measurement were done in triplicate.

$$\Delta \boldsymbol{E} = \left[\Delta \boldsymbol{L}^{*2} + \Delta \boldsymbol{a}^{*2} + \Delta \boldsymbol{b}^{*2}\right]^{\frac{1}{2}} \quad (5)$$

where: L^*, a^*, b^* = CIE tristimulus values. ΔE = CIELAB colour difference.

2.14. Sampling of chicken feathers for characterisation

Feathers differ in size depending on their location on the body of the chicken. Feathers can be distinguished as primary and auxiliary feathers in relation to body area from which they originated. Primary feathers are in the area of the wings and are not uniform in size. Therefore, to optimise measurements of weight and diameter, a random sampling technique was used. For measurement purposes, five different sampling positions were marked at specific distances along the length of the specimen as illustrated in Fig. 3: the average of three replicates was considered as one measurement for each test except for length measurements

2.14.1. Statistical analysis

Data on dimensions, analytical studies and physical parameters were subjected to statistical analyses. Microsoft Excel and Origin were used to analyse for the mean, standard deviation (SD) and coefficient of variation (Cv). Arithmetic mean and SD were calculated for all the data on barb, rachis and whole feather.

3. Results and discussions

3.1. Length

Figs. 4–6 and Table 1 show the fibre length distribution of chicken feather barbules, barb and rachis. The averages of 100 readings at different sampling positions for a total of 100 samples were noted. The results show that the order of fibre lengths of the samples was barbules > rachis > barbs.

3.1.1. Rachis

The length of the chicken feather rachis ranged between 40 mm and 150 mm. This gave the range of the chicken feather rachis as 110 mm. The range was high, due to the different sizes of the rachis at different sampling position of the chicken body. The median length was 124.85 mm and the mean length was 92.13 mm with a SD of 55.28 mm. The length distribution of chicken feather rachis was not normal and showed a positive degree of kurtosis from 121 to 140 mm (Fig. 4). From the data, it can be deduced that the chicken feather rachis is of lengths that can be spun since spinning is applicable for fibres with lengths of greater than 12.7 mm (May, 2002).

3.1.2. Barbs

The distributions of chicken feather barb fraction were not normal but rather showed a positive degree of kurtosis from 21 to 30 mm (Fig. 5). The lengths of the barbs ranged between 1 mm and 45 mm. This gave the range of the fibres as 44 mm.

The data in Table 1 indicate that barbs of chicken feathers are of a length that is suitable for spinning into yarn fibres (Hearle, and Morton, 2008). However, the fibre lengths of the barbs lie between short staple and medium staple textile fibres: this will affect the spinning limit, handling of the product, the lustre of the product, quality of the yarn. The higher the amount of short fibres the more end breakage will occur during processing, which negatively affects the quality of the product and the production rate. The length distributions of each chicken feather barb along the length of one rachis were not consistent along their lengths; the mean Cv for ten samples at five sampling positions was 53.53% demonstrating the heterogeneity of the sample. However, variations of barb length up to the third sampling position were consistent varying by less than 15%.

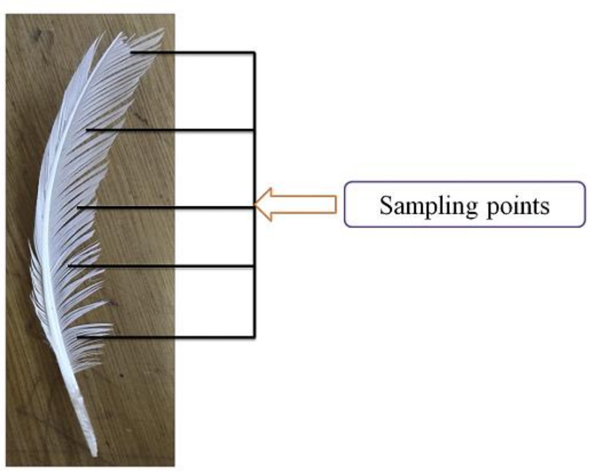


Fig. 3. Selection of sampling points for measurement along a chicken feather.

3.1.3. Barbules

The fibre length distributions of chicken feather barbules were approximately normal (Fig. 6) and ranged between 1 and 800 μm. The data indicate that barbules of chicken feathers are of a length that is not suitable for spinning.

3.2. Fibre diameter

The data in Table 2 illustrate the diameter of the barbules, barbs and rachis of chicken feathers. The averages of three readings from different places along a single sample were used for 25 samples, for a total of 75 readings.

As can be seen from Table 2, the mean diameter of the chicken feather barbules was 4.93 μm, with a SD of 1.73 μm and a Cv of 35.12%. The diameter of the barb was relatively small: the mean diameter was 46.65 μm, with a SD of 34.37 μm and a Cv of 73%. The variation in diameter was high indicating that the barbs were of widely different diameters. Uniformity of barb width is an important aspect in the quality and flexibility of yarn spinning. Due to its contribution to softness and to the fact that finer fibre generates fibre yarns which produce lightweight fabrics, fibre diameter is the first requirement in yarn production. As the demand by the modern consumer is to seek comfort and enjoyment in wear, this is critical in the modern textile industry which is found especially in light weight fabrics.

The mean diameter of the rachis of the chicken feathers was 2.26 mm, with a SD of 1.17 mm and a Cv of 51.65%. The Cv of the measurement was relatively high and the diameter of the rachis was very high. The diameter of fibres affects the spinning quality and flexibility of the fibre: the finer the fibre the better the spinning quality. The diameter of the barb of the chicken feathers were in the range of spinnable diameter for the textile application (Hearle, and Morton, 2008: Jones et al., 1998). Our results indicate that the rachis of chicken feathers will not be suitable for spinning into textile yarns.

The distributions of diameter widths of chicken feather barb and barbules were very consistent along their length, varying by less than 10% and 4%: only the extreme distal ends of the barb and barbules differed in diameter from the rest of the samples. The distribution of the diameter widths of the rachis was not consistent along the length of the rachis, varying by greater than 40%: the extreme distal end of the rachis is wider but the apex of the shaft is thinner than the rest of the rachis.

As shown in Fig. 7, the fibre diameter widths distributions of barbules were approximately normal; however, the diameters of the barb and rachis were narrower (i.e., exhibited a negative degree of kurtosis from 5 to 50 μm and a positive degree of kurtosis from 3 to 4 mm). ANOVA statistics showed that the diameter width distributions of the different feather fractions were significantly different from each another.

The variation in fibre length and diameter of the barbs and

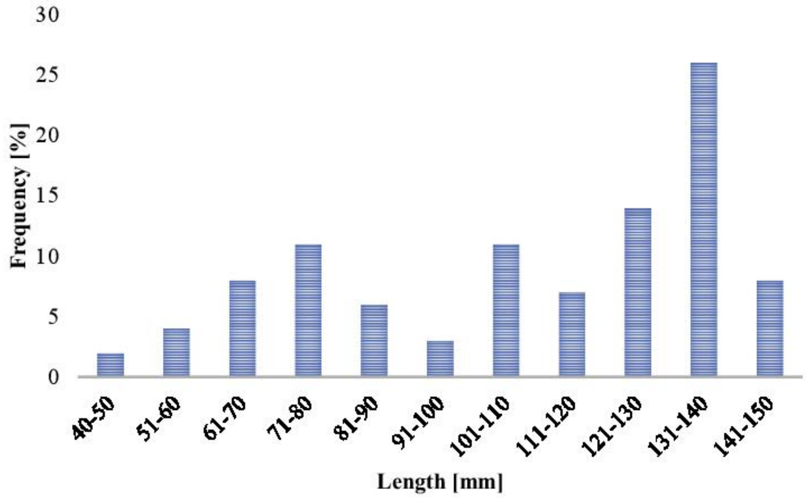


Fig. 4. Fibre length distribution of chicken feather rachis.

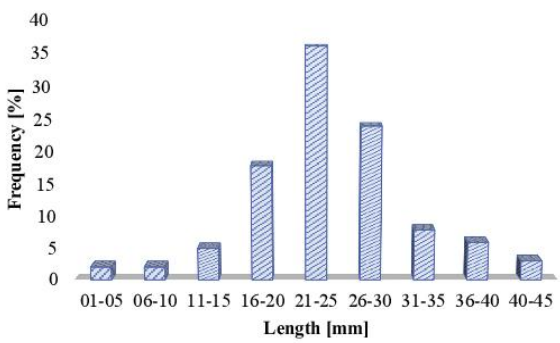


Fig. 5. Fibre length distribution of chicken feather barbs.

Table 1
Fibre length distribution of chicken feather fractions.

	Barbules	Barb	Rachis
Mean	398.00 μm	24.75 mm	92.13 mm
SD	154.58 μm	19.14 mm	55.28 mm
Median	379.79 μm	25.31 mm	124.85 mm
Cv	38.84%	77.31%	60.01%

Table 2
Diameter of chicken feather barbules, barb and rachis.

	Barbules	Barb	Rachis
Mean	4.92 μm	46.65 μm	2.26 mm
SD	1.73 μm	34.37 μm	1.17 mm
Cv	35.12%	73.66%	51.65%

rachis was very large, most probably because the feather samples originated from different positions on the chickens and from different sized chickens. Barbs and rachis from big chickens are longer than those from smaller chickens whereas barbs and rachis of small chickens are fluffier than those from large chickens. Also, barbs and rachis from big chicken feathers originating from the

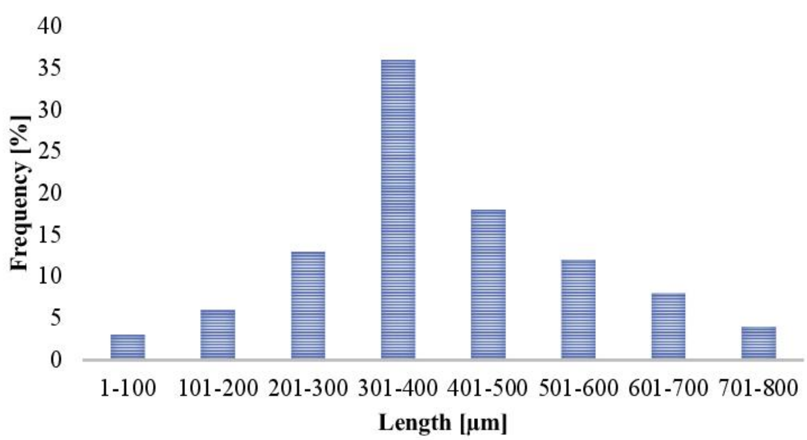


Fig. 6. Fibre length distribution of chicken feather barbules.

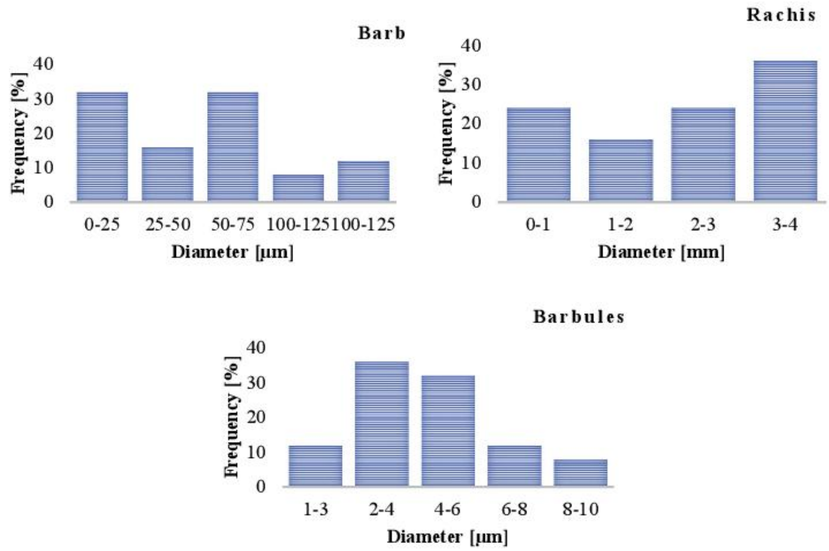


Fig. 7. The distributions of diameter widths of chicken feather fractions.

outer body of a chicken are much longer than those of small feathers from the inner body part of a chicken.

3.3. Linear density of barbs

The diameter dimensions of chicken feather barbs show that they are very fine fibres – determination of the linear density of this fraction is very complicated. However, the measurements were done and the results in Table 3 show that the linear density of a chicken feather barb bundle is 52.92 Tex with a SD of 15.69 Tex. The Cv of the linear density was 29.66% and this low variation indicates that the sample was naturally homogeneous. Possible applications for this type of linear density include composites for applications in diverse areas such as automotive, aerospace, geotextile, decorative, and even textile industries (e.g., fabrics blended with wool or cotton).

3.4. Dimensional measurements

Data for medulla diameter, cell wall thickness and length and diameter results for barbs are shown in Fig. 8 and summarised in Table 4. The data for rachis were much bigger than that for barbs. Higher cell wall thickness/cortex of fibres causes more flexibility of fibres in further processing of fibres, e.g., in textile applications. The increase of cell wall thickness has a direct positive effect on strength properties of fibres.

The calculated values for aspect ratio/slenderness ratio and flexibility ratio are shown in Table 4: the barbs exhibited higher slenderness ratio flexibility ratio than the rachis. Table 6 shows that the corresponding average aspect ratio for barb was 530.55 whereas that for rachis was approximately 40.77. Slenderness ratio/aspect ratio is related to the dimensional parameters of fibres such as length and breadth. The preferred length to width ratio for use in textile industries is between 200 and 600 (Fathima and Balasubramanian, 2006). The results from the present work suggest that chicken feather barbs can be used as fibres in textile industries whereas rachis may not be used for such applications.

Table 3
Linear density and fineness of chicken feather barb.

	Linear density
Mean	52.92 Tex
SD	15.69 Tex
Cv	29.66%

The use of any type of textile fibre for composite applications is dictated by its geometric dimensions, specifically a very high length-to-diameter ratio. In weight-sensitive applications such as automotive, aircraft and space vehicles strength-to-density and stiffness-to-density ratios are commonly used as indicators of the effectiveness of a fibre (Ververis et al., 2004). The longer the fibre, the lower the number of ends, and the higher will be the load carrying capability. In general, the strength of fibre composites is dictated by the critical length of the fibre: the strength will be higher if the fibre length exceeds its critical length. If the aspect ratio is greater than 15, the fibre is termed continuous; otherwise, it is termed discontinuous (Gejo et al., 2010).

In this study, chicken feather can be considered as continuous fibre with average aspect ratio greater than 15, but their diameters and lengths varied depending on their location on the body of the chicken. Chicken feather fibres are naturally of short length which allows for accommodation of a number of fibres for the same volume fraction; increase in surface area improves the efficiency of load carrying (Fatima and Balasubramanian, 2006). The workability-reducing effect of fibres depends largely on aspect ratio. Ideally, the aspect ratio should be as small as possible to minimise the loss of workability and as large as possible to maximise the resistance of fibres to pull-out from the matrix and maximising their reinforcing effectiveness.

Fibres with high aspect ratios are thin and long whereas fibres with low aspect ratio are shorter and broader in the transverse direction. It is advantageous to retain as much fibre length as possible since higher aspect ratios give rise to good surface contact and fibre-to-fibre bonding. Long fibre lengths (up to 500 aspect ratio); result in high strength (Fowler et al., 2006). Short and thick fibres produce a poor slenderness ratio which in turn negatively affects the quality of the final products. This is partly because short and thick fibres do not produce good surface contact and fibre to

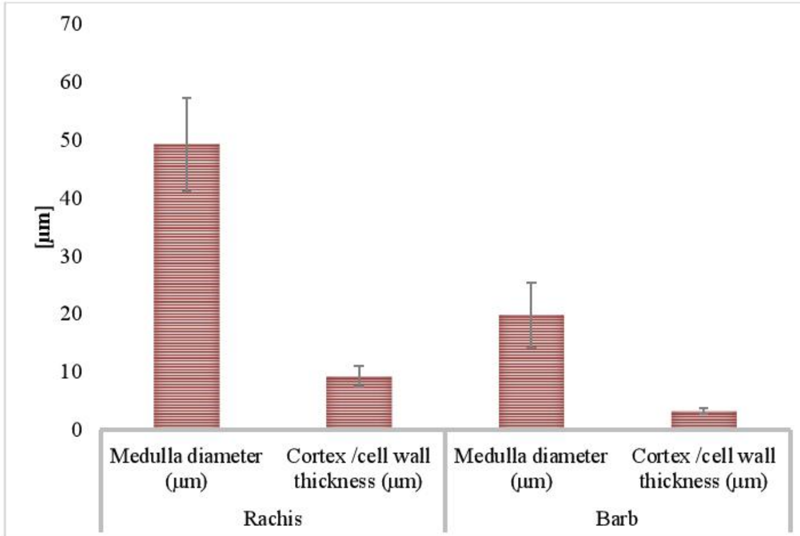


Fig. 8. The dimensional measurements of chicken feather barbs and rachis.

Table 4
Dimensions of chicken feather fractions.

Part of feather	Length (mm)	Diameter (µm)	Medulla diameter (µm)	Wall thickness (µm)	Slenderness ratio	Flexibility ratio
Barbs	24.75	46.65	26.88	3.31	530.55	57.62
Rachis	92.13	2260	49.25	9.27	40.77	0.58

fibre bonding.

The flexibility ratio of chicken feather barbs was 57.62 while that of rachis was 0.58. According to the classification of textile fibres with respect to their flexibility ratio, the flexibility coefficient of chicken feather barbs places them in the elastic fibres group, whereas the rachis is included in the highly rigid fibre group. The flexibility and ability of the barbs to twist and bend will provide good strength, cohesiveness, and spinnability to yarns and fabrics made from them. If barbs are blended with other fibres, the morphological structures of the barbs, barbules and the hooks in the barbules will provide better cohesiveness to the blended yarns.

Fibre diameter and wall thickness govern fibre flexibility. A thick walled fibre adversely affects burst strength, tensile strength, and folding endurance of the final product (e.g., textile fabric, composites, and paper). Product manufactured from thick-walled fibres will be bulky, coarse-surfaced and will contain a large amount of void volume whereas products from thin walled fibres will be dense and well formed.

3.5. Moisture content and regain

The data in Fig. 9, illustrate the results of the moisture content of chicken feathers and fractions thereof. Moisture regain values are more commonly used in textile business transactions than moisture content values since buyers of fabrics are concerned with the weight of fibres and excess moisture impacts the weight of the purchased fabrics (fabrics with higher moister regain values will weigh more that those with low regain values). The results of the proximate analyses of chicken feathers (barb, whole feather and rachis) from different sampling positions of the feathers are presented in Fig. 9. The moisture content of the barbs was the highest at 12.33%, followed by that for whole feathers at 10.54% and rachis at 8.75%. From the data in Fig. 9, the Cv for all samples is very low indicating that the sample was homogeneous. The moisture content values followed the same trend as the regain values except that the values were about 15% smaller.

The ability of chicken feathers and fractions to absorb moisture from the environment has important implications for processing, storage, transportation, and durability of chicken feather containing composite materials, since increases in moisture content may interfere with processing or bonding, increase weight of the products (and transportation costs), or lead to rapid deterioration of the product. However, the average moisture content of the chicken feathers did not exceed 10.54%: this implies that the material could be safely stored for long time periods with no concerns of deterioration. Moisture contents of 8%–13% indicate that chicken feather is hygroscopic. The hygroscopicity increases in chicken feather barbs. This implies that they can absorb enough water to prevent static build-up – useful in applications where static build-up is of importance.

In structural morphology considerations, the presence of a honeycomb structure will provide for the accumulation of liquids in

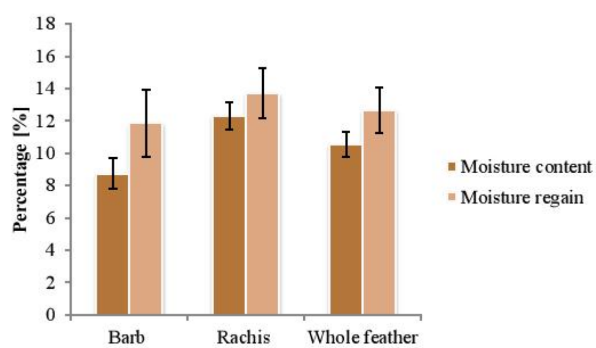


Fig. 9. Moisture contents and regain of chicken feather fractions.

its interior, in addition to the amount of water already absorbed by the dry material: 3.11% for barbs, 1.39% for rachis and 2.13% for whole feathers. Chicken feather fractions could be a good opportunity for several types of applications that require liquid retention. For example, in the medical area, it is possible to insert drugs in microfibrous materials and, with body heat, the drug may be released to the body of the individual.

Fibres with greater regain values probably have more amorphous regions. The value of moisture regain of the chicken feathers was considered low compared to other fibres that have a moisture regain of up to 20%. This probably implies that fabric products made from this material will provide comfort in texture to the end users.

The comfort of textile fabrics are influenced by moisture content and fibres with good moisture regain accept dyes and finishes more readily than fibres with low regain (Freddi et al., 2003); therefore, water-born dyes and finishes can be applied on the chicken feather fabrics. Further research is required to determine the maximum suitable moisture content of chicken feathers and also to assess the effect of variations in moisture on processing, storage, transportation, and durability of the fibres.

3.6. Morphological structure

The morphological features of chicken feather fractions are shown in Fig. 10. As can be seen in Fig. 10a the chicken feather is composed of three distinct units: the rachis, the central shaft of the feather that runs the entire length of the feather to which is attached the secondary structures, the barbs and the tertiary structures, the barbules. The length of the rachis varies depending on the sampling position of the feathers on the body of the chicken; however, the lengths of barbs and barbules do not vary much except that sometimes barbs and barbules at the base of the rachis are longer than those at the tip of the rachis. The lengths of the rachis are about 1–150 mm and barbs are about 1–45 mm. The barbules are about 1–800 μm long and have hook-like structures at their tips as can be seen in Fig. 10a and b. Barbs display a fibrillar surface but no scales. From this information, it can be postulated that mechanical properties of fibrous composites made from feathers will be improved due to the entanglement of barbules with other fibres. Also, the occurrences of microfibrils in chicken feathers that are twisted form helixes imply that their use will impart high mechanical strength to the fibres.

The thickness and stiffness characteristics of chicken feather rachis indicate that rachis fibres are not suitable for use as natural protein fibres. In contrast, the flexibility and length of feather barbs make them suitable to be used as natural protein fibres. As can be seen in Fig. 10c feather barbs show honeycomb shaped hollow cells in the cross-section direction. These honeycomb structure can act as a raw material for light weight high tech materials. The voids inside chicken feathers may be more accessible to fluids or air as length decreases. The presence of hollow honeycomb structures provides high resistance to compressibility and also imparts lightweightiness to barbs and rachis.

The honeycomb structure in the cross-sectional view of the chicken feathers, as shown in Fig. 10e, confirms the existence of extensive air pockets in the feathers: this contributes to the high

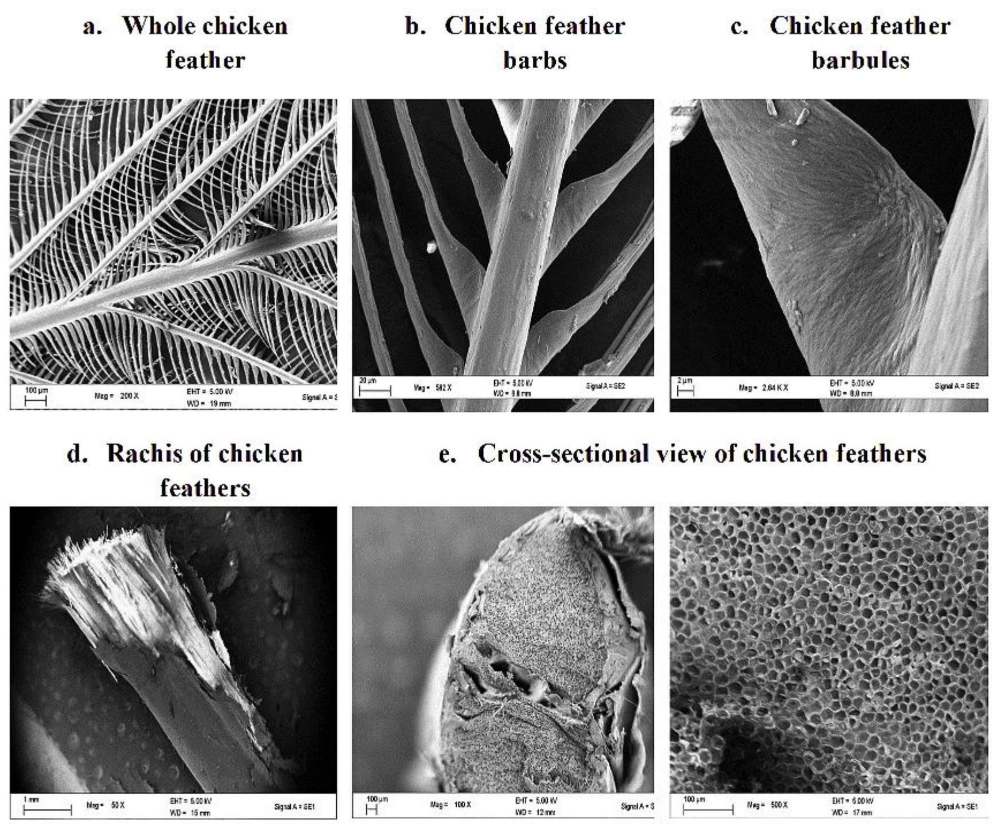


Fig. 10. Morphological structures of chicken feathers (whole chicken feather, chicken barbs, chicken barbules, chicken rachis).

thermal resistance and good moisture transport characteristics of feathers. The presence of two different structures inside the bio-fibres are evident: they are microfibrils and protofibrils. The former have a more ordered and crystalline structure than the feather matrix. The protofibrils exist inside the microfibrils and are also surrounded by the matrix. The images in Fig. 10e confirm that the microstructure of feathers is nearly round; the medulla in coarse fibres are concentric and irregular in size.

The presence of extensive air pockets in the structure of feathers imply that feathers can be used in the preparation of good thermal retention materials (Birbeck and Mercer, 1957; Das and Ramaswamy, 2006.). This property imparts good resilience features to feathers and explains why feathers are good materials for preparation of products with good heat insulation capacity, e.g., winter outerwear coats.

3.7. Fine details of chicken feather fractions cellular structures

From the AFM images of barb and rachis cross-section image, the cuticle, cortex, and epoxy resin regions can be easily recognised (Figs. 11 and 12). Morphologically, the chicken feather barb and rachis consists of two components, outside layers of protecting cells, called cuticles which surround the cortex that consist of macrofibrils (Figs. 11 and 12). The cell membrane complex separates cortex from those of the cuticle and a group of cortical cells were also linked together by cell membrane complex. In rachis of chicken feathers, there is also a central medulla (Fig. 12.3). The cross-sectional shape of the rachis was greatly varied from sample to sample; some were approximately circular, whereas others were oval-shaped whereas the shape of the barbs were less varied in shape and were approximately oval-shaped. Fig. 11.1 (a), the cross-section of the barbules were approximately a hooked/helical structure.

3.7.1. Cuticle

As it is seen in Figs. 11 (11.1 (a) and (b)) and 12 (12.1 (a) and 12.2), a dark region surrounded the barb and rachis cross-section represented the cuticle. The cuticle, which were plate-shaped, form the outer part of the barb and rachis surrounding the cortical cells in layers of flat scales and was only one scale in thickness over most of its area (Figs. 11 and 12). The cuticle of chicken feather fractions were smooth with low scales, indicates the lusterity of the fibre is good. As it is also observed in wool fibre, all interactions with the environment occur through the cuticle, providing resistance to potentially harmful agents that may come into contact. Since the cuticle is such a small part of both barb and rachis cross section, it is unlikely to contribute to the tensile properties.

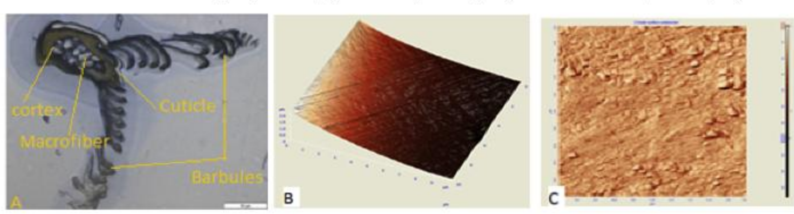
3.7.2. Cortex

The cortex forms the central/principal part of both the barb and rachis cross-section of the chicken feather and two different morphological regions can be seen: the macrofibril and cell membrane complex (Fig. 11 (11.1 (a) and (b - 3 × 3 μm)) and 12 (12.1 (a - 500 × 500 μm) and 12.2). It consists of small spindle-shaped cells which are a bundle of the intermediate filaments, oriented parallel to each other (Figs. 11 and 12). As the diameter of the rachis greater than the barb, so the proportion of cortex in rachis is higher than rachis (Figs. 11 and 12). Unlike in barb, the division of macrofibrils in rachis was quite clear, as fibril matrix divided them (Fig. 12). A cortex cell of both barb and rachis contains a group of macrofibrils and they were separated by fibril matrix and between macrofibrils, there were nuclear remnants of keratinocytes (Fig. 11.2 and 12.4). In the cortex, the nuclear remnants: which are not mature macrofibrils (Fig. 12.1 (a)) were either found in stretched into dendrites or the centre of the macrofibrils. The shape and staining of the nuclear remnants seemed highly probable that they were melanin. The surface roughness is thought to be indicative of immature macrofibrils. Microfibrils are a relatively early stage of development, organised to form macrofibril structures which were also observed (Fig. 11.2 (c - 1 × 1 μm) and 12.5 (B -8x8 μm)) and they consist of protofibrils (Fig. 12.5 (c - 1 × 1 μm)).

3.8. Density of chicken feathers

The density of whole feathers and feather fractions showed clear differences among them but that of the whole feather was very close to that of the barb density in almost all cases. The mean relative density of the barbs was 0.91 g/cm^3 with a SD of 0.22 g/cm^3

11.1. Cross-sectional image of barb (a), Cuticle (b-3x3 μm) and the cortex (c- 2x2 μm)



11.2. Ultrastructure of chicken feather barb (cortex, macrofibrils, fibril matrix, and microfibrils), a-3x3 μm, b-2x2 μm, and c-1x1 μm.

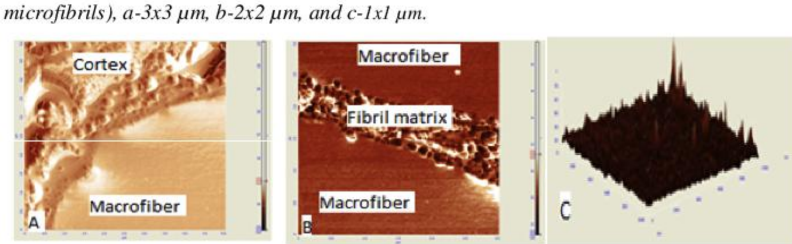
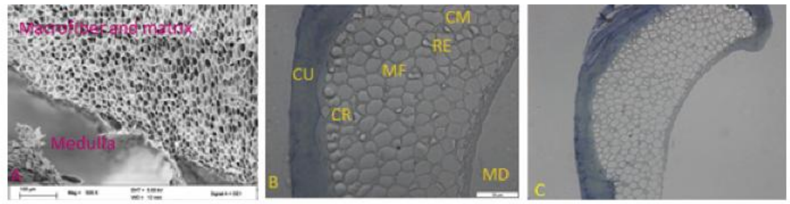
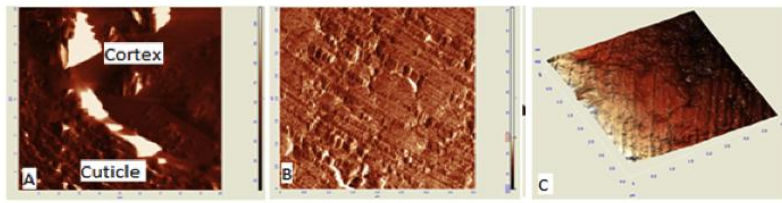


Fig. 11. Cross-sectional images of chicken feather barb and fine detailed images of the cuticle region and cortex region.

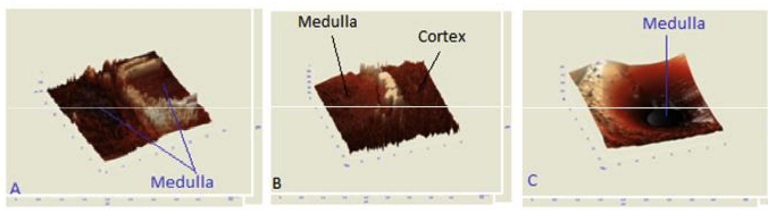


CU; cuticle, CR; cortex, MF; macrofibrils, RE; nuclear remnants, MD; medulla and CM; Cell membrane complex

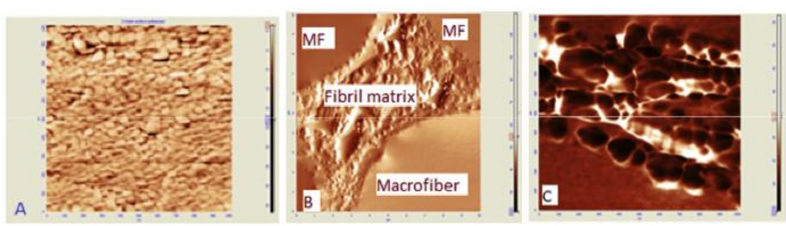
12.2. Cuticle (a - 10x10 μm), (b - 4x4 μm) and (c - 3x3 μm)



12.3. Medulla (a - 12x12 μm), (b - 12x12 μm) and (c - 12x12 μm)



12.4. Cortex (a - 1x1 μm*), Macrofibre and fibril matrix (b* - 10x10 μm*) and fibril matrix (c-* 1x1 μm*)*



12.5. Macrofibrils (a- 10x10 μm*), microfibrils (b-* 8x8 μm*) and protofibrils (c-* 1x1 μm*)*

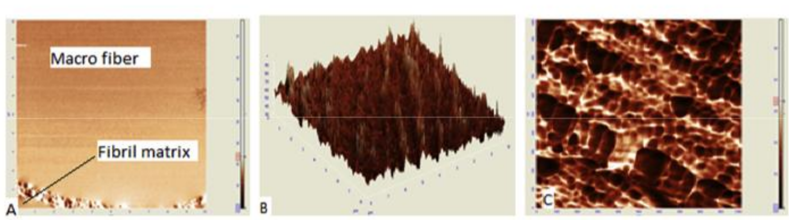


Fig. 12. Cross-sectional images of chicken feather rachis and fine detailed images of the cuticle region and cortex region.

and Cv 24.29%, a relatively low variation indicative of sample homogeneity. The density of chicken feather barbs varied between 0.5 g/cm^3 and 1.5 g/cm^3. The variation in results may be related to the composition differences in the barb samples studied.

The data in Fig. 13 show that the mean recorded relative density of rachis was 0.44 g/cm^3 with a SD of 0.13 g/cm^3 and Cv 28.99%, a

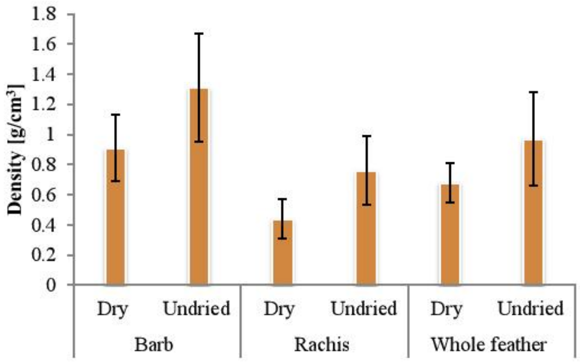


Fig. 13. Density of chicken feather fractions.

relatively low variation indicative of sample homogeneity. The mean density of whole chicken feathers was 0.68 g/cm^3 with a SD of 0.13 g/cm^3 and Cv 18.91% again, the Cv was relatively low and indicative of sample homogeneity. Chicken feather barbs consist of a large concentration of alpha helices whereas the quill or rachis is mainly composed of beta sheets and/or disordered structures. SEM micrographs of cross sections of a rachis (Fig. 10) show an open cell porous structure, which very probably, is responsible for the low-density value of the rachis. The images of chicken feather barbs are typical of feather barbs, barbules, and hooklets.

The mean wet density of rachis was 0.76 g/cm^3 with a SD of 0.23 g/cm^3 and Cv 27.48%, a relatively low variation indicative of sample homogeneity. The mean density of whole chicken feathers was 0.97 g/cm^3 (SD of 0.31 g/cm^3 and Cv 31.96%) and barb was 1.31 g/cm^3 (SD of 0.36 g/cm^3 and Cv 30.26%): again the Cv is relatively low and indicative of sample homogeneity. The result from Fig. 13 shows that the density of chicken feather fractions after drying, indicating that a significant amount of moisture was present in the fractions. The low SD values confirmed the similarities of the density of the samples.

Considering that the chicken feathers used in this study were collected from one chicken processing plant, it is plausible that the density of the chicken feather fractions is likely to be influenced by the effectiveness of the waste chicken feather segregation process employed at the plant. Therefore, density measurements may be used to gauge the degree of the segregation process. Such properties are important in the valorisation of feathers into many applications such as textile yarn and composites.

The density of chicken feathers and fractions thereof, were measured to be 0.44–0.91 g/cm^3: these values correlated well with literature values for protein and cellulosic fibre but were lower than those of animal and plant fibres such as wool (1.31 g/cm^3), silk (1.27 g/cm^3), jute (1.3 g/cm^3), coir (1.2 g/cm^3), and cotton (1.5–1.6 g/cm^3), etc. (Hearle, and Morton, 2008). Considering that the density of composite materials increases as the amount of reinforcing fibre content increases, the inclusion of chicken feather fractions in a composite could potentially lower the density of the resultant composites. This implies that production of lightweight composites containing chicken feather fractions will result in substantial savings in terms of transportation and construction costs due to the inclusion of the lightweight feather fractions. No natural or commercially available synthetic fibres today have a density as low as that of chicken feathers.

Table 5
The mass distributions of chicken feather fractions.

	Whole feather	Rachis	Barb in the whole feather	Single barb
Mean (mg)	95.356	48.28	44.27	0.10
SD (mg)	56.14	25.12	24.52	0.05
Cv (%)	58.87	52.03	55.39	55.02
% age	100	52.13	48.87	–

3.9. *Mass of chicken feather fractions*

The mass distribution of chicken feather fraction and single barbs were significantly different among the fractions as can be seen in Table 5 and Fig. 14. Box and whisker plots of the mass distribution for chicken feather fractions are shown in Fig. 14. The result confirmed that mean weight of the chicken feather rachis was 48.28 mg with a SD of 25.12 mg and Cv at 52.03% having a total percentage of 52.13% of the whole feather. The Cv was relatively high due to the heterogeneity of chicken feather rachis at different positions on the body part of the chicken. The mean weight of barb in a chicken feather was 44.27 mg with a SD of 24.52 mg and Cv 55.39%. The Cv is relatively high due to the heterogeneity of chicken feather barbs at different positions on the body parts of the chicken and rachis. The mean weight of a single barb was 0.10 mg with a SD of 0.05 mg and Cv at 55.02%. The Cv is relatively high due to the heterogeneity of chicken feather barbs length distribution at different positions along the length of the rachis.

3.10. *Colour measurements*

Table 6 shows the colour measurement data for chicken feather barb and rachis. Chicken feather colour varies due to the biological nature of the chicken and how it was processed. The amount of preen oil in chicken feather contributes to the yellowness of the feather and these fatty acid compositions varies for different age intervals. Particulates from dust bathing, pieces of feed and faecal matter may also be present in chicken feathers. Unprocessed white chicken feather collected from poultry industries appeared straw-like and the barbs were stuck to the rachis in a greasy tangle and turned dark brown after 2 days when left at room temperature. A rotten odour was also evident due to the development of bacteria and the bacterial excrement caused the feathers to darken (Fig. 15). As it is shown in Fig. 15, the untreated white chicken feather also contains blood, which looks pink just after collection but turns brown as it dries. The method of transporting the feather, in the poultry industry (from the section to temporary waste storage area) may also affect the colour of the chicken feather and the amount of impurities. The CIE tristimulus (L*, a* and b*) values, whiteness index, yellowness index and colour difference result from Table 6 shows that there is a need to pre-treat the chicken feather in order to improve the colour of the chicken feather before valorisation.

3.11. *BET analysis*

As it is seen from Tables 7 and 8, the physiosorption property of the chicken feather fractions (barb and rachis) shows a significant difference of BET surface area. The difference in surface area of both samples may be due to the microstructural difference between the two samples as it is seen in the morphology section. Since the pore size of both fractions falls in between 2 and 150 nm, it can be concluded that the chicken feather fractions were mesoporous and microporous material (Weber et al., 2010: Gil, and Montes, 1994.).

Rachis: The surface area of the rachis was 1.2528 m^2/g with a single point surface area at P/Po = 0.200876844: 1.2912 m^2/g (Table 7). The pore volume of barb for single point adsorption total pore volume of pores less than 168.9074 nm diameter at P/Po = 0.988792338 was 0.017373 cm^3/g. The chicken feather rachis has a pore size of adsorption average pore width (4V/A by BET)

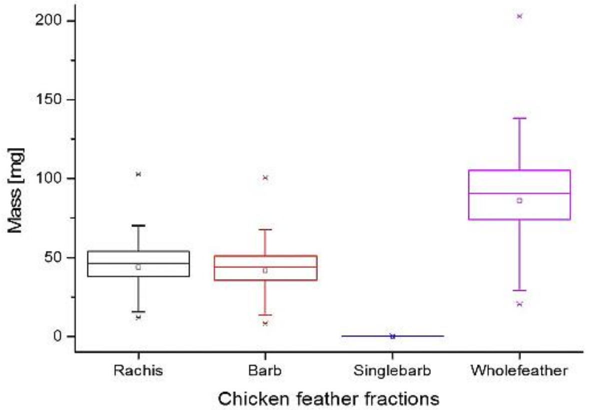


Fig. 14. Box and whisker plots of mass distributions of chicken feather fractions (rachis, barb, single barb and whole feather). * refers to the highest and lowest values, the lower whisker represents the 10th percentile, the □ represents the mean value, the bottom of the box represents the 25th percentile, the line inside the box represents the median value, the top of the box represents the 75th percentile and the top whisker represents the 90th percentile.

Table 6
CIE tristimulus values, whiteness index and colour differences (ΔE) for chicken feathers.

Fraction of chicken feather	L^*	a^*	b^*	ΔE	WI CIE	YI E313
Barb	75.36	2.81	19.59	77.91	−57.75	43.18
Rachis	78.54	1.43	11.32	79.36	48.34	41.62

55.47121 nm, BJH adsorption average pore diameter (4V/A): 42.9203 nm and BJH desorption average pore diameter (4V/A): 28.7849 nm.

Barb: The surface area of the barb was 0.7845 m^2/g with a single point surface area at P/Po = 0.201083043: 0.8712 m^2/g (Table 8). The pore volume of barb for single point adsorption total pore volume of pores less than 139.3977 nm diameter at P/Po = 0.986439263 was 0.007904 cm^3/g. The chicken feather barb has a pore size of adsorption average pore width (4V/A by BET): 40.29871 nm, BJH adsorption average pore diameter (4V/A): 87.0263 nm and BJH desorption average pore diameter (4V/A): 25.8096 nm.

Fig. 16 shows the BET specific surface area of chicken feather fractions. It can be seen from Fig. 16 that the rachis were much more linear and the data is uniformly distributed compared to the barb of chicken feathers. Fig. 16 demonstrates that the amount of the adsorbed nitrogen is noticeably lower for barb compared to the rachis part. This region is the representative of adsorption in micropores, which are the internal adsorption sites inside the chicken feather fraction. These results showed that the material produced from rachis have very stable adsorption and desorption resulting in the higher surface area compared to material produced from chicken feather barb.

Nitrogen adsorption/desorption isotherms at 77 K of the barb and rachis of the chicken feather samples are shown in Fig. 17. Both fractions exhibited the type-III isotherms and explains the formation of multilayers. Fig. 17 shows considerable differences between the adsorption/desorption isotherms of barb and rachis of the chicken feather: the uptake amount at low pressure by rachis were

Fig. 15. Chicken feather from poultry industry (a: during collection; b: after three days).

Table 7
Physiosorption property of the chicken feather rachis.

Surface area	
Single point surface area at P/Po = 0.200876844:	1.2912 m^2/g
BET Surface Area:	1.2528 m^2/g
BJH Adsorption cumulative surface area of pores between 1.7000 nm and 300.0000 nm diameter:	2.171 m^2/g
BJH Desorption cumulative surface area of pores between 1.7000 nm and 300.0000 nm diameter:	3.3714 m^2/g
Pore volume	
Single point adsorption total pore volume of pores less than 168.9074 nm diameter at P/Po = 0.988792338:	0.017373 cm^3/g
BJH Adsorption cumulative volume of pores between 1.7000 nm and 300.0000 nm diameter:	0.023291 cm^3/g
BJH Desorption cumulative volume of pores between 1.7000 nm and 300.0000 nm diameter:	0.024261 cm^3/g
Pore size	
Adsorption average pore width (4V/A by BET):	55.47121 nm
BJH Adsorption average pore diameter (4V/A):	42.9203 nm
BJH Desorption average pore diameter (4V/A):	28.7849 nm

Table 8
Physiosorption property of the chicken feather barb.

Surface area	
Single point surface area at P/Po = 0.201083043:	0.8712 m^2/g
BET Surface Area:	0.7845 m^2/g
BJH Adsorption cumulative surface area of pores between 1.7000 nm and 300.0000 nm diameter:	0.615 m^2/g
BJH Desorption cumulative surface area of pores between 1.7000 nm and 300.0000 nm diameter:	2.1358 m^2/g
Pore volume	
Single point adsorption total pore volume of pores less than 139.3977 nm diameter at P/Po = 0.986439263:	0.007904 cm^3/g
BJH Adsorption cumulative volume of pores between 1.7000 nm and 300.0000 nm diameter:	0.013389 cm^3/g
BJH Desorption cumulative volume of pores between 1.7000 nm and 300.0000 nm diameter:	0.013781 cm^3/g
Pore size	
Adsorption average pore width (4V/A by BET):	40.29871 nm
BJH Adsorption average pore diameter (4V/A):	87.0263 nm
BJH Desorption average pore diameter (4V/A):	25.8096 nm

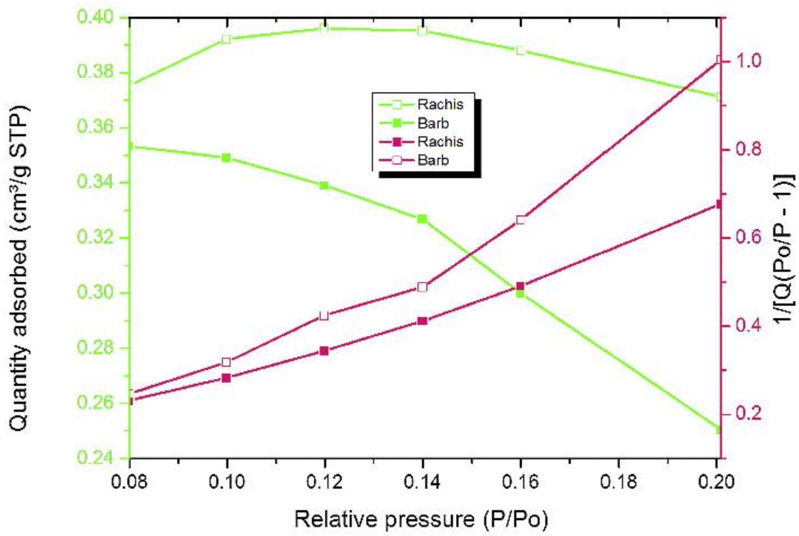


Fig. 16. BET Specific surface area analysis of chicken feather fractions.

much higher than barb this is the indication for the presence of more mesopores. The uptake of nitrogen at very low pressures is due to mesopore and micropores filling from the enhanced adsorbent–adsorbate interactions in the mesopores and is distinct from adsorption in macropores because adsorption in mesopores material is due to multilayer adsorption and capillary condensation (Weber et al., 2010; Gil and Montes, 1994).

Figs. 18 and 19 shows the t-plots of chicken feather fraction and indicates that there is a strong deviation in t-plots between the fractions. But the t-plot of the fractions were identical (Figs. 18 and 19). The vertical line indicates the presence of mesopores and the horizontal line from the straight line indicate the presence of micropores (Weber et al., 2010; Storck et al., 1998).

Figs. 20–23 shows the obtained pore size distribution of chicken feather fractions. The chicken feather fractions have both micropores and mesopores. The pore size distribution shows a maximum

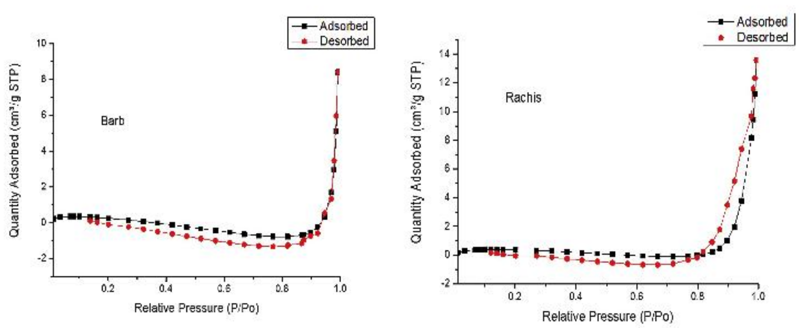


Fig. 17. Adsorption/Desorption isotherm of chicken feather fraction.

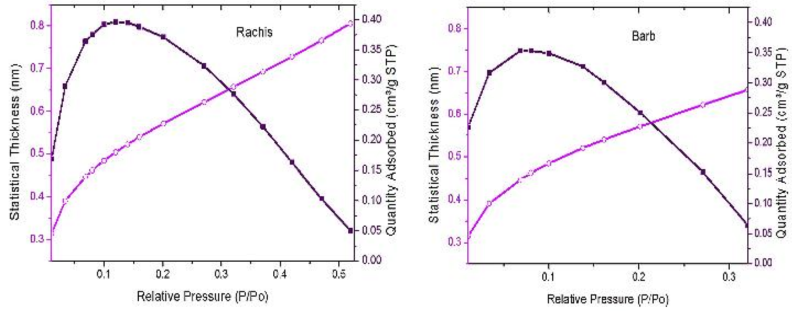


Fig. 18. Thickness curve of chicken feather fraction.

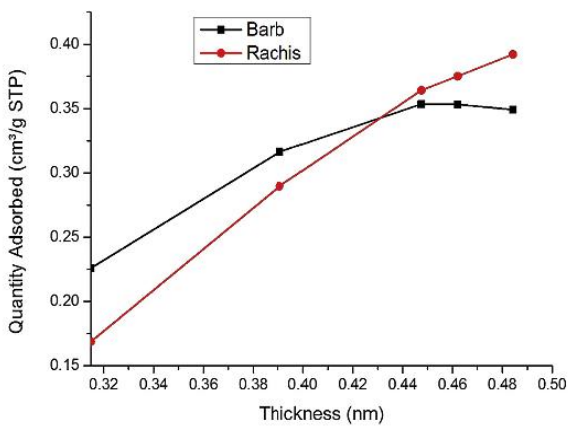


Fig. 19. t-Plots of chicken feather fractions.

at the pore size of 11.8 nm for rachis and 2.89 nm for barb. There is a secondary maximum at a pore size of around 13.95 nm for rachis and 37.55 nm for barb and there are pores in the larger microporous and mesoporous regions, but all these pore distributions are much smaller than the primary maximum.

4. Possibilities for valorisation of chicken feather fractions based on physical and morphological structure

The whole chicken feather, due to its complex structure, cannot be processed into protein fibre; however, its unique properties provide possibilities for valorisation into many applications. One such application is in the manufacture of composites for the construction, automotive and aerospace industries. Other applications could be keratin protein extraction for use in cosmetic, paper and pulp, and biodegradable plastic manufacturing. An added advantage is that chicken feathers are an abundant, renewable, waste-product of the poultry industry. In the textile industry chicken feathers could offer a cost-effective alternative source of raw material to the commonly used natural protein fibres, namely, wool and silk.

4.1. Composites in automobile and aeroplane industries

Currently, most automobile and aeroplane parts are made from petroleum-based raw materials. Owing to remarkable strength (due to the high cysteine content of the keratin protein, and low-priced properties), lightweight nature, and better quality (Figs. 10–12), feathers could be used to produce composites for use in automobile and aeroplane industries such as in dashboards, car parts, seats and cushioning, interior linings etc. to reduce their weight while strengthening them.

4.2. Fibres in yarns and fabrics

It is estimated that there are 67×10^9 kg of synthetic and natural fibres currently in use worldwide (Reddy and Yang, 2005). Due to the diminishing accessibility and expected cost increases of the raw materials and natural resources required to manufacture textiles and composite products, it is important to discover alternative

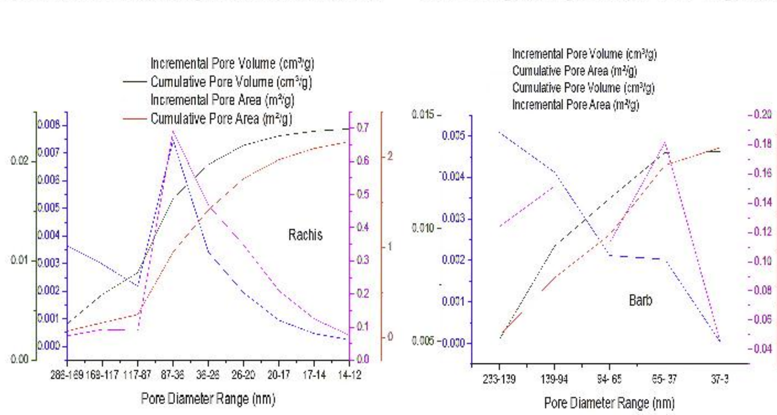


Fig. 20. BJH adsorption pore distribution of chicken feather fractions.

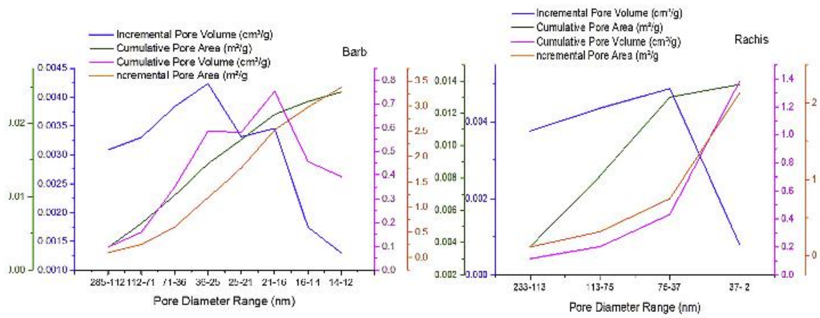


Fig. 21. BJH desorption pore distribution of chicken feather fractions.

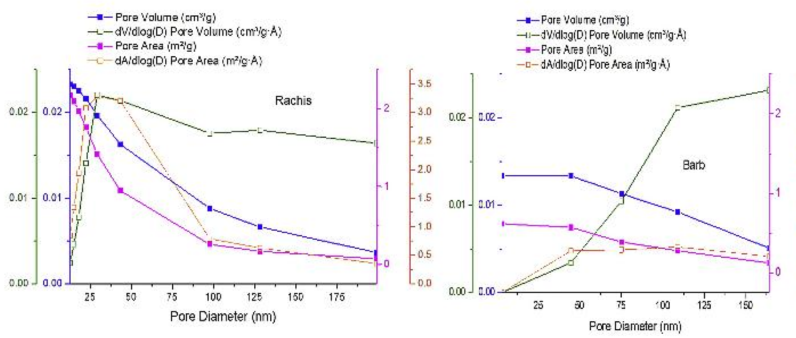


Fig. 22. BJH adsorption cumulative pore volume, pore area, dV/dlog(D) pore volume and dA/dlog(D) pore area of chicken feather fractions.

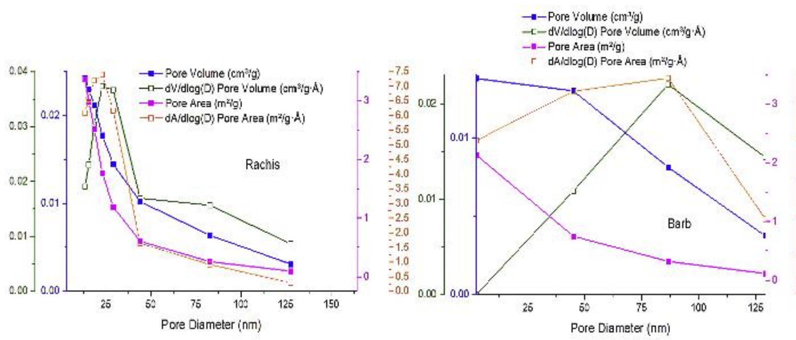


Fig. 23. BJH desorption cumulative pore volume, pore area, dV/dlog(D) pore volume and dA/dlog(D) pore area of chicken feather fractions.

sources. Endeavours are being made to utilise renewable agricultural by-products such as pineapple leaves, soybean husks, corn husks, and rice husk, as unconventional sources for cellulosic fibres (Reddy and Yang, 2006). The production of regenerated fibres from agricultural by-products containing proteins such as zein in soya has been tried (Boyer, 1940). However, none of the attempts to produce high-quality protein fibres from agricultural by-products have been commercially successful.

The rachis of feathers comprises approximately half of the weight of the feather while the barbs make up the other half: more than 30% of the barbs are longer than the 20 mm fibre length required for textile applications (Fig. 5). This means that, on an annual basis, approximately 12×10^9 kg of barbs could be available as natural protein fibres worldwide, with 77.4×10^6 kg of barbs obtainable in South Africa. This translates into an availability of 14 percent of the natural and synthetic fibre consumed annually (see Table 9).

4.3. Construction materials

Feathers could be used as reinforcement materials after prior

Table 9
Availability of chicken feathers.

	World	South Africa
Chicken feathers	$>40 \times 10^9$ kg	$>258 \times 106$ kg
Barbs	20×10^9 kg	129×10^6 kg
Barbs > 20 mm	12×10^9 kg	77.4×106 kg
Barbs < 20 mm and Rachis	28×10^9 kg	180.6×10^6 kg

separation of the feathers into long fibres, short fibres and powdered rachis (Figs. 4–6 and 8 and 9; Table 4). Although more research needs to be done, composites made of chicken feathers can be used in panelling or ceiling applications, and for thermal and sound insulation, but not for walls or pillars. Using chicken feather composites in the construction industry could be a major breakthrough to replace wood and plastic-based construction materials.

4.4. Geotextile materials

Geotextile materials are often used on road construction sites, building operation sites, and for coverage of agricultural areas and other uncovered land where stabilisation of soil is required. The materials are necessary for the conservation of landscapes to avoid removal or loss of sediment during rainfall and to help keep soil nutrients in place. There is a need for low-cost, biodegradable geotextile materials due to the high cost and environmental impact of synthetic erosion control geomaterials currently in use. One possibility is the development of yarns, knitted, and non-woven fabrics from feather fibres. Chicken feather geotextile materials would be strong and very stiff because of the tough keratin property of the feathers (Figs. 4–6 and 8 and 9; Table 4). Geotextiles prepared from feathers could be used to preserve the soil environments. Because of the water holding capacity of feather fibres, the materials could increase the moisture content of the soil and also decrease compaction of the soil due to the bulking properties of feathers.

4.5. Fuel storage applications

Hydrogen, the simplest and most plenteous component in the universe, has long been touted as a clean and ample alternative energy option to fossil fuels (Cheng et al., 2001). Unfortunately, due to its physical properties (lightest element and very low volumetric energy density), it is difficult to store and transport hydrogen. Researchers have been endeavouring to engineer ways to store hydrogen gas on board vehicles at reasonable weights, pressure, and temperatures, to significantly reduce the expenses of a hydrogen infrastructure. However, the alternatives used to store hydrogen, such as metal hybrids and carbon nanotubes, are often very costly (Cheng et al., 2001).

A light-weight and economic material is needed that can bind and release hydrogen, to assist automobiles to use hydrogen fuel; one of these materials could be chicken feathers. Chicken feathers are composed of mainly keratin protein, a natural protein that forms lightweight, strong, hollow tubes (Fig. 10). Seeing that the morphological structure and the adsorption/desorption isotherm of the chicken feather fraction chicken feather could be used as an alternative source for storing hydrogen gas. When pyrolysed, keratin becomes more permeable, expanding its surface, forming hollow tubes between the fibres, and creating crosslinks, which strengthen its structure and become carbon nanotubes. These features increase the ability to bind and store hydrogen. For example, to store and release the gas, one can pump hydrogen gas into feathers at high pressure, and then de-pressurize them, or raise the temperature, in order to release the gas.

4.6. Water purification

Chicken feathers could be used for water purification due to their inherent properties: structural toughness, stability over a wide range of pH, water insolubility, and high tensile strength. Their sorption characteristics will be satisfactory for the removal of heavy metals (e.g. copper, selenium, and zinc), toxic organic compounds and colourants in water, because of the hygroscopic nature of keratin protein (Kar and Misra, 2004). After extraction of keratin from chicken feathers, sponges could be prepared using dilution of the extracted keratin followed by lyophilisation. The sponge can be useful for example, in cleaning up of oil spills in water.

4.7. Filtration applications

The super fine size and shape of feather fibres imply that they may be used in filtration applications. Seeing that the morphological analysis and the BET analysis of chicken feather fractions, nonwovens made out of these fractions will exhibit very good porosity (Figs. 10 and 16–23), good resistance to mild acids and alkaline media, and light weight characteristics leading to a promising future in the chemical industries. Feather fibres could replace wood pulp-based paper products such as filter papers and decorative papers. Wood pulps are the raw material for most paper-based products, but feather fibres have an advantage in full or partial replacement of wood pulp, as they are finer in diameter than wood pulp.

5. Conclusions

The physical and morphological structure studies of chicken feather fractions indicate that feathers can be used as reinforcing materials for composites and as textile fibres for the production of yarns and fabric. Because of the presence of hollow honeycomb structures and a very low-density, chicken feather rachis and barbs could be used for applications that require excellent compressibility and resiliency, warmth retention, fluid absorption, light weight composites and sound protection applications. Results of this study indicate that incorporation of chicken feathers can be beneficial in various industries including construction, automotive, aerospace and plastics to make products that are lightweight, improve sound attenuation, and offer insulate from heat loss. Future studies will entail studies on chemical properties of chicken feathers to ascertain their valorisation pathways.

Acknowledgments

Funding and laboratory facilities were provided by the Thermodynamics Research unit, and the Forestry and Forest Products Research Centre/CSIR, Department of Science and Technology Waste Road Map; editorial assistance was provided by Ms Fiona Higginson.

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PUBLICATION FOUR

Waste Management 68 (2017) 626–635

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Valorisation of chicken feathers: Characterisation of chemical properties

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ARTICLE INFO

Article history:
Received 18 March 2017
Revised 27 June 2017
Accepted 29 June 2017
Available online 4 July 2017

Keywords:
Poultry waste
Feathers
Chemical properties
Burning tests

ABSTRACT

The characterisation of the chemical properties of the whole chicken feather and its fractions (barb and rachis), was undertaken to identify opportunities for valorizing this waste product. The authors have described the physical, morphological, mechanical, electrical and thermal properties of the chicken feathers and related them to potential valorisation routes of the waste. However, identification of their chemical properties is necessary to complete a comprehensive description of chicken feather fractions. Hence, the chicken feathers were thoroughly characterised by proximate and ultimate analyses, elemental composition, spectroscopic analyses, durability in different solvents, burning test, and hydrophobicity. The proximate analysis of chicken feathers revealed the following compositions: crude lipid (0.83%), crude fibre (2.15%), crude protein (82.36%), ash (1.49%), NFE (1.02%) and moisture content (12.33%) whereas the ultimate analyses showed: carbon (64.47%), nitrogen (10.41%), oxygen (22.34%), and sulphur (2.64%). FTIR analysis revealed that the chicken feather fractions contain amide and carboxylic groups indicative of proteinious functional groups; XRD showed a crystallinity index of 22. Durability and burning tests confirmed that feathers behaved similarly to animal fibre. This reveals that chicken feather can be a valuable raw material in textile, plastic, cosmetics, pharmaceuticals, biomedical and bioenergy industries.

1. Introduction

The disposal of waste in an economically and environmentally acceptable manner is a critical issue facing most modern industries. This is mainly due to increased difficulties in finding disposal sites and compliance with stringent environmental policy requirements imposed by waste management and disposal legislations. Worldwide, the poultry–processing industry generates large quantities of feather by-products that amount to 40×10^9 kg annually (Compassion in world farming, 2013) – in South Africa, more than 258×10^6 kg of chicken feathers are produced per annum (DAFF, 2014). The feathers are considered wastes to be disposed of although small amounts are often processed into valuable products such as feather meal and fertilisers (Veerabadran et al., 2012; Stingone and Wing, 2011). The remaining waste is disposed of by incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases (Tronina and Bubel, 2008). Traditional methods to degrade feathers for subsequent use as animal feed include alkali hydrolysis and cooking under steam pressure. For example, the feathers may be hydrolysed, dried and ground to a powder to be used as a feed supplement for a variety of livestock, primarily pigs (Park et al., 2000). This is a fairly expensive process, however, and results in a protein product of low quality for which the demand is low (Veerabadran et al., 2012). These methods are problematic in that they not only destroy the amino acids in the feathers but also consume large amounts of energy.

Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. It is important to find ways to beneficiate chicken feathers because this would not only recycle a waste product to provide high-value materials, it would provide extra financial resources to the poultry industry. Physical and morphological properties of chicken feathers have been studied with the objective of ascertaining their valorisation based on the properties (Tesfaye et al., 2017). However, there is a lack of comprehensive data on chemical characteristics of chicken feathers in the literature. This report, therefore, focuses on a better understanding of the chemical nature of chicken feathers with the ultimate aim of developing valorisation routes for the waste feathers depending on their chemical characteristics.

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http://dx.doi.org/10.1016/j.wasman.2017.06.050
0956-053X/

2. Materials and methods

2.1. Collection and preparation of chicken feather waste

Chicken feathers were collected from a slaughterhouse in Durban, South Africa, that processed 3-week old broiler/meat chickens. On collection, the feathers were a wet mass of blood, faeces, skin, flesh and other slaughterhouse residues. They were washed with water at 50 °C to remove easily removable matters and then dried at 105 °C for 24 h and conditioned at a relative humidity 65 ± 2% and a temperature of 20 ± 2 °C. After drying, barbs were separated by manual stripping from the rachis. A portion of the samples were milled into powder using, and the rest were left intact. The material was then packed and stored at normal room temperature (20–25 °C) into three groups (whole feather, rachis and barb).

2.2. Proximate analysis

This refers to the determination of the major constituents of biomass. For chicken feathers, the following components were determined: water, ash, volatile matter, fixed carbon, crude protein, crude fat, and nitrogen-free extracts. All tests were conducted in triplicate.

2.2.1. Ash content

Ash is inorganic residue obtained after combustion of biomass and is an approximate measure of the mineral salts and inorganic matter in feathers. The ash content was calculated in relation to the dry weight of the original sample after overnight ignition of the sample at 575 ± 25 °C.

2.2.2. Moisture content

The moisture content was measured according to ASTM D1576-90 standard by drying samples in an oven dryer (ASTM D1576-90, 2001).

2.2.3. Volatile matter content

Volatile matter in chicken feathers was determined by heating known weights of samples in capped crucibles in an oven at 800 °C for 40 min under an inert atmosphere. The volatiles liberated were calculated by mass difference before and after heating.

2.2.4. Fixed carbon content

Fixed carbon is a value obtained by abstracting the sum of ash, moisture and volatile matter from 100 where all values are on the same moisture reference base. Thus:

$$Fixed\ carbon = 100 - (ash\ \% + moisture\ \% + volatile\ matter\ \%) \quad (1)$$

2.2.5. Crude protein content

This was determined by measuring the nitrogen content of the feathers and multiplying it by a factor (C) of 6.25. This factor is based on the fact that most protein contains 16% nitrogen. The protein was determined using a Kjeldahl digestion method (AACC, 2000).

$$CP\ \% = \frac{(1.401 * M * (V - V_o))}{W} * K * C \quad (2)$$

where,

CP = crude protein
M = Amount of substance of H_2SO_4 concentration (mol/L)
C = Conversion coefficient of crude protein
K = Correction factor for the instrument determination
V_0=Blank value (mL)
V = Titration volume of H_2SO_4 (mL)
W = Weight of sample used.

2.2.6. Crude fat content

Crude fat, also known as the ether extract, is a measure of the free lipid content in a sample and is calculated using hexane as a solvent in a Soxhlet extraction system (AACC, 2000).

2.2.7. Crude fibre content

"Crude fibre" is considered to be a mixture of largely undigestible substances of vegetable origin obtained as the residue of a precisely defined digestion procedure using acetic, nitric and trichloro-acetic acids (AACC, 2000). It consists chiefly of cellulose and other vegetable cell wall substances.

2.2.8. Nitrogen Free Extract (NFE) content

NFE consists of carbohydrates, sugars, starches, and hemicellulose in biomass. When crude protein, fat, water, ash, and fibre are added and the sum is subtracted from 100, the difference is NFE. Thus NFE was calculated as (AACC, 2000):

$$NFE = 100 - (Crude\ protein\ (\%) + crude\ fat\ (\%) + crude\ fiber\ (\%) + moisture\ content\ (\%) + ash\ content\ (\%)) \quad (3)$$

2.3. Ultimate analysis

Ultimate analysis is more comprehensive than proximate analysis and provides information on quantitative analysis of various elements present in biomass samples, such as carbon, hydrogen, sulphur, oxygen, and nitrogen.

2.3.1. CHNS analysis

The amounts of carbon, nitrogen, hydrogen and sulphur in the chicken feathers were ascertained using a CHNS analyser (Leco VTF-900/CHNS-932).

2.3.2. Energy Dispersive X-ray analysis (EDX)

Elemental composition of chicken feather fractions were characterised by EDX using a Field Emission Gun Scanning Electron Microscope with EDX capability (Carl Zeiss, Oberkochen, Germany).

2.4. Fibre classification

Since chicken feathers contain fibres that can be beneficiated into fabrics, it is useful to classify the fibre present. This is especially important to know since the fabrics may need to be dyed and many dyes are very specific to the type of fibres treated.

2.4.1. Burning test

This is one way to ascertain fibre types and also to ascertain their fire resistance properties (Mylsamy and Rajendean, 2010). The samples were burnt by flame using a disposable lighter (temperature of 575 ± 25 °C). Burning characteristics that can be noted include the way that a fibre burns (or melts); the way it smells when burning; and the type of ash or other residue that is left behind. All these provide clues as to the type of fabric under analysis. Appropriate safety precautions were taken before and during the testing (assurance that the tester does not have sinus problems or a cold and does not use matches or refillable lighters with a strong fuel smell).

2.4.2. Chemical durability in common chemicals

Durability or degradation is a reduction in one or more physical properties of a polymer material due to contact with a chemical. Certain materials may become hard, stiff, or brittle, or they may grow softer, weaker, and swell to several times their original size (Mylsamy and Rajendean, 2010).

Measurement of the chemical durability of chicken feathers was measured as mass loss, over time, of samples stored in cold water, hot water, strong acid (1% (HCl, H_2SO_4 and HNO_3), pH 2–3), and weak acid (1% (citric acid, $C_6H_8O_7$ and oxalic acid, $C_2H_2O_4$) concentration and 5–6 pH), bleaching agent (4% NaOCl), and strong alkali (5% NaOH, pH 10–12), and weak alkali (2–5 Na_2CO_3%, pH 8–9). Known amounts of feather samples (~5 g) were placed in covered Petri dishes and completely covered with the liquids and left to soak at room temperature. For the determination of hot water solubility, 5 g of feather samples were transferred to a 250 mL round bottom flask to which was added 100 mL of hot distilled water and then heated in a boiling water bath. A reflux condenser was attached and the sample was heated for up to 7 days with continual top up of the heating water. Samples were collected for testing after 2 h, 12 h, 24 h, and 7 days of contact time: the samples were dried for 24 h at room temperature and weighed to calculate any changes in weight due to soaking. Chemical durability was calculated as:

$$\textit{Chemical durability}, \% = \frac{A - B}{A} * 100 \tag{4}$$

where,

A = initial weight of the specimen, g oven dry
B = weight of test specimen after soaking, g oven dry.

2.5. Swelling property

Swelling power is the ratio between the volume occupied by a sample and the original sample weight. The swelling of feathers was determined in a number of solvents, viz., distilled water, ethanol, methanol, n-butanol and dimethylformamide (DMF). 100 mg of feather fractions were dispersed in 10 mL of the solvents in 500 mL graduated cylinders. After soaking for 18 h at room temperature, the amount of solvent retained by the fraction was determined.

2.6. Hydrophobicity test

In chemistry, hydrophobicity is the physical property of a molecule (known as a hydrophobe) that is seemingly repelled from a mass of water (Chandler, 2005). Basically, it is the observed tendency of nonpolar substances to aggregate in aqueous solution and excludes water molecules (Chandler, 2005). Currently, research groups around the world use many different kinds of tests to measure hydrophobicity of materials. In this report, the hydrophobic behaviour of chicken feather fractions was determined by contrasting with behaviours of known hydrophilic compounds (i.e., cotton fibre and wood pulp) between an aqueous and organic solvent phase. Dried chicken feathers, cotton fibre and cellulose pulp were immersed separately in an excess of ethyl–ether–water mixture, shaken vigorously and then left to settle overnight at room temperature.

2.7. Functional group analysis

Functional groups are the portions of an organic molecule that dictate how the molecule will react. Fourier transform infrared (FTIR) spectroscopy was used to characterise the functional groups present in chicken feathers. An FTIR spectrometer was used in the attenuated reflectance mode (Frontier Universal, PerkinElmer). Each spectrum contained an average of 4 scans, recorded at a resolution of 4 cm^{-1} in the range of 4000–400 cm^{-1}.

2.8. X-Ray diffraction (XRD)

Crystallinity refers to the degree of structural order in a solid. In a crystal, the atoms or molecules are arranged in a regular, periodic manner (Xu et al., 2006). Crystallinity makes a material strong, but it also makes it brittle. A completely crystalline polymer would be too brittle to be used as plastic. The amorphous regions give a polymer toughness, that is, the ability to bend without breaking. For the production of fibres, polymers should be as crystalline as possible.

XRD analyses of the chicken feather fractions were ascertained using a Bruker D8 Discover model diffractometer, equipped with a diffracted beam monochromator, and a copper target X-ray tube set to 40 kV and 30 mA (Bruker South Africa, Johannesburg). The feather fractions were milled to about 250 μm particle size and made into pellets that were then analysed. The crystallinity, indicating the relative crystallinity degree, long used to characterise keratin fibres such as wool (Das and Ramaswamy, 2006) was calculated using the empirical equation:

$$\textit{Crystallinity index} = \frac{\textit{Maximum crystal latice diffraction with } 2\theta \textit{ at around } 9^{\circ}}{\textit{Minimum diffraction intensity with } 2\theta \textit{ at around } 14^{\circ}} \tag{5}$$

2.9. Statistical analysis

The data collected during the course of the project were subjected to statistical analysis. Microsoft Excel and Origin (Origin Laboratory Corporation, Northampton, Massachusetts, USA) were used to determine statistical parameters (mean, standard deviation, and coefficient of variation).

3. Results and discussions

3.1. Proximate analysis

Results for proximate analysis are shown in Figs. 1 and 2. Basically, the different feather fractions yielded similar data.

3.1.1. Fixed carbon, ash and volatile matter

Results for proximate analyses of chicken feather fractions are displayed in Fig. 1: they indicate that all the samples contain large amounts of volatile matter (78–82%), significant amounts of fixed carbon (17–21%) and small amounts of ash content.

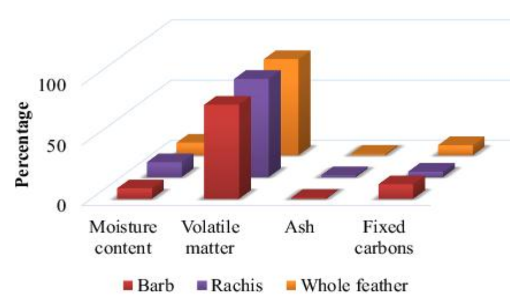

Fig. 1. Proximate analysis of feather fractions.

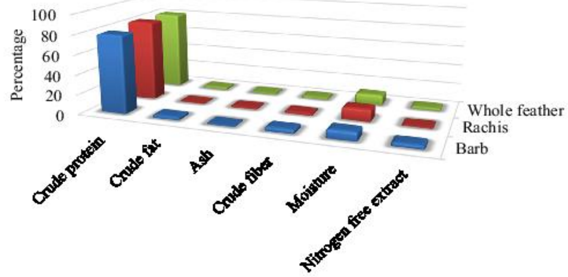

Fig. 2. Ultimate analysis of chicken feather fractions.

In general, fixed carbon is the solid fuel left in the furnace after the volatile matter is distilled off. It consists mostly of carbon but also contains some hydrogen, oxygen, sulphur and nitrogen not driven off with the gases (Ryu et al., 2006). Fixed carbon gives a rough estimate of the heating value of biomass. Volatile matter consists of the combustible gases like methane, hydrocarbons, hydrogen and carbon monoxide, and incombustible gases like carbon dioxide and nitrogen. Thus, volatile matter is an index of the gaseous fuels present in biomass (Ryu et al., 2006). The typical range of volatile matter is 20–35% in woody biomass. In this study, the average volatile content of feathers is very high (81.56%): this indicates that feathers have a good ignition point, removing the excess oxygen demand for a complete burning process.

Ash is an impurity that will not burn. The presence of ash reduces handling and burning capacity, increases handling costs, affects combustion efficiency and boiler efficiency and causes clinkering and slugging (Kwiatkowski et al., 2012). The low ash content of chicken feather samples indicates that they could be suitable for use as fuel. Thus the high content of volatiles, together with a low amount of ash (lower than 1.5%), makes feathers a good material for fixed-bed gasification as reported in the literature (Dudyński et al., 2012.). Using air as the gasification agent ensures a sufficiently high temperature to start the thermal conversion, and to maintain the conditions for satisfying the environmental requirements for waste disposal (Kwiatkowski et al., 2012).

3.1.2. Crude protein

Crude protein is comprised of true protein and non-protein nitrogen. True protein is sometimes called natural protein and is either degradable or not degradable (Msahli et al., 2006; Zhongfu et al., 2015). The data in Fig. 2 indicates that the crude protein content is similar in all samples at about 80%. It should be noted that higher protein content is usually associated with a higher quality protein source (Msahli et al., 2006). The data confirm that feathers can be beneficiated as a good source of protein material.

3.1.3. Crude fibre

The data in Fig. 2 indicate that chicken feathers contain negligible amounts of crude fibre: this is to be expected considering that feather biomass, unlike cellulosic biomass, does not contain cellulose, hemicelluloses, and lignin.

3.1.4. Crude fat

Crude fat, an estimate of total fat content, includes true fat (triglycerides) as well as alcohol, waxes, terpenes, steroids, pigments, esters, aldehydes and other lipids (Matthews, 1921). The significant fat content in feathers (about 3%) determined in this study is indicative of a potential route for beneficiation of feathers. For example, studies have been reported on the production of biodiesel from chicken feathers (Kondamudi et al., 2009). Beneficiation of chicken feathers into other products will require processing of fibres to remove the fat so that the residual grease content is below 2% (Bateup and Warner, 1986). Thus the fibres need to be pretreated and scoured to remove the fat before further processing.

3.1.5. Moisture content

The data in Figs. 1 and 2 indicate that the moisture content of the chicken feather fractions varies between 8.8 and 12.3%. The ability of chicken feathers and fractions to absorb moisture from the environment has important implications for processing, storage, transportation, and durability of chicken feather-containing composite materials. The increases in moisture content may interfere with processing or bonding in the final products, increase the weight of the products (and hence transportation costs), or lead to rapid deterioration of the product since moisture content will lead to microbial growths (Munawar et al., 2007; Jones et al., 1998). However, in this study the average moisture content of the chicken feathers did not exceed 10.5%: this implies that the material could be safely stored for long time periods with no concerns of deterioration due to microbial growths. Moisture contents of 8–13% imply that chicken feathers can absorb enough water to prevent static build-up – a useful property in applications where static build-up is of importance.

3.2. Ultimate analysis

3.2.1. CHNS analysis

Results for CHNS analysis of the feather fractions are shown in Fig. 3: they reveal no significant differences in the composition of the feather fractions. The average composition was 47.4% C; 7.2% H; 15.1% N; 2.9% S; and 27.4% other (oxygen + inorganic matter). The high carbon and hydrogen contents indicate that chicken feathers could be used as a source of energy, while the sulphur content suggests the presence of cysteine protein. Overall, chicken feathers have a nitrogen content of about 15%: this high nitrogen content indicates that chicken feathers can be used to produce bio-compost or animal feed.

3.2.2. Energy dispersive X-ray spectroscopy analysis

The EDX results are shown in Fig. 4. Basically, they corroborate the CHNS analysis results with additional evidence for the presence of oxygen (not detectable with the CHNS analyser). The average elemental composition was 59.14% C; 14.21% N; 24.34% O; and 2.17% S. As with CHNS analysis, the results were identical among the feather fractions.

3.3. Fibre identification

3.3.1. Burning test

The results are summarised in Table 1: in summary, it was observed that chicken feathers do not support continuous burning, and emit an odour like that of burning human hair. They burn with

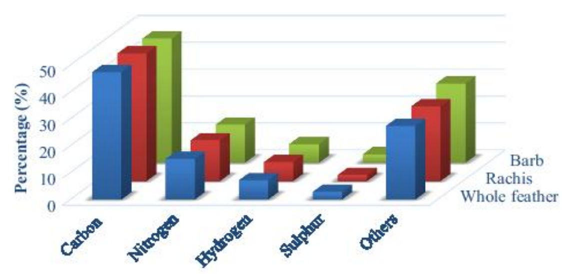

Fig. 3. Elemental analysis of chicken feathers.

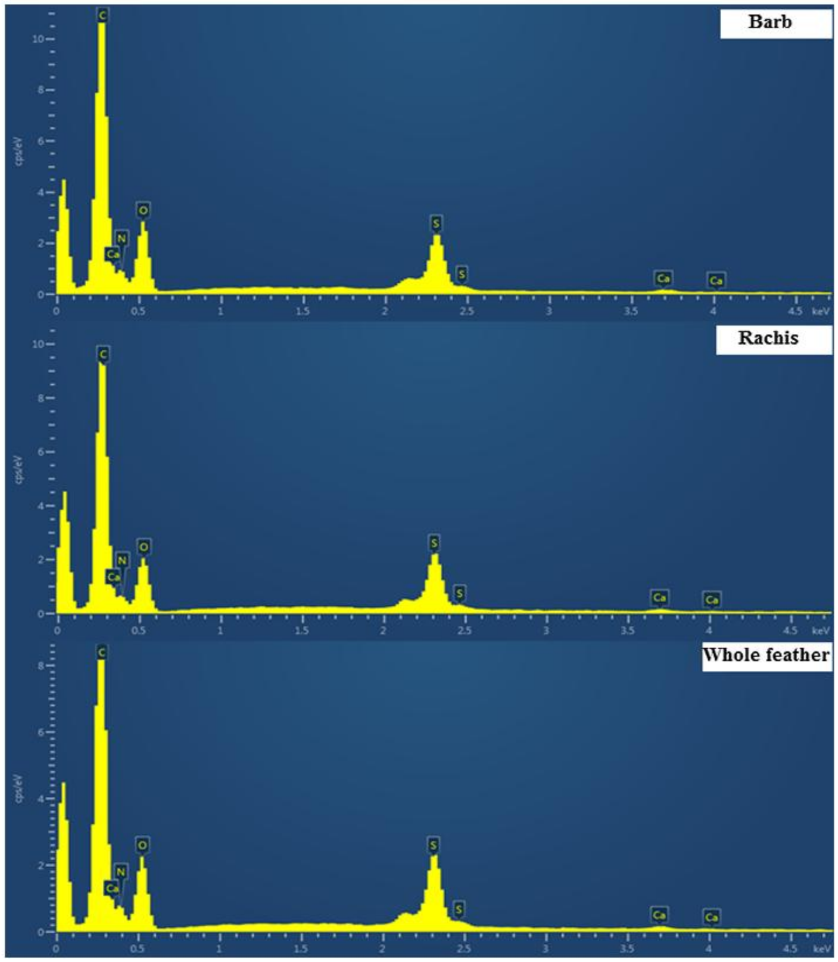

Fig. 4. EDX results of the elemental profile of chicken feather fractions.

an orange sputter colour and do not melt. When the flame died, the feathers supported combustion very slowly for a short period. This indicated that chicken feathers are self-extinguishing, but for them to be used safely near a fire, they need to be fire-proofed by application of appropriate fire-retardant and protective finishes.

Table 1
Burning characteristics of chicken feather fractions.

Chemical properties	Rachis	Barbs	Whole feather
Approaching flame	Smoulders and curls away from flame; ignites slowly	Smoulders and curls away from flame; ignites slowly	Smoulders and curls away from flame; ignites slowly
In the flame	Burns slowly with small flickering/ orange flame; sizzles and curls, no smoke	Burns slowly with small flickering/orange flame; sizzles and curls	Burns slowly with small flickering/orange flame; sizzles and curls
Away from the flame	Supports combustion with difficulty for short time	Supports combustion for a short time melts ahead	Burns slowly/self-extinguishing
Odour	Burning rubber	Burning hair	Burning hair
Residue	Easy crushable black soft ash	Completely fuses	Crisp, dark ash; round, irregular bead; easy to crush

The burning test characteristics indicated in Table 1 were compared to information in the literature on guideline for classification of fibres (Anonymous, 2016). The comparison indicated that chicken feathers are similar to wool fibre - thus they are categorised as a protein fibre.

3.3.2. Chemical durability in common chemicals

Results were compared with control samples of chicken feather fractions soaked in deionized water. The reactions observed included swelling and dissolution, dissolution without swelling, disintegration, colour reaction and changes, and duration time taken for the changes to occur. This test is very important since chemical reactions are utilised in the manufacturing processes of high-value materials from chicken feathers. The chemicals tested were categorised into five groups: water (hot and cold), acids (strong and weak), alkalis (strong and weak). Moisture sensitivity and chemical degradation are serious problems that can affect natural fibres and materials made from them due to potential swelling and rotting of fibres. Contact time will inevitably result in different degrees of damage to feather fractions (Table 2 and Fig. 5).

Table 2
Chemical resistance of chicken feather fractions.

Category	Chemical	Observed reaction Immediate	After 2 h
Water	Hot/cold	No visible change in colour or structure	In cold water, there is no change at all but in cold water folding and curling of feather is observed
Strong acid	Conc. Sulphuric acid	The fibres disintegrated and dissolved. Fibres changed colour from white to brown	Fibres disintegrated and then completely dissolved
	Conc. Nitric Acid	No visible change in structure. The fibre colour changed from white to brown and then was bleached to white	A marked weakening and tendering of fibres resulted. The fibre was partially dissolved
	Conc. hydrochloric acid	The fibre did not change colour or structure	The fibre weakened and partially dissolved
	Acetic acid	The fibre did not change colour or structure	The fibre did not change colour or structure
Weak acids	Citric Acid	The fibre bleached, no change in structure	Fibre remained strong and bleached.
	Oxalic Acid	The fibre bleached, no change in structure	Fibre did not change in structure or colour
Strong Alkalis	Sodium hydroxide	Fibres did not change in colour or structure	Folding and curling of fibre. There was a visible distortion of fibres
	Sodium hypochlorite	Fibre bleached, no change in structure	Fibre weakened and disintegrated
Weak alkalis	Ammonium hydroxide	No reaction noted	No reaction noted
	Sodium hydrogen carbonate	No reaction noted	No reaction noted

3.3.2.1. Chemical durability in alkaline solutions. Upon soaking in alkali (both strong and weak alkali), the chicken feathers dissolved rapidly and completely. From Fig. 5 and Table 2 it is clear that rachis lost less weight than barbs, however, the rachis completely dissolved in 5% NaOH after 24 h, whereas barbs lost weight and became brittle. The results imply that in beneficiation processes that require treating fibres with NaOH for enhancement or induction of certain properties, contact with alkali more for than 1 h is not recommend so as to maintain the stability of feather fibres. After 7 days of soaking, the feather fractions experienced greater than 99% mass loss, indicating that chicken feathers are unstable in strongly alkaline environments. This property indicates that chicken feather can be categorised as animal fibre.

3.3.2.2. Chemical durability in acidic solutions. The feathers have good resistance to mild acid but poor resistance to strong acid in which they dissolved completely. In strong acid, the chicken feathers suffered damage and high weight losses. Fig. 5 and Table 2 show high mass losses relative to results of chicken feather fractions soaked in deionized water. Concentrated sulphuric acid induced more disintegration and severe weight loss than hydrochloric or nitric acids. This indicates that strong acids damage chicken feathers: the bonds connecting the subunits in feathers are destabilised by acidic media, with a corresponding high loss in tensile strength (Munawar et al., 2007).

3.3.2.3. Chemical durability in other chemicals. The most common reagents used in textile fibre processing are bleach and detergents. They are not strongly alkaline or acidic, and thus, can be safely used on the chicken feathers, with low effect on the structure and tenacity thereof. When reacted with concentrated sodium hypochlorite, the feather fractions were bleached, but after prolonged exposure, the feather fractions weakened and disintegrated. This indicates that oxidising solutions like sodium hypochlorite should only be used when cold and diluted, and only for short periods. Also, the reagents should be thoroughly washed out of the fibres to avoid damaging the fibres.

Soaking in hot water removes some extraneous components in waste feathers such as inorganic compounds, sand, gums, and colouring matter. The different feather fractions exhibited variations in hot water solubility: feather rachis had significantly higher hot water extractives content than feather barbs.

3.4. The swelling property

Fig. 6 shows data for the swelling properties of chicken feather fractions in different solvents. The swelling behaviour in different solvents followed the trend: water > ethanol > DMF > n-Butanol. The feather barbs exhibited the most swelling in water: this may be because they contain larger amounts of hydrophilic hydroxyl groups than the other feather fractions. Water can then penetrate more easily and deeper into feather fractions, resulting in more swelling than in organic solvents. The feather fractions showed more swelling in methanol than in ethanol. This may be due to the presence of the bulkier ethyl ($—C_2H_5$) group in ethanol providing a hindrance to sorption. Also, the presence of alkyl groups in chicken feather fractions makes them hydrophobic in nature; therefore, these hydrophobic chains have a strong affinity toward non-polar solvents like DMF. The stability of chicken feathers in n-butanol was fairly good but there was extensive dissolution in DMF. These results indicate that swelling property of chicken feather could be affected by the presence of polar solvents.

It must be emphasised that chemical compatibility of materials can be affected by various parameters such as concentration, temperature, the presence of other chemicals, and other factors. Hence the results presented in the preceding section only serve as a general guide to the chemical compatibility of chicken feathers.

3.5. Hydrophobicity test

As shown in Fig. 7, it is evident that cotton and wood pulp were aggregate in the second layer (water layer) showing the complete wettability of the fibres. However, the chicken feather fractions (barb and rachis) aggregated in the interphase between the water and ethyl ether layers. This indicates poor wettability of chicken feather fractions compared with cotton fibre and wood pulp; these observations confirm the hydrophobic properties of chicken feather fractions.

3.6. Functional group analysis

A comparison of the FTIR of the feather fractions is shown in Fig. 8. The strong signal at 1650 cm^{-1} caused by the elongated C=O amide band was assigned to the C=O amide I, an α-helix conformation (Senoz and Wool, 2010). The peak at 1550 cm^{-1} characteristic of amide II conformation, was observed in all samples, but with lesser intensity that the amide I peak. This is caused by the vibrations of the deformation angle of N—H in plane bending for β sheet conformation and the stretching of C—N in the backbone of keratin. The signal at 1455 cm^{-1} corresponds with CH_2 or CH_3 (Silverstein et al., 2014). In this study, the amide III region was easily resolved and clearly-defined (1330–1200 cm^{-1}), due to the in-phase combination of N—H in-plane bending and C—N stretching vibrations and corresponds to the α-helix conformation

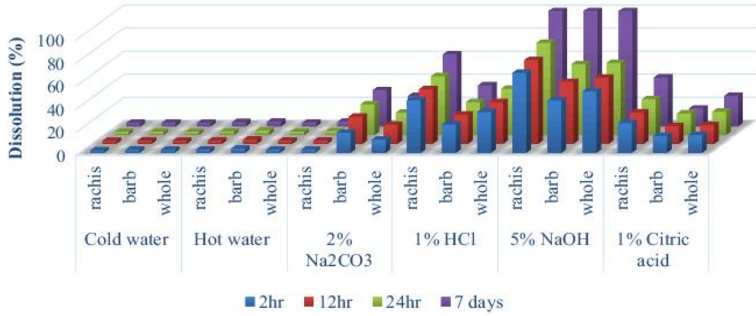

Fig. 5. Chemical resistance of chicken feather fractions in water, acids and base.

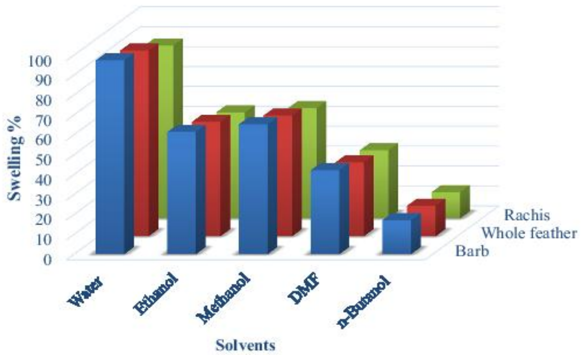

Fig. 6. The swelling properties of chicken feathers.

(Martinez-Hernandez and Velasco-Santos, 2012). The weak peak between 1270 and 1220 cm^{-1}, helps to characterise the presence of a β-sheet structure, from amide III, which corresponds largely to the stretchability of C—N, and the angular deformation in the plane of the N—H group, and weakly to the stretching of the C—C bond and the deformation in the plane C=O. The absorption at 2370 cm^{-1}, attributed to S—H stretch, is believed to cause the sulphide smell from waste feathers (Martinez-Hernandez and Velasco-Santos, 2012). The band close to 1174 cm^{-1} is produced by (C—C link) from side chain amino acids. The region from 1050 to 1150 cm^{-1} also corresponds to skeletal (C—C links). Finally, the (C—S) from alkylthiols is localised approximately at 730–620 cm^{-1}; this group is originated from amino acid cysteine. The signal at 500–730 cm^{-1} is assigned to the (C—S) functional group (Silverstein et al., 2014).

From the FTIR results, it was verified that the chicken feathers reveal a broad band in the range of 3550–3150 cm^{-1}, and a peak at 3075 cm^{-1}, associated with the stretching of the amide group N—H. The bands closer to 3300 cm^{-1} have been associated with the regions that characterise the ordered region, α- helix structure, of secondary proteins (Barth, 2007). This corresponds to the amide groups A and B, i.e., N—H (symmetrical stretching) and O—H modes. The bands in the region 3320–3070 cm^{-1} correspond to the amides A and B resulting from Fermi resonance (Kong and Yu, 2007). Additionally, the range from 2708 to 3100 cm^{-1} was viewed as characteristic of dipolar ion amino acids RCH(NH_3^+)COO$^-$. The NH_3^+ group corresponds to a wide band around 3100–2700 cm^{-1} with NH and NH (asymmetrical stretching vibrations). A shoulder around 2960 cm^{-1} can be assigned to CH_3. The bands from 3230 to 3280 cm^{-1} are equivalent to amide A, and 3075–3130 cm^{-1} are equivalent to amide B. The spectrum showed a double band (2930 and 2965 cm^{-1}) characteristic of symmetric and asymmetric stretching of aliphatic hydrocarbons (primary and secondary carbons), C—H, that are found between 2850 and 2960 cm^{-1} region. This indicates the preservation of CH_2 and CH_3 functional groups in chicken feather fractions (2900–2960 cm^{-1}), (Silverstein et al., 2014; Kim and Hochstrasser, 2009). The presence of proteinious functional group in chicken feather samples indicates that they could be suitable for use as a raw material in

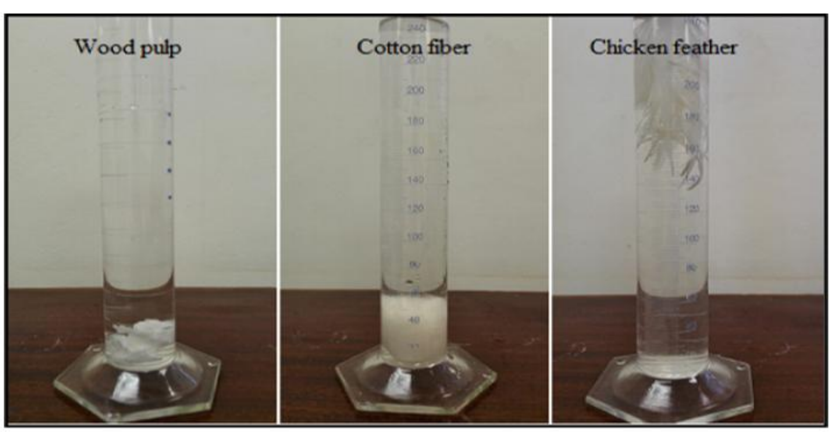

Fig. 7. Hydrophobicity test on wood pulp, cotton fibre and chicken feathers.

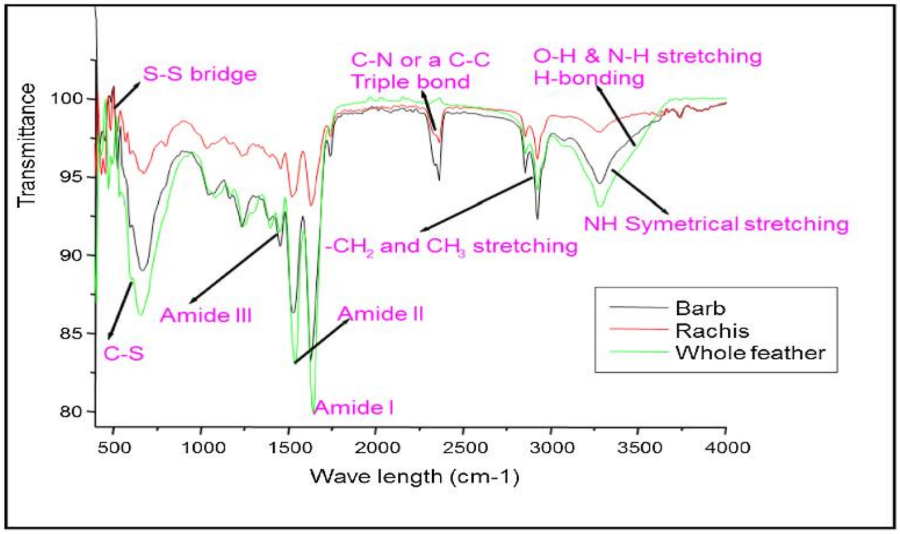

Fig. 8. FTIR spectra of chicken feather fractions.

cosmetics, regenerated fibre, biomedical materials, bioplastic, textile sizing, enzyme production, pharmaceuticals and animal feed.

3.7. Crystallinity index analysis

The crystallinity of chicken feather fractions plays an important role in their physical, chemical, optical and thermal properties. Similarly to other animal fibres, chicken feathers have a kind of macromolecular polymer structure between its crystal and amorphous regions. As can be seen from the crystal diffraction peak (Fig. 9) all feather fractions show a medium diffraction peak around $2\Theta = 9°$ (for the α-helix structure of peptide chains in chicken feather fractions) and a prominent peak around $2\Theta = 22°$. Moreover, a diffraction peak-valley was observed at $2\Theta = 14°$ between the two characteristic diffraction peaks mentioned above, which was assigned to the amorphous region of chicken feather structures. Peak intensity in the diffractograms is indicative of crystal structure content. The results show that rachis possess more β-sheet content than the barb fraction. The peak at $2\Theta = 9°$-Corresponds to the α-helix configuration (Xu et al., 2006; Zhao et al., 2012). The three feather fractions exhibited a sharp peak at this position that is due to the keratin membrane in feathers. The peak intensity of the rachis is stronger than that of the other samples. This suggests that there is a more α-helix structure in the rachis than in the other samples. Based on the above analysis, chicken feather fractions possess two types of crystal structures: i.e., α-helix and β-sheet. The peak intensity around 22° of the barb fraction was lower than that of the whole feather and rachis fraction. The peak around 17 corresponds to the diffraction pattern of the α-helix, whereas the peak around 20° is a typical peak of the β-sheet structure (Zhao et al., 2012). However, the two peaks are usually not clearly assigned due to the overlapping signals; this leads to the broad single peaks at 22°.

It is well known that keratin is semi-crystalline and naturally macromolecular (Xu et al., 2006; Steinert et al., 1976); its XRD profiles have confirmed this. The chicken feathers exhibit two narrow peaks at around $2\theta = 52°$ and 77° (Fig. 9). Besides this being narrow, it is the most intense, at around 52°. These effects are caused by the presence of crystalline regions within the sample. This was also observed for the whole chicken feather fraction, albeit with reduced intensity (Fig. 9). This indicates a reduction in crystallinity. From the results, it is seen that in addition to disulphide bonds, crystallinity also plays an important role in the high strength and stiffness of feather keratins (Xu et al., 2006; Fonollosa et al., 2004; Zhao et al., 2012). From the crystalline peaks, the crystallinity indexes were calculated and the results are summarised in Table 3. It is known that the feathers' mechanical stability, insolubility, and resistance to proteolytic digestion, are consequences of the tight packing of the protein chain in β-sheets (β-keratin) into a supercoiled polypeptide chain (Fonollosa et al., 2004; Onifade

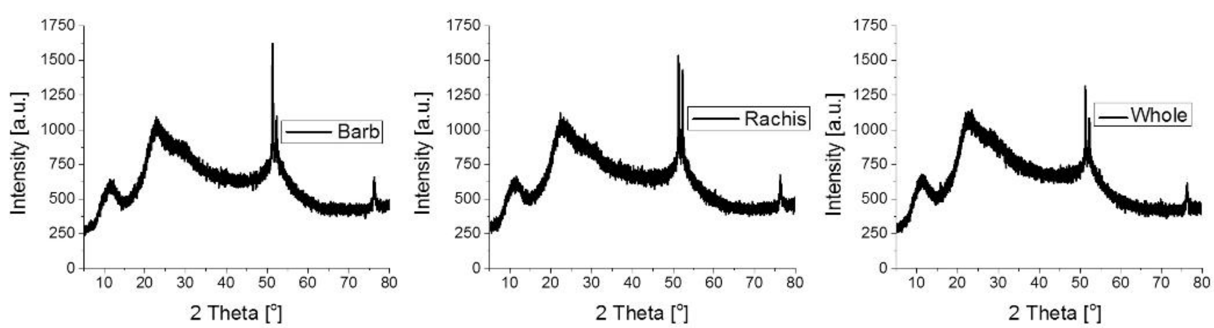

Fig. 9. XRD patterns of chicken feather fractions.

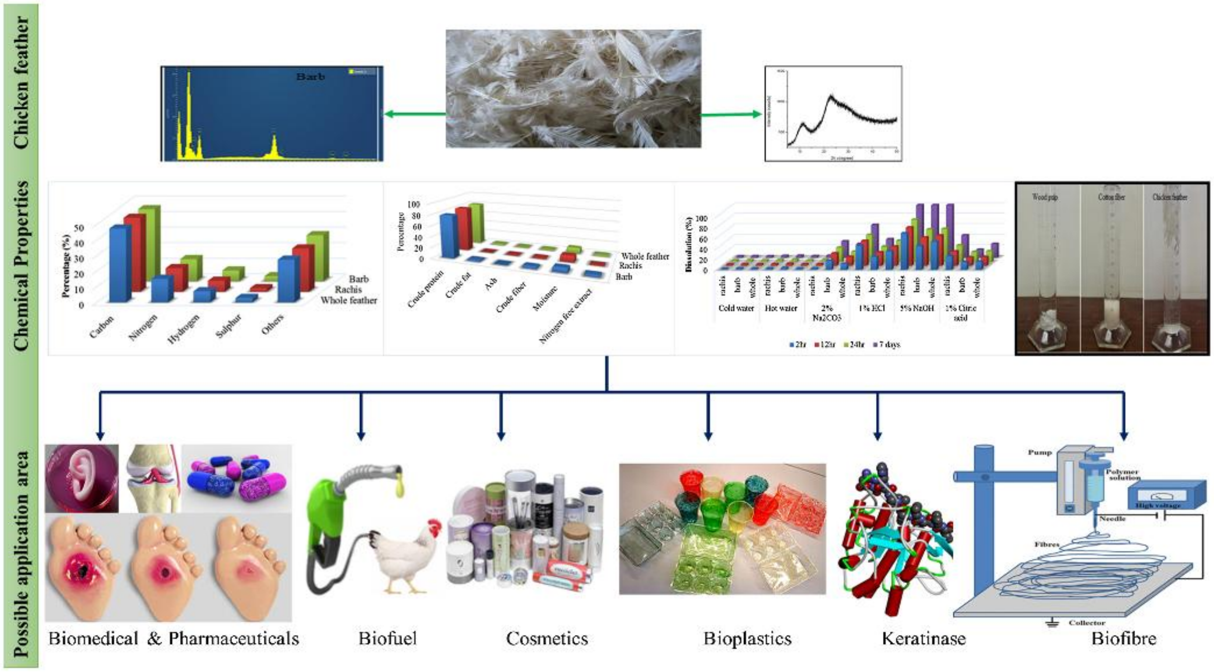

Fig. 10. Possible valorisation route of waste chicken feather based on chemical properties.

Table 3
Crystallinity index of chicken feather fractions.

Feather fraction	Barb	Rachis	Whole feather
Crystallinity (%)	22.09	19.36	20.55

et al., 1998). The decrease of crystallinity and decomposition of the β-sheet structure could improve the extraction, dissolubility, and enzymatic accessibility of the feather keratins.

4. Potential valorisation of chicken feather fractions based on chemical properties

The results on the chemical characterisation chicken feathers imply that they could be used in a variety applications such as in the agricultural industry (biofertilizer and animal feed); the textile industry (as a source of regenerated fibre, sizing agents to replace costly starch-based sizing agents, as a binder and thickener in textile finishing and printing, as a finish to impart flame retardancy); in the energy industry (biofuel, biogas and energy storage devices), in the cosmetics industry (as a source of keratin), in the health industry (as a source of pharmaceuticals and biomedical materials), and in the packaging industry (as a source of biodegradable plastics) (Fig. 10) (Tesfaye et al., 2017).

5. Conclusions

A detailed characterisation of chemical properties of chicken feathers has been conducted with the objective of ascertaining valorisation products that can be made from this waste material. The characterisation included proximate and ultimate analysis, durability tests as well spectroscopic techniques. The proximate analysis of chicken feathers revealed the following nutrients and anti-nutrients: crude lipid (0.83%), crude fibre (2.15%), crude protein (82.36%), ash (1.49%), NFE (1.02%) and moisture content (12.33%) whereas the ultimate analyses showed: carbon (64.47%), nitrogen (10.41%), oxygen (22.34%), and sulphur (2.64%). FTIR analysis revealed that the chicken feather fractions contain amide and carboxylic groups indicative of proteinaceous functional groups; XRD showed a crystallinity index of 22. Durability and burning tests confirmed that feathers behaved similarly to animal proteins. The results confirm that chicken feathers contain animal fibres. Future studies will entail extraction of valuable materials from chicken feathers for conversion into relevant high-value products. They include proteins for conversion into, e.g., cosmetic products, and fibres for conversion into biomaterials or superabsorbent fabric materials. The proper utilisation of this waste would open up new industries and job opportunities, and make the poultry industry more competitive.

Acknowledgments

The authors would like to acknowledge the DST/NRF South African Research Chairs Initiative (SARChI), the Biorefinery Industry Development Facility at the CSIR, and the Department of Science and Technology for the support of this research, Mr. Pradeep Suthan for carrying out the XRD test and Ms. Fiona for editing the manuscript.

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PUBLICATION SIX

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Clean Technologies and Environmental Policy
Focusing on Technology Research, Innovation, Demonstration, Insights and Policy Issues for Sustainable Technologies

ISSN 1618-954X
Volume 19
Number 10

Clean Techn Environ Policy (2017) 19:2363-2378
DOI 10.1007/s10098-017-1443-9

Springer

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REVIEW

Valorisation of chicken feathers: a review on recycling and recovery route—current status and future prospects

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Received: 22 August 2017 / Accepted: 13 October 2017 / Published online: 20 October 2017

Abstract Worldwide, the poultry meat processing industry generates large quantities of feather by-products that amount to 40×10^9 kg annually. The feathers are considered wastes although small amounts are often processed into valuable products such as feather meal and fertilisers. The remaining waste is disposed of by incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases. Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. A closer look at the structure and composition of feathers shows that the whole part of a chicken feather (rachis and barb) can be used as a source of a pure structural protein called keratin which can be exploited for conversion into a number of high-value bioproducts. Additionally, several technologies can be used to convert other biological components of feathers into high value-added products. Thus, conversion of the waste into valuable products can make feathers an attractive raw material for the production of bioproducts. In this review, possible applications of chicken feathers in a variety of technologies and products are discussed. Thus, using waste feathers as a valuable resource can help the poultry industry to dispose of the waste feathers in an environmentally sustainable manner that also generates extra income for the industry. Their valorisation can result in their sustainable conversion into high-value materials and products on the proviso of existence or development of cost-effective technologies for converting this waste into the useful products.

Keywords Poultry waste · Feathers · Biodegradable product · Value-added product · Keratin

Introduction

There is a critical need and increasing interest across the world to decrease the consumption of petroleum-based products and to develop bioproducts using renewable and sustainable sources (Robertson 2012). Many such efforts have already been made and practised in both developing and developed countries. Such efforts are necessary to satisfy the food, clothing, pharmaceutical, automobile, cosmetic, plastic and other basic needs of the future generation. Due to limited fossil resources, the recent focus is to utilise agricultural by-products and co-products as a replacement in industrial application. These products are inexpensive and environmentally sustainable renewable resources for use in the development of bioproducts. Nourishment squanders are produced by a mixture of sources, extending from rural operations to household consumption. Excluding food and agricultural waste generated during agricultural processing, households produce up to 42% of the waste, 38% of the of the food waste occurs during food preparation, and 20% is disseminated along the food processing chain (Baiano 2014). Currently, legislations around the world encourage valorisation of waste and

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by-products of manufacturing processes (Baiano 2014). This valorisation of waste can be accomplished through the extraction of essential segments, for example, filaments, polysaccharides, flavour mixes, proteins and phytochemicals, which can be re-utilised in the nutrition, textile, cosmetic, composite materials and pharmacological functional industries (Ambrose and Clanton 2004).

The chicken meat processing industry is developing at a rapid growth rate all over the world. Reasons for the great pace include efficient feed to weight gain ratio, the fast growth rate of chickens, poultry being a rich source of nutrients for human consumption, fast production time, and low economic value of poultry per unit (Rahayu and Bata 2015). Almost all sections of the society, encompassing all customs and religions, consume chicken meat. According to the USA Foreign Agricultural Service, the total domestic per capita consumption of chickens is 59 kg in the USA; 48.0 kg in Saudi Arabia, 67.1 kg in Hong Kong, 69.7 kg in Israel, and 35.4 kg in Canada (USDA Foreign Agricultural Service 2014). In South Africa the consumption rate in 2011 was 36.27 kg (DAFF 2014). This large consumption of chicken results in the generation of huge amounts of chicken feathers each year worldwide. Unfortunately, the demand for feathers is low, and most of them are disposed of by burning, landfilling, or conversion into feather meal and fed to livestock or used as fertiliser (Gurav and Jadhav 2013).

In this report, we review the possibilities of beneficiation of chicken feathers into high-value products. Since poultry feathers are rich sources of keratin proteins and amino acids, we believe that they are a valuable resource—their valorisation can result in their sustainable conversion into high-value materials and products on the proviso of existence or development of cost-effective technologies for converting this waste into useful products.

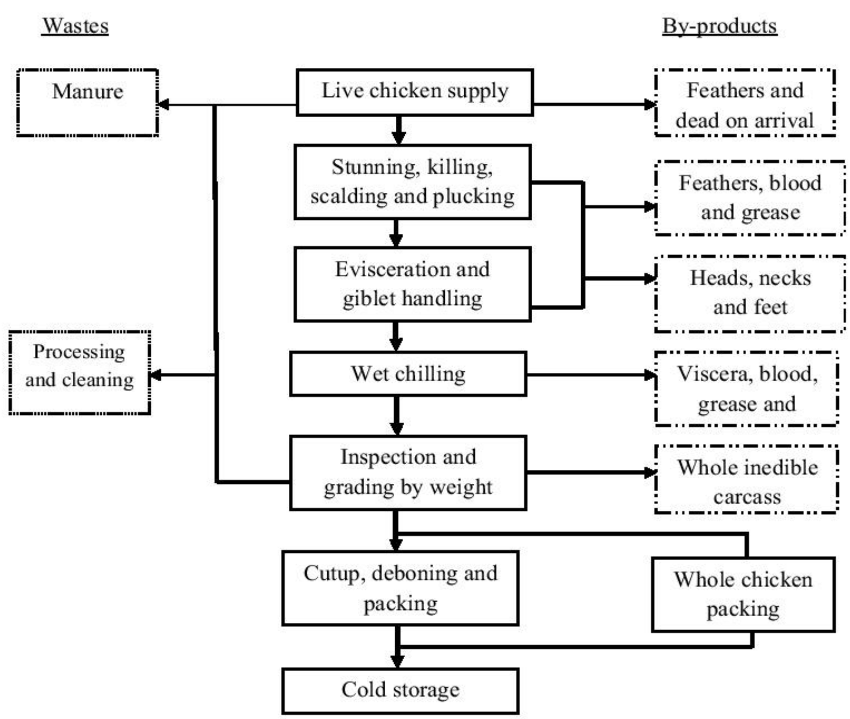
The poultry industry

Chickens can be classified into broilers, used for chicken meat supply, and layers, used for egg laying. Broilers are selected for competent feed to weight gain ratio and rapid growth rate. Chickens are slaughtered and processed from chicks that grow from a hatch weight of 45 g–2.5 kg after 42–45 days (Rahayu and Bata 2015). The poultry processing procedure is summarised in Fig. 1, starting with live chickens up to meat packaging and storage. The process leads to the production of both inedible and edible by-products. Feathers are major components of the inedible by-products.

Collection and disposal of chicken feathers

During poultry processing, many inedible by-products unfit for consumption are produced. After the

Fig. 1 Typical poultry processing procedure (Molapo 2009)



chickens have been slaughtered, the feathers are plucked by mechanical pluckers fitted with rubber fingers on rotating discs and followed by manually finish plucking the feathers by operators called pinners. The feathers, together with dilute blood, grease and cleaning water, are then pumped into a container followed by screening (Saravanan and Dhurai 2012). Then the feathers are conveyed into temporary storage area before disposal. The amount of poultry by-products produced at a single location is increasing because of centralisation and escalation of poultry slaughtering and chicken meat processing.

The gathering, stockpiling, disposal, and processing of slaughterhouse by-products is an important veterinary occupation in locations with concentrated animal husbandry and meat production establishments. Environmental pollution and transmission of diseases through improper and/or off-base treatment of slaughterhouse by-products must be anticipated (Franke-Whittle and Insam 2013). The use of slaughterhouse by-products for value-added products could be of economic benefit to slaughterhouses and could reduce the environmental pollution and transmission of diseases due to processing.

The microbial quality of poultry by-products is a major concern, and the presence of microbial toxins cannot be excluded. Most poultry by-products are sullied with high quantities of microorganisms, e.g., microbes, infections, parasites and yeasts (Franke-Whittle and Insam 2013). Slaughterhouse by-products constitute a potential danger to human and creature well-being and may additionally pollute the environment. Until recently, not much efforts have been invested to gathering and disposal of these by-products. There are, however, socio-economic reasons to increase scientific knowledge about handling and disposal of slaughter by-products:

A. Storage of by-products at slaughterhouses for long periods (6–30 h) under non-chilled conditions can results in large amounts of metabolites of degradation procedures in the products, making them unsuitable as raw material for animal feed. High-quality raw materials are the first requirement for production of high-quality animal feed. Furthermore, the degradation products pollute the environment due to the formation of off-odours (Kraham 2017);
B. Disposal of poultry wastes, often contaminated and with bad-smelling by-products, is mainly by road transportation to disposal sites. This poses a high risk of the spread of microorganisms and environmental pollution (Kraham 2017).

Utilisation of feathers: present scenario

According to statistics on broiler chickens provided by Compassion in World Farming, around 58×10^9 chickens are slaughtered for meat in the world every year (Compassion in World Farming 2013). The United States of Department of Agriculture estimates that 46.6×10^9 kg of chicken meat was processed in the USA poultry processing industry in 2014 (USDA Foreign Agricultural Service 2014). Processing of this chicken generates more than 40×10^9 kg of feathers per annum worldwide (Compassion in World Farming 2013). In the competitive poultry industry, the challenge is to transform chicken feathers into significant new products that add to the organisation's bottom line.

Currently, feathers are a waste product for which disposal is difficult. For example, the feathers may be hydrolysed, dried and ground to a powder to be used as a feed supplement for a variety of livestock, primarily pigs (Park et al. 2000). This is a fairly expensive process, however, and results in a protein product of low quality for which the demand is low. Other disposal means such as burning or burying are also occasionally utilised, but these methods are considered environmentally unsound and are therefore largely prohibited. The world poultry industry has struggled with this question: what to do with more than 40×10^9 of poultry feather waste their business generates each year? The next section reviews current recuperation and disposal practices and prerequisites for chicken feathers.

Disposal technique

Incineration

Incineration is a thermal destruction technology that is one of the most effective methods for destroying conceivably infectious agents. In this procedure, air discharges, process conditions, and the disposal of solid and liquid deposits should be entirely controlled. Smouldering poultry squanders might create as much or more toxic air emissions than coal plants. Analysis led by the North Carolina Department of Environment and Natural Resources found that a 57 MW poultry waste burning plant emitted levels of carbon dioxide (CO_2), nitrogen oxides (NO_2), particulate matter (PM), and carbon monoxide (CO) per unit of power generated that were higher than those for new coal plants (Stingone and Wing 2011).

Burial and controlled landfilling

Burial and controlled landfilling of chicken feathers on farms should be strictly monitored to keep away from groundwater contamination. As the operation, monitoring, and control of land filling likewise turn out to be more tightly regulated, landfilling must be prevented as much as could reasonably be expected because of its unfriendly consequences for the nearby environment, especially the contamination of surface water, groundwater, soil and air. Every one of these measures may increase the expenses of landfilling (Veerabadran et al. 2012).

Current uses

Feathers for decorative purposes

Artificial flowers have been made from feathers of large birds. The critical criteria for determination of feathers for decorative intentions are their shading, shape, size, and plumage designs. Since feathers from cock pheasants are splendidly shaded, they are in extraordinary interest for decorative purposes (Levine 1991).

Feathers in medical applications

Chicken feathers are utilised as a part of traditional medications. For instance, in South America blends produced using the feathers of condors are utilised as a part of conventional pharmaceutical and in India; feathers of Indian peacocks have been utilised as a part of traditional medication for barrenness, hacks and snakebites (Murari et al. 2005).

Feathers in religion and culture

Different flying creatures and their plumages serve as cultural symbols all throughout the world, from the hawk in ancient Egypt to the bald eagle and the turkey (bird) in the USA. Numerous sorts of feathers have cultural and religious significance, e.g., eagle feathers have extraordinary spiritual and social worth to local American societies. In the USA the religious utilisation of eagle and hawk feathers is governed by the eagle feather law (Levine 1991). Different birds and their plumage serve as cultural symbols all through the world, e.g., birds of prey, bald eagles, and so on (Murari et al. 2005).

Feathers as sporting equipment

Feathers are utilised as sporting equipment. For this reason, feathers are deliberately chosen from particular parts of the body of the birds, e.g., hardened wing feathers are utilised to make shuttlecocks, turkey feathers are utilised on fletching arrows, and other chose feathers are utilised to produce artificial lures for fishing (Levine 1991).

Feathers as fertiliser

Feathers contain more than 13% nitrogen content (Tesfaye et al. 2017b); this is higher than the best quality blood meal also utilised for such purposes, so they are astounding for compost purposes (Fig. 2) (Choi and Nelson 1996). Thus, feathers are used in plants growing operations that require rich nitrogen dressings. However, feathers are highly cross-linked with cysteine linkages and difficult to degrade (Park et al. 2000). Therefore, the availability of nitrogen from the feathers as fertiliser is considerably low. Feathers can also be used as mulching material. This is on account of; they deteriorate gradually and continuously discharge their nitrogen. Their tough, fibrous structure is ineffectively processed by most protein-degrading compounds; however, when blended with compost they degrade well (Gurav and Jadhav 2013). At the point when the feathers are composted, their produced by-products do a reversal as organic matter into the land which further adds to the soil fruitfulness. They form an important poultry composite blend in light of the fact that they add nitrogen, a critical fertiliser component (Veerabadran et al. 2012).

Feathers as dusters

A feather duster is a cleaning gadget in which feathers are utilised to expel the dust from the objects, since when rubbed they build up friction based electricity, which catches and hold dust particles until shaken out. The high-quality feathers from the external layers of ostrich plumes are exceptionally attractive for this reason because their fine delicate points won't scratch furniture surfaces. This is a scientific property of feathers that makes them trap dust; furthermore,

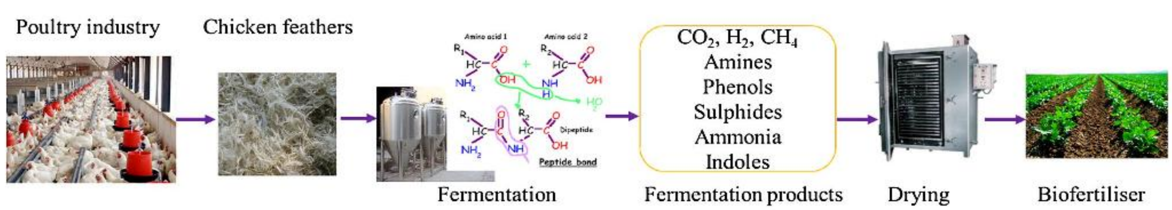


Fig. 2 Schematic diagram of biofertiliser production from chicken feather

the structural characteristics for the feathers give them tiny fingers to catch dust (Poopathi and Abidha 2007).

Feathers as bedding material

Since they fulfil all the necessities of good bedding, such as cleanliness, warmth, fluff ability, low absorption, softness, drapability, fire resistance, launderability and durability, feathers are also used as bedding material. Additionally, feathers have superior lofting performance and insulating capability. These attributes make goose down the favoured fill material for cushions and extravagance comforters. Also, feathers are warm, soft, have the ability to expand from compression and lightweight (Bonser and Dawson 1999).

Feather meal as a feedstock

Most feathers are not suitable for the aforementioned applications due to their hazardous nature (presence of microbiological pathogens) and their poor digestibility if land filled. Therefore, the fundamental strategy for feather waste administration is the conversion into feather meal to be utilised as stock food (Fig. 3). For the generation of feather meal, the rachis must be broken down by hydrolysis to make it digestible. A typical process is as follows:

- Feathers are washed with water, after collection from processing plants.
- Followed by de-watering by mechanical pressure rather than heat.
- They would have steamed and wet-cooked for hydrolysis under pressure for 1–2 h, after removing of water.
- The feathers are then cooled, dried and ground.
- To remove coarse metal particles, the ground meal is then passed through metal detectors (El Boushy et al. 1990).

Cooking time and pressure (amount of hydrolysis) directly affect the digestibility of feather meal (McCasland and Richardson 1966). Feather meal contains about 92% crude protein (ranges 70–80% as digestible protein) (Table 1), be that as it may, the protein edibility is extremely poor on account of the vicinity of disulphide bonds which are refractory to digestive enzyme present in chickens. Feather meal is inadequate in four fundamental amino acids, methionine, histidine, lysine, and tryptophan; however, it is rich in arginine, threonine and cysteine (El Boushy et al. 1990). A reasonable level of utilisation of feather meal as a feedstock is about 0.5–1.5%. (Park et al. 2000).

The applications mentioned in the preceding paragraphs utilise only a small portion of waste feathers generated by the poultry processing industry. More uses of the waste are needed and may be possible to achieve.

Table 1 Compositions of feather meal (McCasland and Richardson 1966)

Composition	Percentage
Protein	92.3% (ranges 70–80%) as digestible protein
Moisture	5.9%
Fat	1.3%

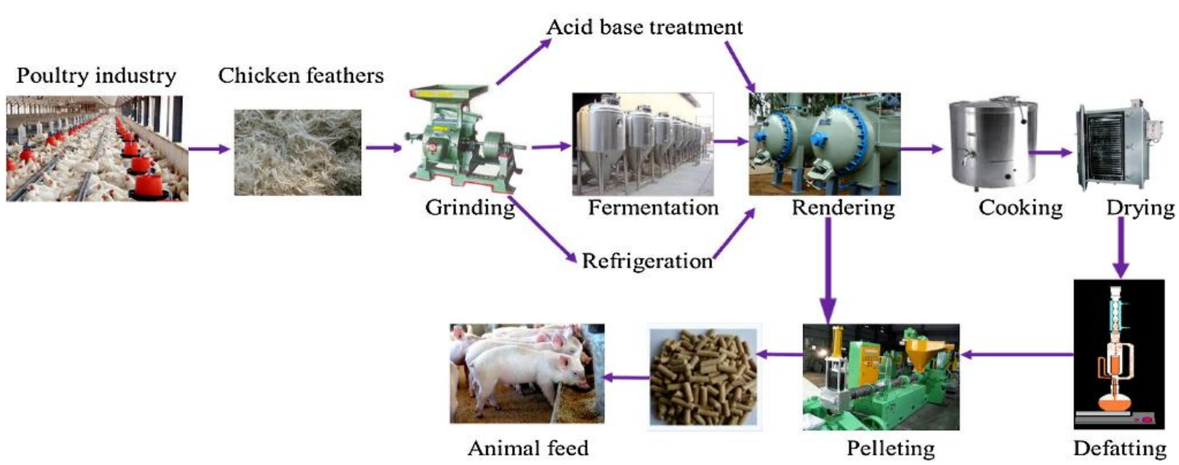


Fig. 3 Schematic diagram of animal feed production from chicken feather

Physicochemical properties of chicken feathers

Characterisation of physicochemical properties of the chicken feather is an essential step to identify possible avenues for valorisation of this waste biomass. A comprehensive characterisation of waste chicken feathers for their chemical, physical, thermal, mechanical and electrical properties and morphological and fine detail structures have described by the authors.

Physical properties of chicken feathers

Chicken feathers have low density than any other natural or engineered filaments commercially available today. Their low density, low thickness, warmth retention, astounding compressibility and strength, capacity to hose sound and particular morphological structure of their barbs make them remarkable fibre (Tesfaye et al. 2017a; Saravanan and Dhurai 2012). Besides the special structure and properties, feathers are cheap, richly accessible and a renewable hotspot for protein fibre. A feather is essentially made out of three particular units: rachis, barbs and barbules as shown in Fig. 4. Rachis is the solid and focal shaft of the feather to which the auxiliary structures, the barbs are joined. In the tertiary structures of the feathers, the barbules are joined to the barbs in a way like the barbs being attached to the rachis. The rachis runs the whole length of the rachis up to 15 cm long. The barbs have lengths anywhere in the range of 1–4.5 cm, contingent upon their area along the length of the rachis. Individual strands at the base of the rachis are longer than those at the tip (Tesfaye et al. 2017a).

Chemical properties of chicken feathers

Chicken feathers contain approximately 91% protein (keratin), 1% lipids, and 8% water. The amino acid succession of a chicken feather is precisely the same as, reptilian keratins from claws (Saravanan and Dhurai 2012). The amino acid sequence is mainly composed of cysteine, glutamine, proline and serine as shown in Table 2. However, histidine, lysine, tryptophan, glutamic acid and glycine are absent. Serine (16%) is the most abundant amino acid in chicken feathers (Saravanan and Dhurai 2012). Keratins are insoluble proteins present in rachis, fleece, hooves, scales, hair, nails (hard keratins) furthermore in the stratum corneum (delicate keratins) (Misra and Kar 2004). These particular proteins, which belongs to the scleroprotein groups, intensify that are exceedingly impervious to physical, chemical and biological activities. Mechanical stability and high resistance to proteolytic degradation of keratin is because of the presence of disulphide bonds, hydrogen bonds, salt linkages and cross-linkages (Misra and Kar 2004).

Basically, a chicken feather consists of α-helical and some β-sheet conformations. Its outer rachis is almost entirely made up of β-sheet conformations and few α-helical conformations (Tesfaye et al. 2017b). Hard β-sheet keratins have higher cysteine content than soft α-helix keratins and thus a much greater presence of disulphide (S–S) bonds that link adjacent keratin proteins. The presence of strong covalent bonds stabilises the three-dimensional protein structure and are very difficult to break (Saravanan and Dhurai 2012). Feathers contain ~ 91% keratin protein, and thus, potentially, feathers can be beneficiated into high-value compounds or products comprised of keratin proteins or keratin fibres. Thus, valorisation of feathers could be a viable option for sustainable disposal of the waste.

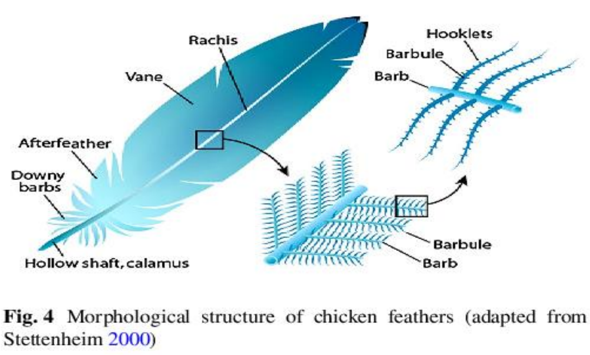


Fig. 4 Morphological structure of chicken feathers (adapted from Stettenheim 2000)

Table 2 Amino acid content in keratin fibre from chicken feathers (adapted from Saravanan and Dhurai 2012)

Functional group	Amino acid	Per cent content
Positively charged	Arginine	4.30
Negatively charged	Aspartic acid	6.00
	Glutamine	7.62
Hydrophobic	Tyrosine	1.00
	Leucine	2.62
	Isoleucine	3.32
	Valine	1.61
	Cysteine	8.85
	Alanine	3.44
	Phenylalanine	0.86
	Methionine	1.02
Hygroscopic	Threonine	4.00
	Serine	16.00
Special	Proline	12.00
	Asparagine	4.00

Utilisation of feathers: future prospects

Of the 58×10^9 chickens killed each year, poultry processors around the world throw away almost all their feathers: more than 40×10^9 into landfills (DAFF 2014). Conventional waste disposal methods, namely incineration, burial and controlled landfilling or recycling the feathers for fertiliser and animal feeds are problematic as they have high water and energy demands and there are also health concerns such as bird flu (Edwards and Daniel 1992; Urlings et al. 1992). Because of the keratin protein that retards degradation of feathers, the feathers take up a lot of space in landfills and take a long time to decay and incineration releases greenhouse gases.

The costs to the poultry processing industry to dispose their feather waste are increasingly high due to reduced availability of landfill space. It is very likely that poultry industries in the future will not be permitted to dispose their waste to landfill. For example, the South African government has promulgated legislation for proper disposal and waste minimisation. The National Environmental Management bill enforces the generators of waste to deal with their waste according to the hierarchy of waste management in a sustainable way. That is, every industry will need to re-utilise, recycle, minimise, avoid, treat and dispose of waste as a last a last alternative (Molapo 2009). The sustainability of the poultry processing plants is threatened, and the challenge is to design technologies that convert waste on site into valuable products which can be used on site or sold. There is still a lot of research to be explored in the utilisation of chicken feathers for beneficial use. The valorisation of waste feathers can take advantage of their chemical constituents, their cheapness (free availability), ease of availability, and potential to offer sustainable procedures for their disposal. Examples of how and where chicken feather waste can be a useful resource are described below.

Feathers in automobile and aeroplane industries

Modern day material science industries are looking for lightweight, low-cost and biodegradable raw materials for manufacturing of different parts of automobiles and aeroplanes using environmentally sustainable materials. Currently, most automobile and aeroplane parts are made from petroleum-based raw materials. Owing to remarkable strength (due to the high cysteine content of the keratin protein, and low-priced properties), lightweight nature, and better quality (Tesfaye et al. 2017a), feathers could be used to produce composites for use in automobile and aeroplane industries such as in dashboards, car parts, seats and cushioning, interior linings to reduce their weight while strengthening them.

Textile industry

Feathers in fibre, yarn and fabrics

Scientists are investigating ways to process agricultural and food industry waste product into significant consumer products, replacing natural fibres, man-made fibres and saving trees in textile processing. High surface area, toughness, flexibility, fine diameter, durability property of the chicken feather makes feather valuable resources to replace expensive natural fibres, wood pulp, and synthetic fibres. Because of the structural property of the chicken feather, the feathers cannot be rehabilitated directly into new products. The malleable interconnectedness strands for materials that develop from the rachis (the barbs) must be stripped off from the hardened focal centre of the feather (the rachis) because this delicate barb material satisfies the property of textile fibre. Even though the whole feather contains keratin, the soft but durable barbs protein is different from that in the crystal structure of the rachis (Tesfaye et al. 2017a; Bonser and Dawson 1999). Only the barbs have the desirable properties to be used as textile fibre. There are two options to use chicken feathers as a fibre source.

The first one is blending chicken feather barb fibres with other fibres for spinning into yarns. This is because chicken feather barbs have fibres that can be processed into yarns (after stripping the barbs from the rachis). The air flow technique could be an efficient method for separating the rachis from barbs because of density difference. Stripped rachis and barb parts have different shapes and lengths. Since individual fibres from feather are too short to be spun into yarns, they can be blended with wool, cotton and man-made fibres and then spun into yarns.

The second option could be producing regenerated fibres from the whole chicken feather (Fig. 5). Chicken feathers contain more than 91% fibrous structural keratin protein; the monomers inside the keratin composition assemble into bundle to form intermediate filament. Keratin proteins, like all intermediate filaments, form filamentous polymers in a series of assembly steps starting with dimerisation; dimers collect into tetramers and tetramers into octamers and after that into unit-length filaments capable of annealing end-to-end into long fibres (Tesfaye et al. 2017b; Stuurman et al., 1996). Alternatively, after extracting the keratin protein from chicken feathers, the protein could be spun into filamentous regenerated fibres using electro-spinning techniques. The resultant fibres could be used in manufacturing plastics, fabrics, technical materials and other products.

Fifty years ago, scientists produced the first regenerated fabrics made from unusual materials, like milk proteins, peanuts, and corn (Poole et al. 2008). Although they performed poorly when wet, the fabrics from the regenerated fibres had the feel and look of wool and silk, which are

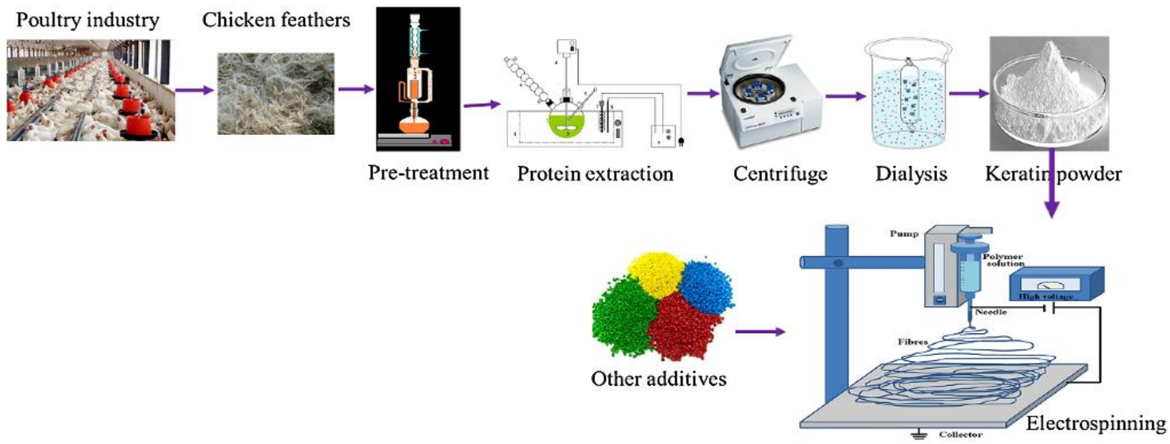


Fig. 5 Schematic diagram of regenerated fibre production from chicken feather (adapted from Tesfaye et al. 2017)

conventional protein-based fabrics. This issue, consolidated with the presentation of petroleum-based engineered filaments, created the generation of these abnormal fabrics to stop. In any case, worries about skin well-being issues, high costs, environmental problems and consumer's interest for eco-friendly products and renewable fabrics produced using unusual waste materials are presently now poised to make a return. Agricultural and food wastes like cellulose and proteins could be valuable resources for the manufacture of fabrics. Advances in nanotechnology and chemical cross-linking technology could enable commercial production of eco-friendly clothing by improving the strength and biodegradability of the final product. The filament fibre from the electro-spinning machine could be woven into warm and cosy fabric made from chicken feathers.

Feathers in warp yarn sizing and fabric finishing

Warp yarn sizing agent is a protective layer added on to the surface of yarns to improve weaving performance. The warp of textile yarns has traditionally been sized using starch, modified starch derivatives, CMC, polyvinyl alcohol, or a combination thereof, along with other fibre binding ingredients. Starch and starch derivatives have been the predominant sizing agents. However, starch is extracted from food-based raw materials, and this creates socio-economic problems. The protein in feathers has film forming and binding ability (Reddy et al. 2014); thus, it could be a good source as a textile sizing and binding agent, and in textile printing.

Feathers in flame retardant finishes of fabrics

The presence of high amount of nitrogen (Tesfaye et al. 2017b) in feathers made it a useful material as flame retardants. Hydrolysed feathers were used to prepare flame retardant finish (Guan and Chen 2006). High flame retardancy was imparted to the cotton fabrics after treating with the flame retardant which was based on feathers.

Feathers to create leather composites

Various treatment processes utilised in leather tanning can bring about cancer, additionally skin and respiratory ailments, so there is a need to replace them with environmentally friendly materials. In this regard, Wool and colleagues have developed bio-composites, using techniques developed by aerospace engineers to process scraped, downy fibres from chicken feathers into the synthetic leather (Fig. 6). Wool consolidates natural fibres and plant oil resins under heat and pressure to produce a composite material that is similar to leather (Sydney 2015).

Fig. 6 Shoe prototype made from feather composite (adapted from Sydney 2015)

Feathers in other textile application

Because of their thermal property, warmth, fluff ability, softness, drapability, fire resistance, launderability and durability chicken feather can be used for filling materials in winter clothing and non-woven fabric manufacturing and keratin hydrolysate from waste chicken feather could be used in cationization of fabric and subsequent treatment in textile dyeing process.

Plastic and packaging industry

Feathers in biodegradable plastics

There are two types of plastics: thermoplastics and thermosetting plastics. Thermoplastics include polystyrene, polyvinyl chloride, nylon, polyethylene, etc., and dozens of other kinds. A thermoplastic is a material which becomes soft when heated and hard when cooled, while thermosetting plastics harden and melted once and cannot be remelted again: examples include epoxy resin, melamine formaldehyde, urea formaldehyde, etc. Both thermosetting and thermoplastic plastics are made for the most part from ingredients obtained from crude oil or natural gas. Researchers are working to discover non-fossil based ingredients as an option, on account of worries about petroleum maintainability, supplies, and costs (Jin et al. 2011; Moore 2008). One possible route is to utilise waste materials and other renewable resources to make bioplastics that have an extra favourable position of being biodegradable once disposed of into the earth. Since they are reasonably cheap and inexhaustible, chicken feathers are a fabulous prospect. Feathers are inherently non-thermoplastic and do not melt, but simple alkaline hydrolysis makes them thermoplastic and suitable to develop films after cross-linking using citric acid (Tesfaye et al. 2017b; Misra and Kar 2004). The other route could be graft polymerisation using acrylic monomers. Grafting could impart thermoplasticity which could allow the feathers to be made into films (Fig. 7). What makes chicken feathers ideal is that they are rich in keratin, a tough natural protein polymer composed of natural monomers. In contrast to other biological sources like plant proteins and modified starch, keratin-based plastics could offer greater strength and tear resistance because of the tough keratin proteins (Khosa and Ullah 2013).

Feathers in packaging materials

Petroleum-based products in packaging have long been a cause for concern regarding the health of the environment and the country's economy. Not only petroleum is an expensive, non-renewable resource, but the manufacturing, usage and disposal of crude oil-based packaging can have a harmful impact on the environment. Chicken feathers could be a good source of raw materials to replace petroleum-based products. Keratin could be used to replace fossil fuel in some products since the main component required to make plastics with chicken feathers is keratin. The utilisation of chicken feathers as a raw material for the manufacturing of packaging material may never be a complete replacement for petroleum. However, any cutback in petroleum use is still a major

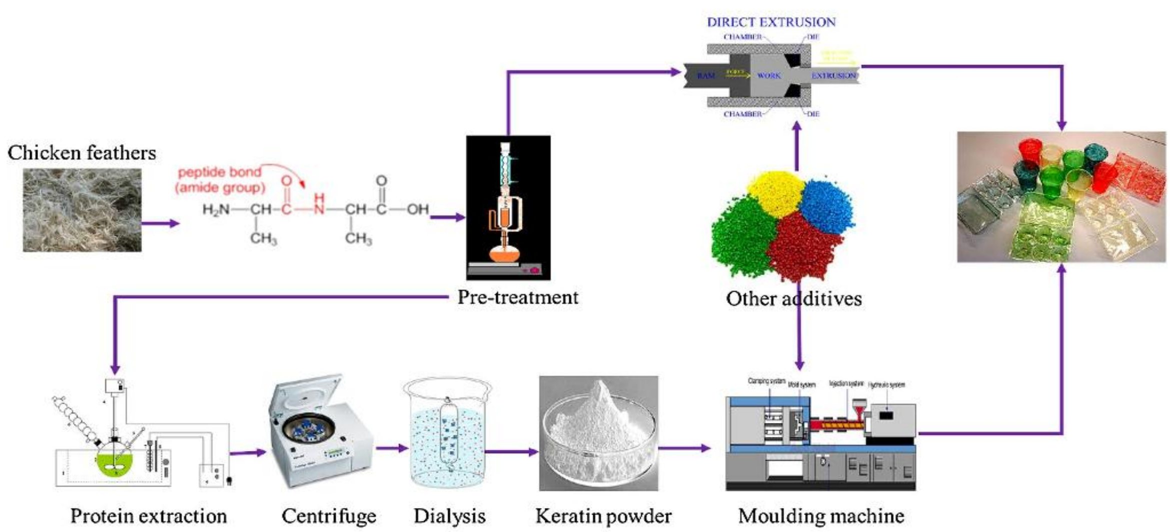


Fig. 7 Schematic diagram of bioplastic production from chicken feather (adapted from Tesfaye et al. 2017)

step forward for the environment. When transporting delicate materials from place to place without damage, cartons lined with chicken feathers non-wovens could be put inside as the interlining to guarantee that the materials are firmly stuffed. This would replace the use of environmentally unfriendly polystyrene films. Non-wovens are made of any kind of fibrous material via three techniques: chemical bonding, thermal bonding and needle punching techniques. After stripping the fibres, the chicken fibres should be laid using hand or machine laying techniques, after which bonding will be performed.

Feathers in filtration and paper applications

The super fine size and shape of feather fibres imply that they may be used in filtration applications. Non-wovens made out of chicken feathers will exhibit very good porosity, good resistance to mild acids and alkaline media, and lightweight characteristics—a promising future in chemical industries. Feather fibres could replace wood pulp-based paper products such as filter papers and decorative papers. Wood pulps are the raw material for most paper-based products, but feather fibres have an advantage in full or partial replacement of wood pulp, as they are finer in diameter than wood pulp (Fig. 8). Feather fibres have a width of 5 μm, whereas that of wood pulp fibres is 10–20 microns (Tesfaye et al. 2017a; Jin et al. 2011). Therefore, filters produced from feather fibres are likely to have smaller holes with good ability to entrap spores, dust and dander from the air.

Construction industry

Feathers in lightweight construction composites

In recent years, researchers have focused their efforts in the manufacture of composite materials from thermoplastics and natural fibres for different applications. These natural fibres offer good strength, low cost, low density, good thermal property, high toughness and biodegradability to the composites. In addition, natural fibres reduce consumption of synthetic polymers and, therefore, decrease the consumption of petroleum products. However, natural fibres are cellulosic and are incompatible with the hydrophobic nature of polymer materials. Chicken feathers can be used instead. The feathers could be used as reinforcement material after prior separation of the feathers into long fibres, short fibres and powdered rachis. Since feathers contain more than 91% keratin protein (Tesfaye et al. 2017b; Reddy et al. 2014), it could be possible to melt and use them as a matrix material. The thermoplastic properties of the feathers could be modified or enhanced by using acrylic polymers (Misra and Kar 2004). The keratin in feathers makes them (and their composites) resistant to insect infestation as the keratin is indigestible and inedible to termites and insects. Additionally, the use of feathers would result in composites that are not combustible, unlike conventional composite boards. Although more research needs to be done, composites made of chicken feather can be used in panelling or ceiling applications, and for thermal and sound insulation, but not for walls or pillars. Using chicken feathers composite building board in construction industry could be a major breakthrough to replace wood and plastic-based construction materials.

Fig. 8 Process flow diagram for chicken feather/wood pulp handsheet preparation (adapted from Tesfaye et al. 2017c)

Feathers in geotextile materials

Geotextile materials are often used on road construction sites, building sites, agricultural areas and other areas that have uncovered land, where the stabilisation of soil is required. This material is necessary to conserve the landscape to avoid the removal of sediment during rainfall and to keep the nutrients in place. There is a need for low-cost, biodegradable geotextile materials due to the high cost and environmental impact of synthetic erosion control. One possibility is development of yarns, knitted, and non-woven fabrics from feather fibres. Chicken feathers geotextile materials could be strong and very stiff because of the tough keratin property of the feathers, thus when placed on soil, the geotextile material preserves the soil. Because of the water holding capacity of the feather fibre, the materials could increase the moisture content of the soil and also decrease compaction of soil due to feathers occupying more space. For successful ecological restoration of habitats, all these are critical properties.

Bioenergy production

Feathers in biogas production

Chicken feathers contain high amounts of crude protein, carbon, nitrogen and hydrogen elements (Tesfaye et al. 2017b). Proteins are composed of amino acids linked by peptide bonds, which are hydrolysed by proteases upon decomposition. The degradation products include short or branched chain organic acids, NH_3, CO_2 and H_2. Figure 9 shows the process flow for the production of biogas from chicken feather waste.

Feathers in biofuel production

In the world, man is facing two major challenges, waste disposal and the need for an abundant source of clean energy. The perfect solution to both of these problems is to turn the waste into energy which could significantly cut carbon emissions while replacing the need for fossil fuels. Soybean, corn, sunflower and cottonseed are the primary sources of renewable energy via biodiesel production. The use of these raw materials faces social problems, availability and cost effectiveness (Demirbas 2008). Thus, finding alternative non-food, raw materials is a priority. Chicken feathers contain substantial amounts of fat that could be processed for the production of biodiesel from feather meal (Fig. 10). The biodiesel production, the fats could be extracted from feather meal by solvent extraction and subsequently transesterified into biodiesel using catalysts, nitrogen and methanol. From the huge amounts of waste chicken feathers that are generated worldwide, it can be estimated that hundreds of millions of litres of biodiesel can be generated from the waste. This energy from waste could cut carbon emissions by a large per cent while replacing the need for large amounts of petroleum.

Feathers in biohydrogen production

Energy sustainability and alarming increase in pollution of the fossil fuels are the main challenges facing the energy industry in the world. Bioenergy is a sustainable, promising and eco-friendly alternative to fossil fuel energy (Zhu et al. 2011). Hydrogen has been projected as the most promising renewable energy carriers, emitting only water vapour as a by-product (Chandrasekhar et al. 2015). However, the current industrial processes for hydrogen production use fossil fuel through steam reforming, pyrolysis, autothermal

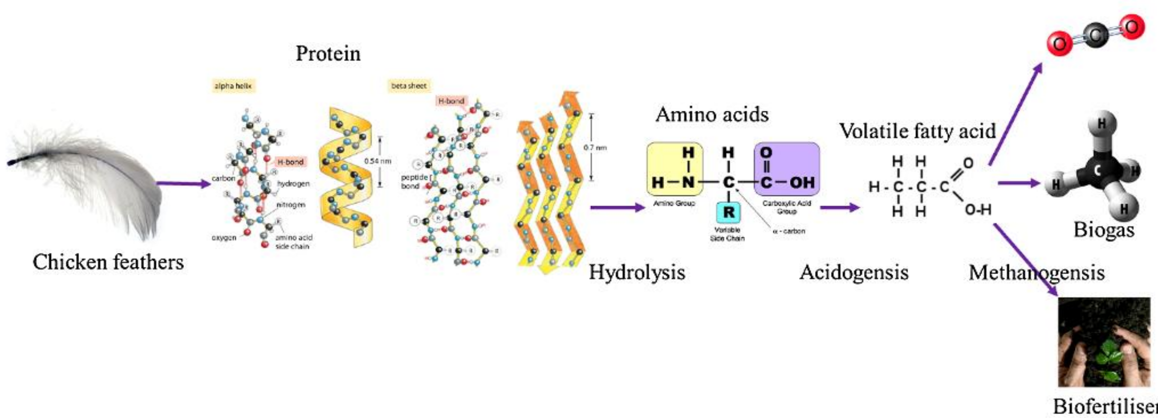


Fig. 9 Schematic process flow of biogas production from chicken feathers (adapted from Tesfaye et al. 2017)

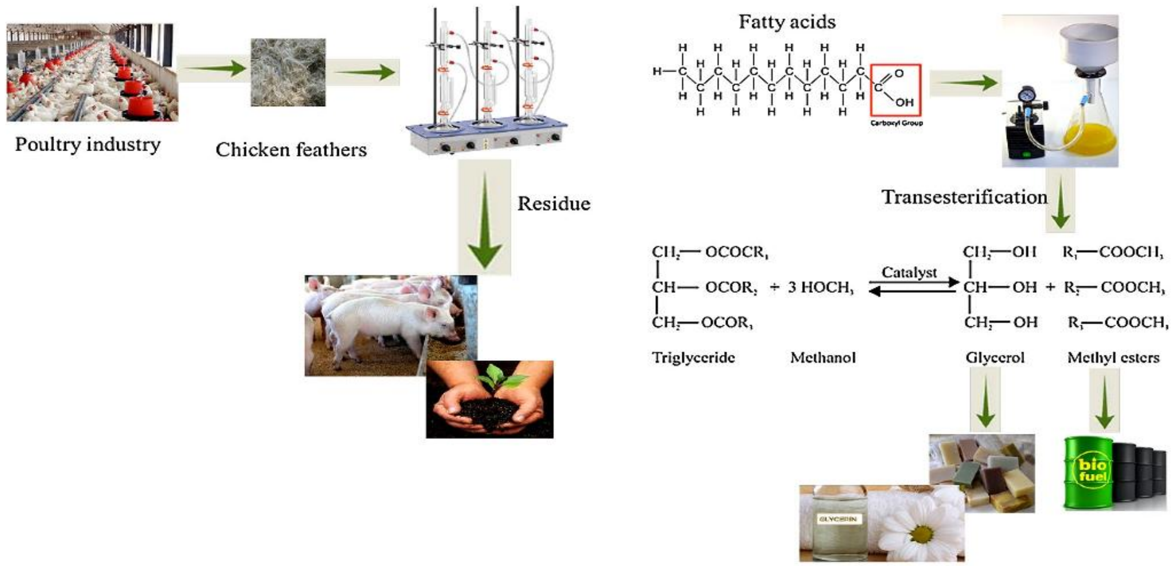


Fig. 10 Schematic process flow of production of biofuel from chicken feather

reforming, thermal decomposition, catalytic oxidation, and steam gasification (Kapdan and Kargi 2006). Since the current production increases the emissions of greenhouse gases, the production hydrogen gas from biomass through biological pathways will be an emerging technology. The presence of hydrogen in chicken feather can be used as a raw material for hydrogen gas production to replace fossil fuel.

Feathers in fuel storage applications

Hydrogen, the simplest and most plenteous component in the universe, has long been touted as a clean and ample energy option to fossil fuels (Cheng et al. 2001). When hydrogen reacts with different components, it forms numerous compounds, a portion of the basic ones are: methane (CH_4), ammonia (NH_3), water (H_2O), hydrochloric acid (HCl), hydrogen peroxide (H_2O_2) and table sugar ($C_{12}H_{22}O_{11}$). Unfortunately, due to its physical property (lightest element and very low volumetric energy density), it is difficult to store and transport hydrogen. Researchers have been endeavouring to engineer ways to store hydrogen gas on board vehicles at reasonable weights, pressure and temperatures, to significantly reduce the expenses of a hydrogen infrastructure. On the other hand, the alternatives used to store hydrogen, such as metal hydrides and carbon nanotubes, are often very costly (Cheng et al. 2001). So the world needs a light weighted and economic material which can bind and release hydrogen to assist autos to use hydrogen fuel in the future; one of these materials can be chicken feathers. The feathers might not have a chance to be the fuel, but they might help to store it. Chicken feathers are composed of mainly keratin protein (Tesfaye et al. 2017b; Reddy et al. 2014) the same protein found in claws, beaks, nails and scales, a natural protein that forms lightweight, strong, hollow tubes. When heated, keratin turns out to be more permeable, expanding its surface territory, forms hollow tubes between the fibres, and creates cross-link which strengthens its structure; these features increase its ability to bind and store hydrogen. Thus, to store and release the gas, one can pump hydrogen gas into the feather at high pressure, and one just de-pressurises it or raises the temperature, respectively.

Pharmaceuticals and biomedical engineering

Feathers in pharmaceuticals

Feathers contain fats (Tesfaye et al. 2017b) that are a good source of cholesterol (Moore 1989). Cholesterol is a steroid found mainly in the spinal cord, and it makes up 10% of the dry matter in the brain, and it plays an important role in metabolism. Cholesterol is necessary for proper body functioning, and to make hormones (Asano 2003). Chicken feather cholesterol could be used as a building block for the synthesis of different pharmaceuticals. For example:

1. The cholesterol can be a pioneer in the production of vitamin D3. Vitamin D3 is necessary for teeth and bone formation (Holick 2004).

2. The cholesterol can be utilised as a supplement for male sex hormones since they are used in the synthesis of steroid pharmaceuticals (Moore 1989).
3. The cholesterol can be a precursor of bile salts that are vital in the blend of steroid hormones. Steroids are used for proper digestion of foods and absorption of fats in the intestine, menopausal syndromes, and they also prevent breast swelling (Asano 2003).
4. Since bile salts can break down and emulsify fats, the cholesterol could also be used as a bio-emulsifier/biosurfactant in the cosmetics industry (Asano 2003).

Feathers in biomedical engineering

Acceptability by the human body is the first essential requirement of materials to be used in biomedical applications (Rouse and Van Dyke 2010). Ninety-one per cent of chicken fibres are keratin protein (Tesfaye et al. 2017b; Reddy et al. 2014), and this protein is the foundation for different biomedical applications starting from the drug delivery carriers, to tissue engineering and to self-assembled nanofibrous scaffolds (Fig. 11). Chemical, biological behaviour and physical properties of these biomaterials contribute to the use of chicken feather for biomedical application. These properties include biodegradability, bioresorbability, biocompatibility, sterilisability, functionality, self-assembly, and manufacturability as well as mechanical and thermal properties (Ambrose and Clanton 2004). The acceptability, biocompatibility and self-assembly phenomenon are evident in the highly preserved superstructure of the protein keratin (Reddy and Yang 2011; Rouse and Van Dyke 2010) and are responsible for the reproducible dimensionality porosity and architecture of feathers, when processed correctly. In addition, keratin biomaterials derived from chicken feathers are capable of supporting cellular attachment since they could own cell binding motifs, such as glutamic acid-aspartic acid-serine and leucine-aspartic acid-valine binding residues.

Feathers in cosmetic applications

The beauty industry has a long history of using unusual ingredients, one of them being human hair that is ground to make the keratin available for use in beauty products. Hydrolysed keratin has turned into a typical cosmetic ingredient (Barba et al. 2008). The fundamental capacity of keratin is to protect the cortex of the human cell from injuries brought on by factors, for example, heat, daily maintenance and chemicals. Topical application of hydrolysed keratin gives noteworthy increment in skin flexibility and hydration. Because of its moisturising properties, the keratin can be fused into shampoos and conditioners, hair loss concealing products, and hair-thickening accessories (Villa et al. 2013). Protein hydrolysates are proficient restorers in hair care processing (Niinimaki et al. 1998). These dynamic

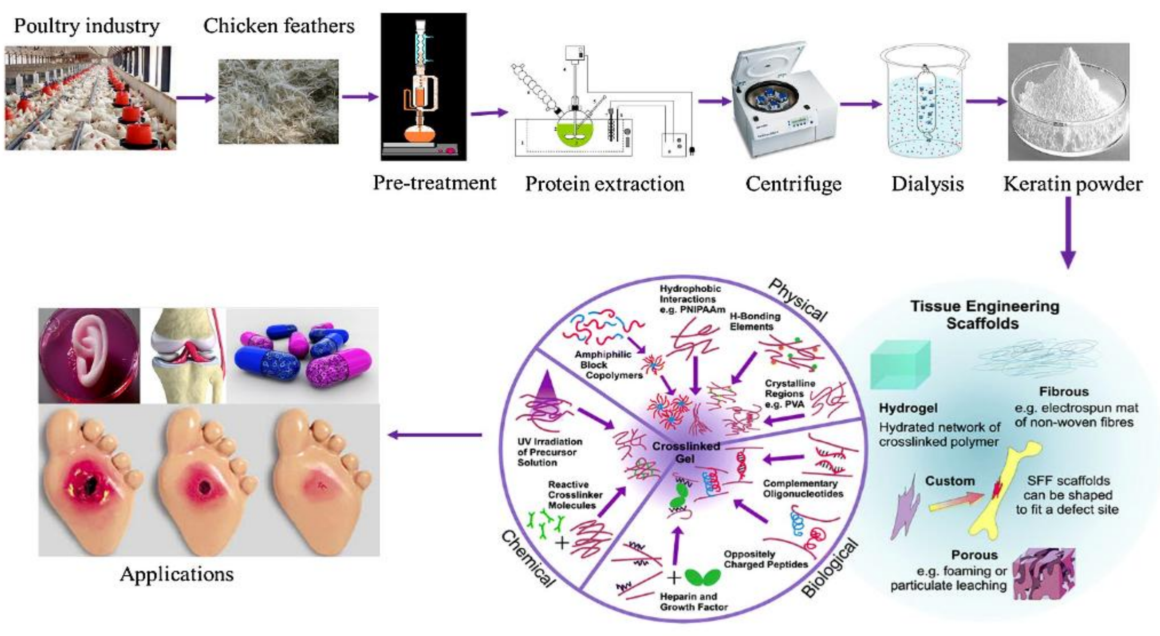


Fig. 11 Schematic diagram of biomedical products production from chicken feather

peptides are reparative and conditioning agents and give advantages to the hair, for example, fortifying hair filaments, strengthening and decreasing fibre breakages. The addition of protein hydrolysates to hair shading splashes and toners empowers hair to retain colours more uniformly. Numerous sorts of plants and animal protein hydrolysates have been utilised as a part of hair repair products furthermore in skin beautifying agents; they include wheat protein (Villa et al. 2013) and wool, nails, and horns keratin (Barba et al. 2008). Since chicken feathers contain keratin and amino acids, their hydrolysates can be used in hair treatment and skin treatment procedures.

Feathers in enzyme production

Keratins are the most abundant structural protein and are components of the epidermal and skeletal tissues. Keratinase is a proteolytic enzyme that attacks disulphide bridges to convert keratin from complex to simplified forms (Fig. 12) (Villa et al. 2013; Paul et al. 2014). Keratinases are used in a wide variety of applications such as for de-hairing of skins in leather manufacturing, fertilisers, or animal nutrients in the agricultural industry, food supplements in the food industry, textile processing, detergents, and in the biomedical and pharmaceutical industries. Thus, chicken feathers could be used as a raw material to produce cheap keratinase enzymes since they contain high protein content, and keratin is the raw material for keratinase.

Feathers in waste water purification

Chicken feathers could be used for water purification due to their inherent properties: structural toughness, stability over a wide range of pH, water insolubility, and high tensile strength. Their sorption purposes will be satisfactory for the removal of heavy metals (e.g., copper, selenium, and zinc), toxic organic compounds and colourants in water, because of the hygroscopic nature of keratin protein (Kar and Misra 2004; Misra et al. 2001). After extraction of keratin from chicken feathers, sponges could be prepared using dilution of the extracted keratin followed by lyophilisation. The sponge can be useful, for example, in cleaning up of oil spills in water.

Feathers in electrical components

The current goal of material engineering and science is to find low-cost, lightweight and biodegradable materials. To conduct any kind of electricity, one must have a presence of electrons that are free to move within a substance (like metals), ions (like in water) in an electrolyte fluid, or both (Ku and Liepins 1993). But chicken feathers lack moisture content; hence, they have very good electrical resistance properties, which make them good candidates for use as insulating materials. Feathers are made of keratin protein, which is in fibre form, and are extremely light; they are hollow and tough enough to withstand mechanical and thermal stresses due to keratin compound, and helix structured coupled with their low cost (Tesfaye et al. 2017b) could considered to be an ideal raw material to develop uniform microporous materials with high surface area as electrode materials that are also environmentally friendly. Dielectric materials are used in a variety of applications including insulation, encapsulation, printed circuit boards, capacitors and other devices. For the material to be dielectric it should have hollow structure or porosity. Since it offers no resistance, air is considered to be a perfect dielectric material with a minimum dielectric constant of 1 (Ku and Liepins 1993). There are very few dielectric materials in current use that have a dielectric constant close to 1, e.g., porcelain, glass and most plastics. Since feathers contain hollow structures, they could be useful as dielectric materials.

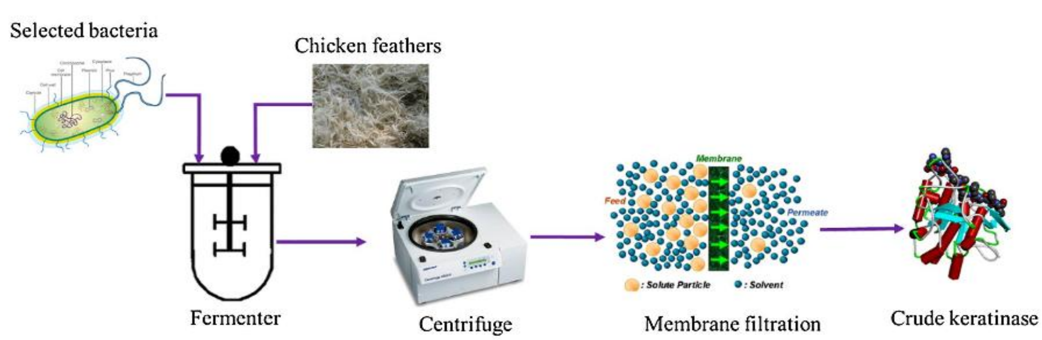


Fig. 12 Schematic diagram of keratinase production from chicken feather

Conclusions

Chicken feathers are produced in large quantities as a by-product at poultry processing plants. Their disposal by incineration or landfilling is fraught with problems, e.g., environmental pollution and transmission of diseases due to microbial contamination. However, chicken feathers are composed of materials and components that can be valorised into valuable products and materials. Thus, they should be regarded as a valuable resource for extraction of fibres for conversion into fabrics and composite materials; for extraction of composites that can be converted into high-value products that are normally sourced from petroleum-based products. Thus, using waste chicken feathers for such purposes will minimise environmental pollution as well as reduce reliance on use of petroleum-based products. Extensive research and development work is required to develop appropriate technologies for their full utilisation as a source of some of the proposed applications mentioned in this review.

Acknowledgements The authors are highly grateful for the financial and technical support received from the Institute of Technology for Textile and Fashion Design/EiTEX at Bahir Dar University, Thermodynamics Research Unit at Chemical Engineering of University of KwaZulu-Natal, the Biorefinery Industry Development Facility, CSIR, Department of Science and Technology, Waste Research Development and Innovation Roadmap, and Rainbow Chicken Limited Foods.

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PUBLICATION EIGHT

Journal of Cleaner Production 164 (2017) 1324–1331

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Valorisation of chicken feathers: Application in paper production

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ARTICLE INFO

Article history:
Received 26 April 2017
Received in revised form
5 July 2017
Accepted 5 July 2017
Available online 6 July 2017

Keywords:
Feather
Wood pulp
handsheet
Sustainable

ABSTRACT

Reducing waste materials through reuse has in the recent past contributed to sustainable manufacturing in many industries. With the development of large-scale poultry farming, the treatment of large amounts of chicken feathers has become a problem and threatened its use as a renewable resource. This paper examines the use of chicken feathers in the paper making process; a process which would traditionally use wood as the raw material. The effects of combining feather fibre and wood pulp on paper performance were studied and compared to the properties of handsheets made with 100% wood pulp. With the increase of feather content, properties such as tightness, tensile index and bursting index decreased, whilst air permeability improved. There was no significant difference in water absorbency between various chicken feather/wood pulp handsheet samples however, the water absorbency started to decrease above 80% of chicken feather content. This could potentially open up a new avenue for the use of chicken feathers in applications that are meant to tolerate high humidity conditions, e.g., packaging products.

1. Introduction

Paper is an integral part of everyday life, even with the advent of the digital age (The Paper Story, 2016; Eric and Ariane, 2014). An estimated 95% of all business information is stored on paper and 500×10^6 newspapers are printed and read around the world every day (Fibre Processing and Manufacturing Sector Education and Training Authority, 2014). South Africa is ranked the 15th largest producer of pulp in the world and 24th in paper production (Fibre Processing and Manufacturing Sector Education and Training Authority, 2014). In 2013, the paper industry added $1.36 \times 10^9 to South Africa's economy – this equates to 0.6% of the country's gross domestic product (The Paper Story, 2016). The industry now produces more than 2.5×10^6 tonnes of product each year, i.e., ca. 1% of international capacity. In terms of land use, the afforested area used in paper production is ca. 1.27×10^6 ha or about 1% of the total South African land area – 122.3×10^6 ha (Pogue et al., 2008). In the South African context, per capita consumption of paper products is 46 kg per annum, which approximates to the international average (Macdonald, 2004; The Paper Story, 2016). The pulp and paper industry generates income greater than 200×10^9 per annum (Pogue et al., 2008).

Worldwide, more than 90% of total production of fibre for paper production come from wood (Eric and Ariane, 2014; Sridach, 2010a, b; Mohd Aripin, 2014). Insufficient planted trees and huge environmental issues due to deforestation are the major constraints to growth faced by the sector. Due to the awareness of sustainability, the environmental problems have brought forward the need for cleaner technologies where new non-wood resources have to be introduced (Mohd Aripin, 2014). Cleaner production technologies should be applied to achieve increased production with minimum effect on the environment. The abundance of non-wood fibres may be considered as the best and more profitable alternative in the paper-based industry (Gonzalo et al., 2017; Sridach, 2010a, b; Mohd Aripin, 2014). Studies have shown that sugarcane bagasse, hemp, bamboo, flax (Sridach, 2010a, b), Tunisian alfa (Marrakchi et al., 2011), wheat straw (Jiménez et al., 2002), grass, giant reed (Shatalov and Pereira, 2006), tobacco (Shakhes et al., 2011), canola straw (Hosseinpour et al., 2010), vine (Mansouri et al., 2012), rags, cotton linters and other textile wastes (Paterson Brown et al., 2003; Sczostak, 2009; Mohd Aripin, 2014) can partially substitute wood pulp in paper production.

Chicken feathers are considered as waste material from the poultry industry; however, they are a sustainable and renewable

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http://dx.doi.org/10.1016/j.jclepro.2017.07.034
0959-6526/

source of proteinaceous fibres. In South Africa, there are approximately 258 × 10^6 kg of chicken feathers produced per annum (DAFF, 2014) with the majority being considered as waste for disposal. Small amounts are often processed into valuable products such as feather meal and fertilisers (Veerabadran et al., 2012; Stingone and Wing, 2011). The remaining waste is disposed of through incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases (Tronina and Bube, 2008). Are there better ways to beneficiate these wastes?

Studies have shown that waste chicken feathers can be beneficiated in, e.g., textile applications (Reddy and Yang, 2005; Paul et al., 2014; Reddy et al., 2014); composite building applications (Winandy et al., 2003; Jeffrey, 2006); biobased plastic resins (Roh et al., 2012); removal of heavy metals from wastewater (Al-Asheh and Banat, 2003); fibre and fibre products (Gassner et al., 1998; Bartels, 2003). However, very little work has been done on beneficiation of waste chicken feathers for partial or full replacement of wood fibres in the paper industry. The only known report is a patent by Gassner whereby fibre and fibre products were made from chicken feathers and used as a binder or filler in paper products (Gassner et al., 1998). No other reports have been written on application of feathers in the paper industry. This paper discusses the potential utilisation of waste chicken feathers in the manufacture of paper: handsheets made from chicken feather and wood pulp mixtures were prepared and then characterised to ascertain their papermaking qualities. The data from this paper provides new knowledge into possible valorisation of chicken feathers for use in paper manufacturing.

2. Materials and methods

2.1. Materials

Feathers: Chicken feathers were obtained from a slaughterhouse in the province of KwaZulu-Natal, South Africa.

Cleaning agent: Sodium dodecyl sulphate (SDS) 99.0% was purchased from Sigma-Aldrich.

Pulp: A fully bleached sulphite pulp was produced from a Eucalyptus species via the acid bisulphite pulping process.

2.2. Methods

2.2.1. Pre-treatment of chicken feathers

Freshly plucked wet untreated chicken feathers were purified by washing with a 1 g/L aqueous solutions of SDS. Untreated waste chicken feathers (10 g) feather samples were placed in a beaker to which was added the SDS solution at a liquid to solid ratio of 40:1. The sample was agitated at 500 rpm using a magnetic stirrer with the beaker on a hot plate maintained at 50 °C for 30 min. The treated feathers were further purified by rinsing in distilled water for 10 min and then laid on aluminium foil and dried to a constant mass at 100 °C in an air-forced dryer. Thereafter the sample was placed in plastic bag that was sealed and then stored in a controlled laboratory environment (20 °C, 65% relative humidity). The treated feathers were subsequently milled to 350 μm size using a heavy-duty milling machine before use. Ten replicate samples were processed in this manner.

2.2.2. Preparation of handsheets

Suspensions of feather and pulp mixtures were prepared in 100/0, 80/20, 60/40, 40/60, 20/80, and 0/100 ratios and defibrillated in a disintegrator (Disintegrator MK.III C, Messmer Instruments Limited, UK) (5 min and 5000 revolutions) containing 1000 mL of water. Once defibrillated, 9000 mL water was then added to bring the volume to 10,000 mL of chicken feather/pulp suspension that was then mixed by sparging with compressed air in a stock divider (NG Brown and Associates, Melbourne, Australia). Each handsheet was made using 1000 mL of suspension to obtain ten handsheets per mixture, except for the samples containing 100 and 90% chicken feathers handsheets where 2000 mL/handsheet was used due to the low wood fibre content. The handsheets were made on a Rapid-Kothen Blattbildner sheet former (PTI laboratory equipment, Vorchdrof, Austria). After each handsheet was formed, it was pressed using a sheet press (William Apparatus Co., Watertown, NY). Thereafter all 10 handsheets were pressed in a compression machine for 5 min. The samples were then air dried on a hot plate in the handsheet former machine. Fig. 1 shows a schematic of the process flow diagram for handsheet preparations.

2.3. Characterisation of handsheets

All samples were pre-conditioned and conditioned using Technical Association of the Pulp and Paper Industry/TAPPI standard conditions (23 °C and 50% RH) for 24 h prior to characterisation. Six handsheets were used for each characterisation test.

2.3.1. Canadian standard freeness (CSF)

CSF is a measure of the rate at which a dilute pulp suspension may be drained. It is an important parameter for measuring pulp quality. The freeness of the suspension was determined as per TAPPI T 227 om-99 standard method (TAPPI T227 om-99, 1999) using L& W BK freeness tester (AB Lorentezen and welter, Stockholm Sweden).

2.3.2. Grammage/basis weight

The grammage of a handsheet is defined as the mass per unit area in g/m^2. The ISO 536 standard method was used for basis weight determination (ISO 536:2012, 2012). Five handsheets (area of each sheet was 200 cm^2) were weighed on a balance to the closest 0.01 g, and the total mass of the handsheets recorded. Grammage was then calculated from Equation (1):

$$\textit{Basis weight} = \frac{W}{5} \times 27.56 \qquad (1)$$

2.3.3. Air permeability

The air permeability was measured on a Messmer Büchel Roughness & Air Permeance Tester per ISO 5636-5 standard method (ISO 5636-5:2013, 2013). The differential pressure was noted for samples which exhibited air permeance greater than 5000 mL/min limit. The differential pressure relates to the air permeability of a sample.

2.3.4. Morphological structure

The morphological structure of the handsheets was obtained using low-resolution scanning electron microscope (SEM) (conventional SEM and X-ray microanalysis) – ZEISS, LEO 1450).

2.3.5. Tensile strength

The tensile strength index of the handsheets was tested according to ISO 1924-3 (ISO, 1924-2:2008, 2008). The testing was done on a tensile testing machine maintaining a constant rate of elongation. The tensile strength was then used to calculate the tensile index given in Equation (2):

Fig. 1. Process flow diagram for chicken feather/wood pulp handsheet preparation.

$$\text{Tensile strength index} = \frac{\text{Tensile strength}\,\frac{kN}{m}}{\text{Grammage}\,\frac{g}{m^2}} \quad (2)$$

2.3.6. Bursting strength

The burst index (kPa.m^2/g) of the handsheets was determined with the ISO 2758 (ISO 2758:2014, 2014). The burst index is calculated by Equation (3):

$$\text{Burst index} = \frac{\text{Bursting strength kPa}}{\text{Grammage}\,\frac{g}{m^2}} \quad (3)$$

2.3.7. Tear resistance index

The tear index of the handsheets was measured with the ISO 1974, which are Elmendorf-type methods (ISO, 1974:2012, 2012). The apparatus used was the Elmendorf tear tester. The tear index was calculated using Equation (4):

$$\text{Tearing resistance index} = \frac{\text{Tearing resistance mN}}{\text{Grammage}\,\frac{g}{m^2}} \quad (4)$$

2.3.8. Water absorbent capacity

Water absorbent capacity was measured by cutting a 100 cm^2 sample from the handsheet. After preconditioning and conditioning the cut sheet, its dry weight (W_1) was recorded. The sample was soaked in a 500 mL beaker filled containing ca. 100 mL of water for 10 s. The sample was then removed from the beaker and allowed to drain for 30 s and the wet weight (W_2) recorded. The water absorbance capacity in g/g was determined from Equation (5) (TAPPI T441 om-98, 2013):

$$\text{Specific absorbent capacity} = \frac{W_2 - W_1}{W_1} \times 100 \quad (5)$$

2.3.9. Brightness

The ISO brightness of the handsheet samples were measured using a Zeiss Elrepho 65843 reflectance photometer. In the reflectance photometer, the handsheet samples are illuminated with a C light source CIE illuminant; a daylight illuminant containing a U.V. energy (ISO 2470-1:2009, 2009).

2.3.10. Fourier transform infrared spectroscopy (FTIR) analysis

FTIR analysis of the handsheets was performed using a Fourier Infrared Spectrometer (ATR-Frontier Universal, PerkinElmer) in the absorbance mode. In each case, the spectrum was obtained at a nominal resolution of 4 scans, and the spectrum region was recorded between 4000 cm^{-1} and 550 cm^{-1}.

2.4. Statistical analysis

The characterisations of the handsheets were based on a randomised design with six different chicken feathers to wood pulp combinations. Statistical analysis was done using Statistica 13.0 Stat-Ease, Minneapolis, USA and Origin 9.0 (Origin Laboratory Corporation, Northampton, Massachusetts, USA) software. The handsheet made from 100% wood pulp was designated as a blank handsheet.

3. Results and discussions

3.1. Handsheet preparation

Fig. 2 is a visual comparison of the handsheets that were prepared. Each handsheet sample exhibited two-sidedness; a smooth top and a rough bottom side. The 100% wood pulp handsheet was white in colour, had a rough surface, but did not appear fibrous. It was soft to the touch and easily flexible. With increase in chicken feather content in the handsheet, the uniformity of the handsheet decreased and loose fibres started to appear. The 80/20–100/0% chicken feather/wood pulp handsheets were soft and fluffy in texture, less brittle and very thick compared to the other handsheets. The fibre content was not uniform and varied in colour from light brown to amber colour; the fibres flaked off easily and appeared fibrous. Bonding among the individual fibres of the handsheets appeared loose and showed facile flaking when the chicken feather content was higher than 60%.

3.2. Canadian standard freeness

The CSF of the suspensions decreased from 620 to 330 mL as the chicken feather content increased (Table 1). This affects the drainage of the suspension negatively. Due to the rigidity of the chicken feather, beating is required to improve the freeness of the suspension. This indicates that the blank handsheet (100% wood fibres) has better fines content, interfibre bonding, and flexibility compared to chicken feather fibres that are rigid (Tesfaye et al., 2017). Further studies, entailing beating and refining conditions are required to optimise the fines content and flexibility of chicken feathers.

Fig. 2. Image of chicken feather/wood pulp hand sheet.

Table 1
Properties of chicken feather and wood pulp handsheets.

Feather wood pulp ratio	Freeness (mL)	Basis weight (gsm)	Air permeability (mL/min)	Tensile strength (kN/m)	Bursting strength (kPa)	Tear strength (mN)
0/100	620	65	3893	0.72	40.8	130.0
20/80	600	62	>5000	0.46	41.3	98.2
40/60	610	95.7	>5000	0.44	41.4	105.0
60/40	420	95.7	>5000	0.20	41.5	45.9
80/20	410	121	>5000	0.12	41.6	36.8
100/0	330	231	>5000	0.21	42.7	73.3

3.3. Basis weight

An average value for basis weight of five handsheets, done in duplicate, was obtained and used to calculate the mechanical properties of the handsheets. The grammage of the chicken feather/wood pulp handsheet decreased by comparison to the blank handsheet - this may be due to the low density of chicken feather fractions. This suggests that the wall thickness of chicken feather fractions is very high (Tesfaye et al., 2017) thus resulting in a higher specific volume in the handsheets. The increase in bulk was due to a decrease in the relative bonded area of the chicken feather fractions. This suggests that chicken feathers have a bulk forming property.

3.4. Air permeability

The air permeability values of all chicken feather containing handsheets were similar (>5000) and dramatically greater than that of the blank handsheet (3893) (Table 1). This suggests that the chicken feathers are more porous (Tesfaye et al., 2017) than the wood pulp, thereby allowing more air flow through the handsheets. The lower air permeability of the blank handsheet may be due to the strong fibre-to-fibre bonding and hydrogen bonding that result in a reduced void volume in the sheets (Ren et al., 2009). This implies that there is very little fibre-to-fibre bonding among chicken feather fibres.

3.5. Morphological structure of the handsheets

Fig. 3 shows the SEM images of the blank and chicken feather/wood pulp handsheets. In the blank handsheet, some of the fibres are open and flat; fibre-to-fibre interactions appear high, and in some cases twisted fibre surfaces are visible. These observations support the results presented in Table 1 where the bulkiness and air permeability properties of the handsheet are reduced whereas the tensile, burst and tear strength properties improved relative to those of the chicken feather/wood pulp handsheets. The SEM images show that as the chicken feather content increases, the sheet becomes more open and its porosity increases whereas the fibre-to-fibre interactions decrease. Ultimately this will improve air permeability and bulkiness of the handsheet, whilst reducing its mechanical properties (Hosseinpour et al., 2010).

3.6. Tensile testing

Fig. 4 presents the tensile index data of the chicken feather/wood pulp and 100% wood pulp handsheets. The 100% wood pulp (blank) handsheet showed a significantly higher tensile strength index (about 11 Nm/g) due to better fibrillation and fibre-to-fibre bonding (Fig. 3). Addition of feathers weakened the handsheets significantly. This could be attributed to less hydrogen bonding energy amongst chicken feathers and wood pulp fibres (Fig. 4). These results support the air permeance results presented Table 1, i.e., the higher the air permeance, the weaker the handsheet. The fibre-to-fibre bonding of chicken feather/wood pulp and 100%

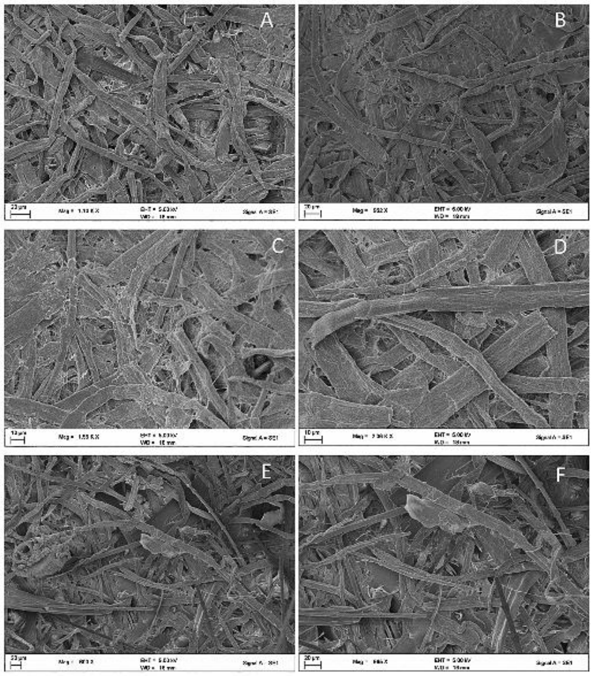

Fig. 3. Images of handsheets with zero beating (A. 100% Eucalyptus B. 20/80, C. 40/60, D. 60/40, E. 80/20 and F. 100/0 chicken feather/wood pulp).

chicken feather handsheet appear low (about 1%) (Fig. 3). This results in reduction of the tensile properties of the handsheet. The tensile energy absorption (TEA) of wood pulp/chicken feather handsheets decreased significantly with increase in chicken feather content (Fig. 4) however beyond 80% chicken feather fraction TEA

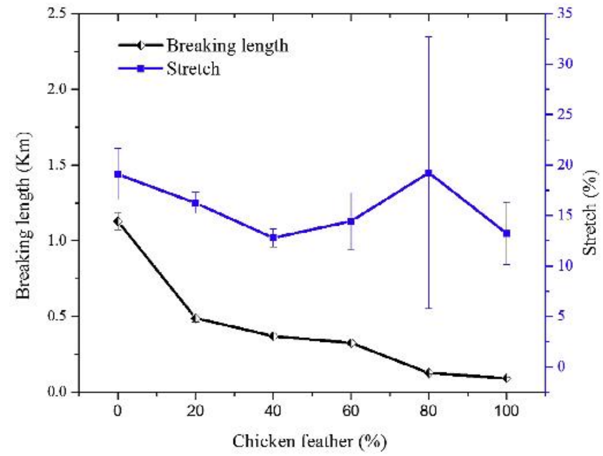

Fig. 5. Breaking strength and stretch properties of the handsheets.

increased due to the uniformity of the handsheet/no weak fibre to fibre interaction will occur because of its similar nature of the fibre. The TEA of chicken feather/wood pulp handsheets decreases (8–44%) as the chicken feather content increases (Fig. 4). This indicates that the energy required to rupture the chicken feather/wood pulp handsheet is lower than that required to rupture the blank handsheet.

The breaking length of the handsheets decreased with an increase in feather content in the sheets (Fig. 5). This result is in agreement with the tensile properties of the handsheet (Fig. 4), as the breaking length is used to characterise the inherent strength of the handsheet. Further studies are required to improve the breaking length and the tensile properties of the chicken feather/wood pulp handsheets. The weak spots and defects of the

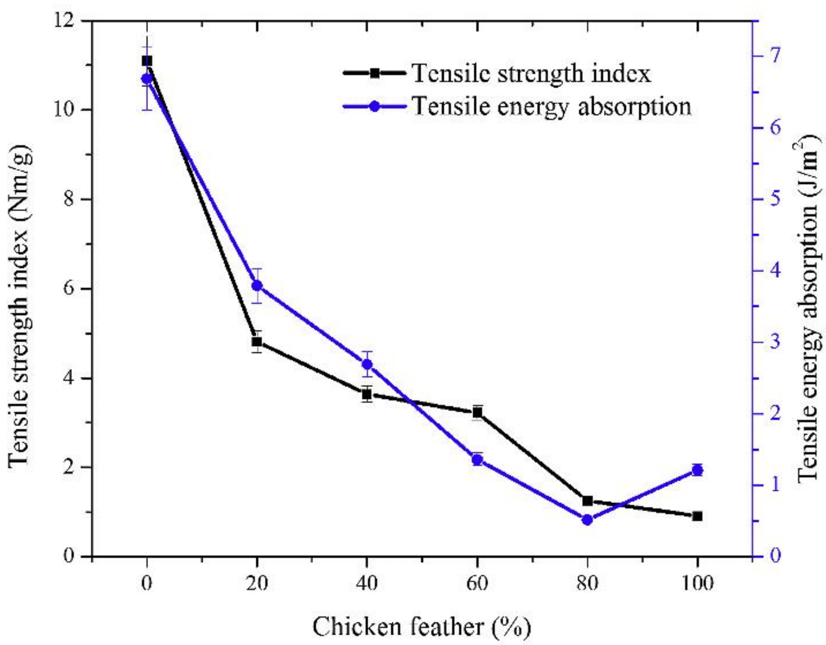

Fig. 4. Chicken feather/wood pulp handsheet tensile strength index and TEA.

handsheets could be minimised by using different feather pulp preparation techniques. High elongation to break together with low bending stiffness is indicative of the ability of paper to conform to the desired contour and therefore is important for creped papers, towels, and bagging. The percentage elongation of a handsheet at the instant of failure is called stretch. The stretch values for all samples are below 2%, with no significant difference among them (Fig. 5). This type of handsheet is typically considered a rigid paper. Handsheet breaking length increased linearly with increasing sheet density and this agrees with a study that chicken feather fibres are less dense than any other fibre (Tesfaye et al., 2017). Handsheet stretch values, on the other hand, decreased by 15 percent (Table 1, Fig. 5). The higher error value at 80% chicken feather content could be due to high variation of the chicken feather properties (Tesfaye et al., 2017) and nonuniform fibre distribution in the sampling position due to the difference in fibre properties like density, fibre cohesion force and others. In general, the greater the stretch and breaking length, the better will be the papermaking qualities of the handsheet.

3.7. Bursting strength

Fig. 6 shows the bursting strength data of the handsheets. The bursting strength decreased with increasing chicken feather content in the handsheet. This indicates that the bursting and tensile strength exhibit similar trends since they both depend on fibre-to-fibre bonding. However, the bursting strength starts increasing at 40% chicken feather content and reaches its highest value (about 2 kPa m^2/g) at 60% chicken feather, and then decreases. This could be due to the higher variability of chicken feather properties and the nonuniformity of the wood and chicken feather distribution in the handsheet.

3.8. Tear index

Tear resistance index depends on flexibility of the handsheet, fibre length, fibre bonding and the total number of fibres (Hosseinpour et al., 2010). The force required to tear paper is much less than the force necessary to break a strip of the paper. Tearing resistance depends strongly on the fibre length since more fibres are pulled out than broken along the length of the fibres in a weakly bonded sheet (Jiménez et al., 2002). The 100% wood pulp hand sheet shows high fibre bonding (SEM image in Fig. 3). This results in a high tear strength (about 2 mN m^2/g) (Fig. 6) and can be considered as a flexible sheet. The flexibility of the sheet is determined by the number of fibres participating in the rupture. The 100% chicken feather handsheet exhibited the lowest tear strength index and can be considered as a rigid sheet (about 0.4 mN m^2/g). The force in the rigid sheet will be concentrated on a few fibres. As the chicken feather content in the handsheet increases, the number of fibres, fibre-fibre bonding and the flexibility of handsheet are reduced and the fibre rupture requires less energy, hence the tear strength is reduced.

3.9. Water absorbent capacity

Fig. 7 shows the water absorbance capacity of the handsheets.

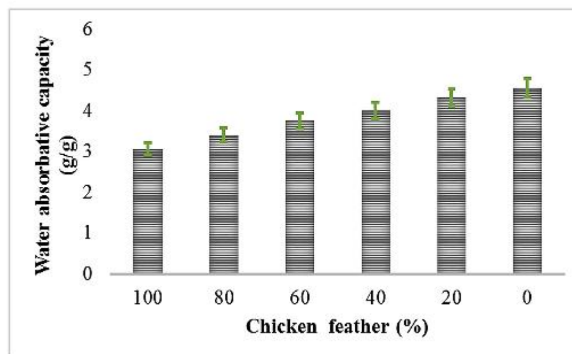

Fig. 7. Water absorbance capacity of chicken feather/wood pulp handsheets.

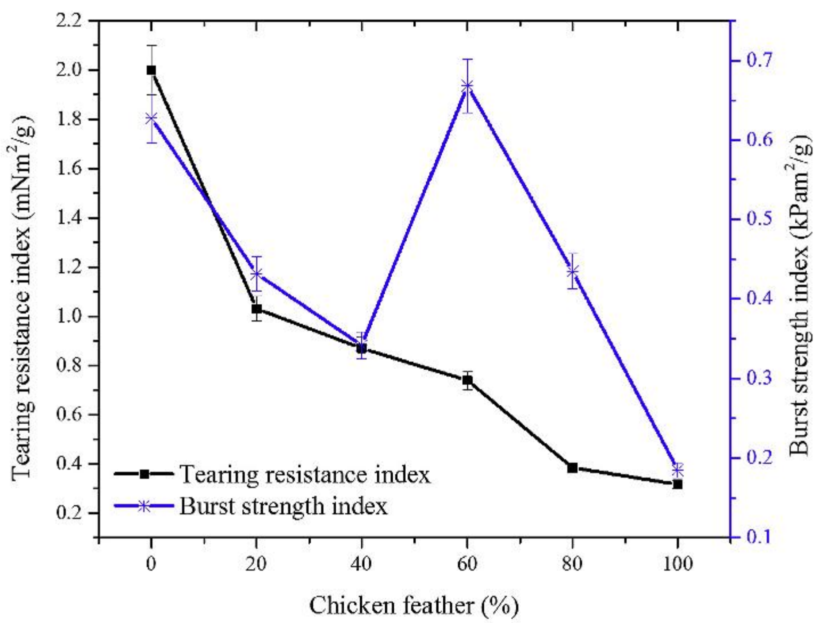

Fig. 6. Chicken feather/wood pulp handsheet burst and tear strength index.

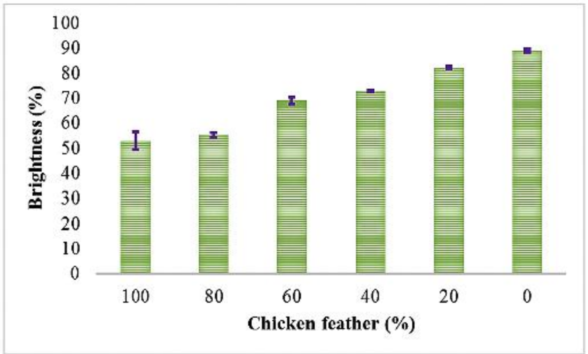

Fig. 8. ISO brightness values of chicken feather/wood pulp handsheets.

Chicken feathers are protein-based animal fibres that show both hydrophobic and hydrophilic tendencies (Tesfaye et al., 2017). The water absorbency capacity of the handsheet decreases as the chicken feather content increases. The reduction in the water retention capacity of the handsheet may be due to the hydrophobic nature of the chicken feather. The water absorbance for the 100% chicken feather sheet decreased approximately 25% when compared to that of the 100% wood pulp sample (Fig. 7). These results will restrict the end use of chicken feather containing papers only for applications that require low water absorbance, e.g., packaging papers.

3.10. Brightness

The ISO brightness values of the handsheet indicated that incorporation of chicken feathers lowered the brightness (Fig. 8). There was a significant difference of about 30% between the blank wood pulp handsheet and the 100% chicken feather handsheet. To improve the brightness property of the chicken feather handsheets, further studies are needed to evaluate the effect of pre-treatment agents such as sodium dodecyl sulphate and hydrogen peroxide or the addition of optical brightening agents.

3.11. Fourier transform infrared spectroscopy (FTIR) analysis

Fig. 9 shows the FTIR spectra of the different handsheets. The 100% wood pulp handsheet shows major peaks of cellulosic fibres whereas the 100% chicken feather handsheet shows major peaks of keratin/proteinaceous fibres. The chicken feather/wood pulp handsheets share the properties of both fibres. The presence of S—S (620 cm^{-1}), C—S (1070 and 1075 cm^{-1}) and N—H (1540 cm^{-1}) groups in the handsheet confirmed the presence of chicken feather fibres. Results in Fig. 2 confirmed that there is an increment of hydrogen bonding for the 100% wood pulp and it decreased as the chicken feather content increased. Hydrogen bonding is a dominant factor contributing to paper strength characteristics. The intensity of the peak at 3200–3600 cm^{-1} is related to the OH vibration: this indicates the numerous hydrogen bonds with the hydroxyl groups of cellulose fibres that result in the higher tensile property of sheets containing wood fibres.

4. Conclusions

From this preliminary study, it is evident that chicken feathers can be incorporated in the paper manufacturing process. The air permeability of chicken feather/wood pulp handsheets was enhanced whereas the bursting strength, tensile index and tear strength were lower than in the 100% wood pulp handsheet. The results show that it is possible to vary the proportion of the chicken feather fibres up to 100% for paper manufacturing. There was no significant difference in water absorbency between the various chicken feather/wood pulp handsheet samples; however, the water absorbency started to decrease above 80% chicken feather content. This could potentially open up a new avenue for the use of chicken feathers in applications that are meant to tolerate high humidity conditions, e.g., packaging products. The paper strength qualities of

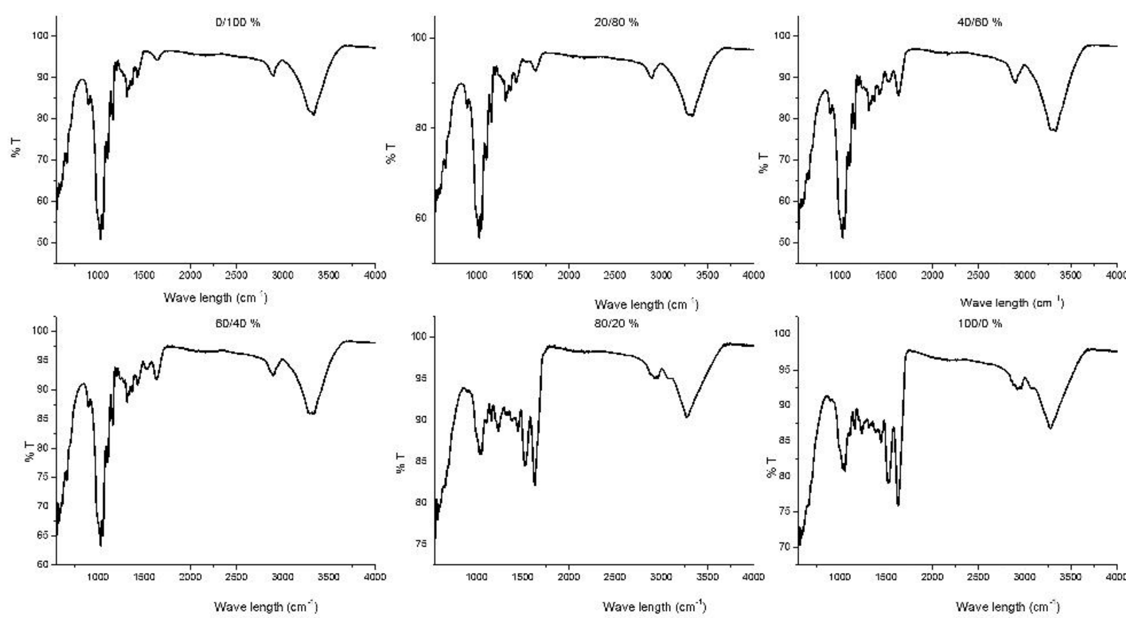

Fig. 9. FTIR spectra of chicken feather/wood pulp handsheets.

the handsheets decreased with increase in chicken fibre content. However, the strength properties could be improved by addition of binders. Indeed, chicken feathers can be beneficiated into binders and these can subsequently be used to enhance the strength of papers containing chicken feathers. The performance of chicken feathers in making paper for mainstream applications will be studied further by varying process parameters (e.g., refining conditions, bleaching conditions, beating condition and change in freeness values) to improve performance characteristics of the papers.

Acknowledgments

The authors are highly grateful for the financial and technical support received from the Thermodynamics Research Unit at, Chemical Engineering at the University of KwaZulu-Natal, the Biorefinery Industry Development Facility, CSIR, and the Department of Science and Technology, Waste Research Development and Innovation Roadmap. Thanks also to Mr. Vishal Bharuth (UKZN) for assisting with the morphological analysis and Mrs. Elsie Sibande (CSIR) for the preparation of the handsheets.

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VALORISATION OF CHICKEN FEATHERS: RECYCLING AND RECOVERY ROUTES

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SUMMARY: The poultry industry generates large amount of feathers as a waste by-product. Small amounts are often processed into valuable products such as feather meal and fertilisers and the remaining waste is disposed of by incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases. Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. A closer look at the structure and composition of feathers shows that the whole part of a chicken feather (rachis and barb) can be used as a source of a pure structural protein called keratin which can be exploited for conversion into a number of high-value bioproducts. Thus, conversion of the waste into valuable products can make feathers an attractive raw material for the production of bioproducts. In this review, possible applications of chicken feathers in a variety of technologies and products are discussed. Their valorisation can result in their sustainable conversion into high-value materials and products on the proviso of existence or development of cost-effective technologies for converting this waste into the useful products.

1. INTRODUCTION

There is a critical need and increasing interest across the world to decrease the consumption of petroleum-based products and to develop bioproducts using renewable and sustainable sources (Robertson, 2012). Many such efforts have already been made and practised in both developing and developed countries. Such efforts are necessary to satisfy the food, clothing, pharmaceutical, automobile, cosmetic, plastic and other basic needs of the future generation. Due to limited fossil resources, the recent focus is to utilise agricultural by-products and co-products as a replacement in industrial applications. These products are inexpensive (waste materials) and environmentally sustainable renewable resources for use in the development of bioproducts. The food and agricultural industries generate massive amounts of wastes. In addition to the food and agricultural wastes produced during agricultural processing, households produce up to 42 % of the waste, 38 % of the generation of the food waste occurs during food preparation, and 20 % is generated along the food processing chain (Baiano, 2014). At present, legislations around the world encourage valorisation of waste and by-products of manufacturing

Proceedings Sardinia 2017 / Sixteenth International Waste Management and Landfill Symposium / 2 - 6 October 2017
S. Margherita di Pula, Cagliari, Italy / © 2017 by CISA Publisher, Italy

processes (Baiano, 2014). This valorisation of waste can be accomplished through the extraction of new value chains from the waste, for example, fibre filaments, polysaccharides, flavour mixes, proteins and phytochemicals, which can be re-utilized in the nutrition, textile, cosmetic, composite materials and pharmacological functional industries (Ambrose and Clanton, 2004).

The chicken meat processing industry is developing at a rapid growth rate all over the world. Reasons for the great pace include efficient feed to weight gain ratio, the fast growth rate of chickens, poultry being a rich source of nutrients for human consumption, fast production time, and low economic value of poultry per unit (Rahayu and Bata, 2015). Almost all sections of the society, encompassing all customs and religions, consume chicken. According to figures available from the USA Foreign Agricultural Service post reports, the total domestic per capita consumption of chickens is 59 kg in the United States; 48.0 kg in Saudi Arabia, 67.1 kg in Hong Kong, 69.7 kg in Israel, and 35.4 kg in Canada (USDA Foreign Agricultural Service, 2014). In South Africa, the consumption rate for chicken in 2011 was 36.27 kg (DAFF, 2014). This large consumption of chicken results in the generation of huge amounts of chicken feathers each year worldwide. Unfortunately, the demand for use of feathers is rather low, and most of them are disposed of by burning, landfilling, or conversion into feather meal and fed to livestock or used as fertiliser (Gurav and Jadhav, 2013).

In this report, we review some possibilities of use and conversion of chicken feathers into high-value products. Since poultry feathers are rich sources of keratin proteins and amino acids, we believe that they are a valuable resource – their valorisation can result in their sustainable conversion into high-value materials and products on the proviso of existence or development of cost-effective technologies for converting this waste into useful products.

2. CURRENT STATUS

2.1 Disposal techniques

2.1.1 Incineration

Incineration is a thermal destruction technology that is one of the most effective methods for destroying conceivably infectious agents. Analysis led by the North Carolina Department of Environment and Natural Resources found that a 57 MW poultry waste burning plant emitted levels of carbon dioxide (CO_2), nitrogen oxides (NO_2), particulate matter (PM), and carbon monoxide (CO) per unit of power generated, that were higher than those for new coal plants (Stingone and Wing, 2011). Thus disposal of feathers by incineration is not ideal.

2.1.2 Burial and controlled landfilling

Burial and controlled landfilling of chicken feathers on farms should be strictly monitored to ensure that there will be no groundwater contamination. Since the operation, monitoring, and control of land filling are tightly regulated, landfilling must be prevented as much as could reasonably be expected because of its unfriendly consequences for the nearby environment, especially the contamination of surface water, groundwater, soil and air. Every one of these measures may increase the expenses of landfilling (Veerabadran et al., 2012).

2.2 Utilisation

2.2.1 Feathers as fertiliser

Feathers contain more than 13 % nitrogen content (Tamrat et al., 2017); this is higher than the best quality blood meal also utilised for such purposes, hence feathers are suitable for compost purposes (Choi and Nelson, 1996). Thus, feathers are used in plant growing operations that require rich nitrogen dressings. Unfortunately, feathers are highly cross-linked with cysteine linkages and difficult to degrade (Park et al., 2000). Their tough, fibrous structure is ineffectively processed by most protein-degrading compounds, however, when blended with compost they degrade well (Gurav and Jahav, 2013). At the point when the feathers are composted, their produced by-products do a reversal as organic matter into the land which further adds to the soil fruitfulness. They form an important poultry composite blend in light of the fact that they add nitrogen, a critical fertiliser component (Veerabadran et al., 2012).

2.2.2 Feather meal as a feedstock

Most feathers are not suitable for the aforementioned applications due to their hazardous nature (presence of microbiological pathogens) and their poor digestibility if land filled. Therefore, the fundamental strategy for feather waste management is their conversion into feather meal to be utilised as feedstock. For the production of feather meal, the rachis of the feathers must be broken down by hydrolysis to make them digestible (Table 1) (El Boushy et al., 1990).

Table 1. Compositions of feather meal (McCasland and Richardson, 1966).

Composition	Percentage
Protein	92.3 % (ranges 70-80 %) as digestible protein.
Moisture	5.9 %
Fat	1.3 %.

3. PHYSICOCHEMICAL PROPERTIES

3.1 Physical properties of chicken feathers

Chicken feathers have the lowest density compared to any other natural or engineered filaments commercially available today. Their low density, low thickness, warmth retention property, high compressibility and strength properties, capacity to absorb sound, and particular morphological structure of their barbs make them remarkable fibres (Tamrat et al., 2017; Saravanan and Dhurai, 2012). Besides the special structure and properties, feathers are cheap (waste material), richly accessible and a renewable resource for protein fibre. A feather is essentially comprised of three units; rachis, barbs and barbules as shown in Figure 1. Rachis is the solid and focal shaft of the feather to which the auxiliary structures, the barbs are joined. In the tertiary structures of the feathers, the barbules are joined to the barbs in such a way that the barbs are attached to the rachis. The lengths of the rachis can be up to 15 cm. The barbs have lengths anywhere in the range of 1 to 4.5 cm, contingent upon their location along the length of the rachis. Individual strands at the base of the rachis are longer than those at the tip (Tamrat et al., 2017).

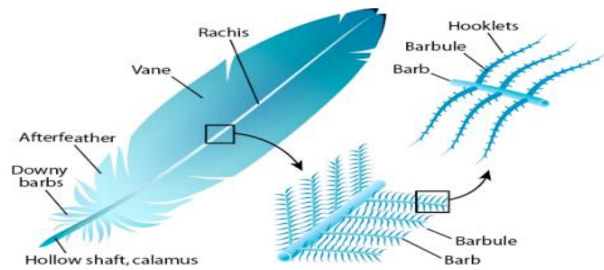

Figure 1. Morphological structure of chicken feathers (Stettenheim, 2000).

3.2 Chemical properties of chicken feathers

Chicken feathers contain approximately 91 % keratin, 1 % lipids, and 8 % water. The amino acid sequence succession of a chicken feather is precisely the same as that of reptilian keratins from claws except for the absence of histidine, lysine, tryptophan, glutamic acid and glycine (Saravanan and Dhurai, 2012). Serine (16 %) is the most abundant amino acid in chicken feathers (Saravanan and Dhurai, 2012).

Keratins are insoluble proteins present in rachis, fleece, hooves, scales, hair, nails (hard keratins) furthermore in the stratum corneum (delicate keratins) (Misra and Kar, 2004). These particular proteins, which belong to the scleroprotein groups, are exceedingly impervious to physical, chemical and biological activities. Mechanical stability and high resistance to proteolytic degradation of keratin is because of the presence of disulphide bonds, hydrogen bonds, salt linkages, and cross linkages (Misra and Kar, 2004).

4. FUTURE VALORISATION PROSPECTS

The costs to the poultry processing industry to dispose their feather waste are increasingly high due to reduced availability of landfill space. It is very likely in future the industry will not be permitted to dispose of the waste in landfills. For example, the South African government has promulgated legislation for proper disposal and waste minimisation. The National Environmental Management enforces generators of waste to deal with their waste according to the hierarchy of waste management in a sustainable way. That is, every industry will need to re-utilise, recycle, minimise, avoid, treat, and, as an alast resort, dispose of waste (Molapo, 2009). Valorisation of waste feathers can take advantage of their chemical constituents, their cheapness (free waste), ease of availability, and potential to offer sustainable procedures for their disposal. Examples of how and where chicken feather waste can be a useful resource are described below.

4.1 Automobile and aeroplane industries

Modern day material science industries are looking for light weight, low cost and biodegradable raw materials for the manufacture of various parts of automobiles and aeroplanes using environmentally sustainable materials. Currently, most automobile and aeroplane parts are made from petroleum-based raw materials. Owing to remarkable strength properties of feathers and their lightweight characteristics (Tamrat et al., 2017), feathers could be used to produce strong lightweight composites for use in automobile and aeroplane industries.

4.2 Textile industry

Scientists are investigating ways to process agricultural and food industry wastes into textile consumer products by replacing natural fibres and man-made fibres. Properties such as high surface area, toughness, flexibility, fine diameter, and durability make chicken feathers valuable resources to replace expensive natural fibres, wood pulp, and synthetic fibres. However, the structural properties of a chicken feather are such that feathers cannot be used as is directly into new products. Even though the whole feather contains keratin, the crystal structure of proteins in barbs is different from that of the rachis (Tamrat et al., 2017; Bonser and Dawson, 1999). Only the barbs have the desirable properties to be used as textile fibre. There are two options to use chicken feathers as a fibre source. The first one is blending chicken feather barb fibres with other fibres for spinning into yarns. This is because chicken feather barbs have fibres that can be processed into yarns (after stripping the barbs from the rachis). The second option could be producing regenerated fibres from the whole chicken feather (Figure 2) after keratin extraction.

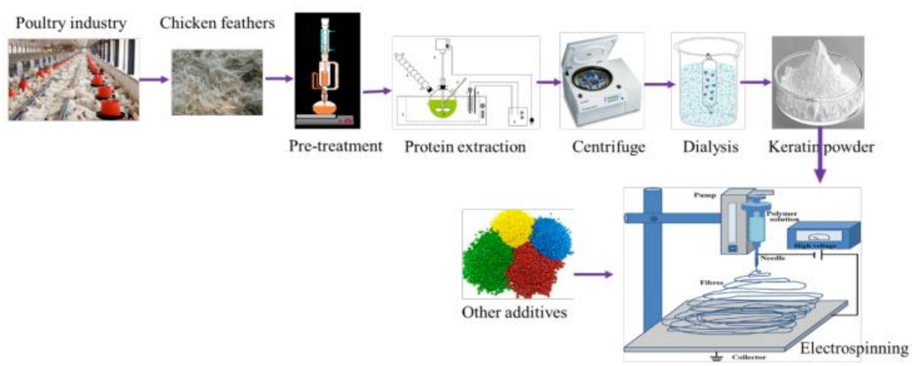

Figure 2. Schematic diagram of regenerated fibre production from chicken feathers.

4.3 Plastic and packaging industries

Researchers are working to discover environmentally sourced sustainable materials to replace fossil-based ones (Jin et al., 2011). One possible route is to utilise renewable waste resources to make biodegradable bioplastics. Feathers are inherently non-thermoplastic and do not melt, but simple alkaline hydrolysis makes them thermoplastic and thus suitable for conversion into films after cross-linking, e.g., using citric acid (Tamrat et al., 2017; Misra, 2004). Another route could be graft polymerization using acrylic monomers to impart thermoplasticity that could allow the feathers to be converted into films (Figure 3). What makes chicken feathers ideal is that they are rich in keratin, a tough natural protein polymer composed of natural monomers. In contrast to other biological sources such as plant proteins and modified starch, keratin based plastics could offer greater strength and tear resistance properties because of the tough keratin protein crystallinity structure.

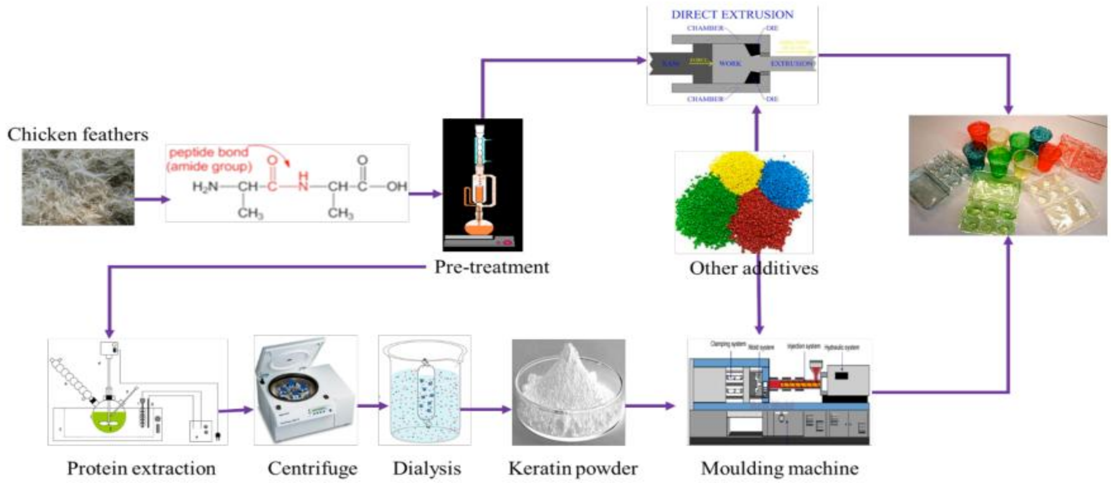

Figure 3. Schematic diagram of bioplastic production from chicken feather

4.4 Bioenergy production

4.4.1 Biogas: Chicken feathers contain high amounts of crude protein, carbon, nitrogen and hydrogen (Tamrat et al., 2017). Proteins are composed of amino acids linked by peptide bonds, which are hydrolysed by proteases upon decomposition. The degradation products include short or branched chain organic acids, NH_3, CO_2 and H_2. Figure 4 shows the process flow for the production of biogas from chicken feather waste.

Figure 4. Schematic process flow of biogas production from chicken feathers

4.4.2. Biofuels: The world man is facing two major challenges: waste disposal and the need for an abundant source of clean energy. A perfect solution to both of these problems could be to turn the waste into energy which could significantly cut carbon emissions while replacing the need for fossil fuels. Soybean, corn, sunflower and cottonseed are the primary sources of renewable energy via biodiesel production. However, the use of these raw materials faces social problems as their use competes with the food market (Demirbas, 2008). Thus, finding alternative non-food raw materials for biofuel production is a priority. Chicken feathers contain substantial amounts of fat that could be processed for the production of biodiesel (Figure 5). This energy from waste could cut carbon emissions by a large percent while replacing the need for large amounts of petroleum.

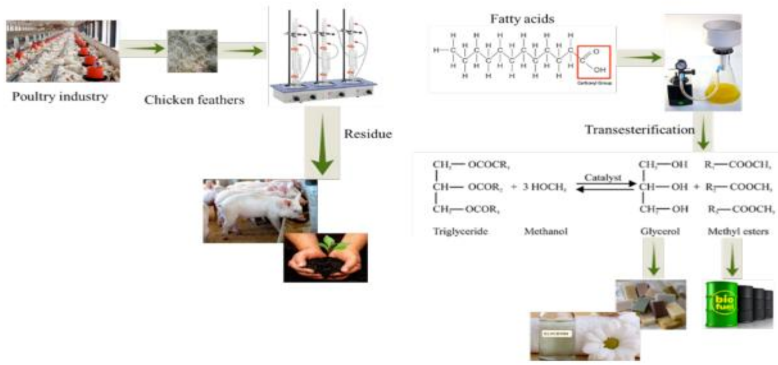

Figure 5. The schematic process flow of production of biofuel from chicken feather

4.5 Biomedical engineering

Acceptability by the human body is the first essential requirement of materials to be used in biomedical applications (Rouse and Van, 2010). Chicken fibres are comprised of 91% keratin protein (Tamrat et al., 2017; Reddy et al., 2014) - this protein is the foundation for various biomedical applications including drug delivery carriers, tissue engineering, and self-assembled nanofibrous scaffolds for medical applications (Figure 6). Chemical, biological and physical properties of chicken feathers make them amenable for conversion into biomaterials for use in biomedical applications. The biomaterials would have desirability such as properties include biodegradability, bioresorbability, biocompatibility, serialisability, functionality, self-assembly, as well as mechanical and thermal properties (Ambrose and Clanton, 2004).

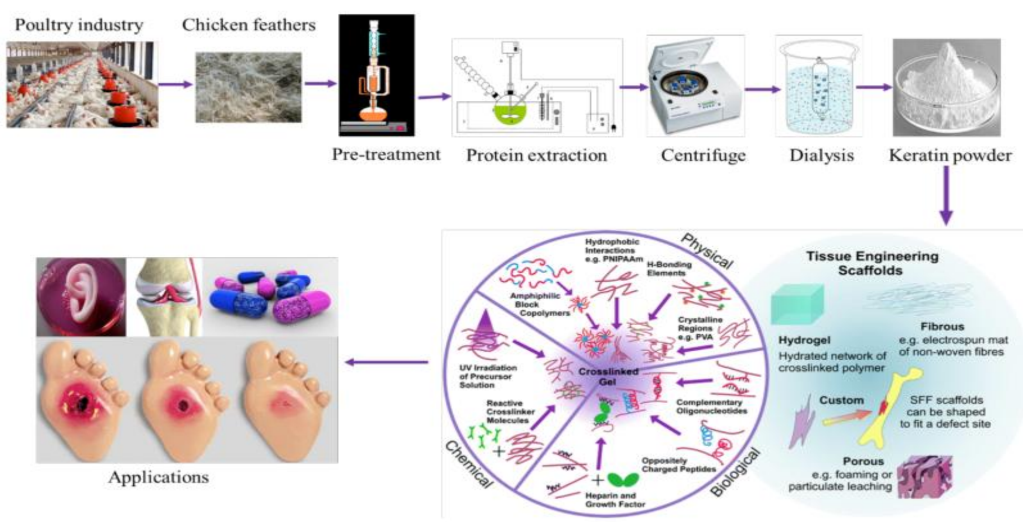

Figure 6. Schematic diagram of biomedical products production from chicken feather

4.6 Enzyme production

Keratinase is a proteolytic enzyme that attacks disulphide bridges to convert keratin from complex to simplified forms (Figure 7) (Villa et al., 2013; Paul et al., 2014). Keratinases are used in a wide variety of applications such as for de-hairing of skins in leather manufacturing, fertilisers, or animal nutrients in the agricultural industry, food supplements in the food industry, textile processing, detergents, and in biomedical and pharmaceutical industries. Thus, chicken feathers could be used as a raw material to produce cheap keratinase enzymes since they contain high protein content, and keratin is the raw material for keratinase.

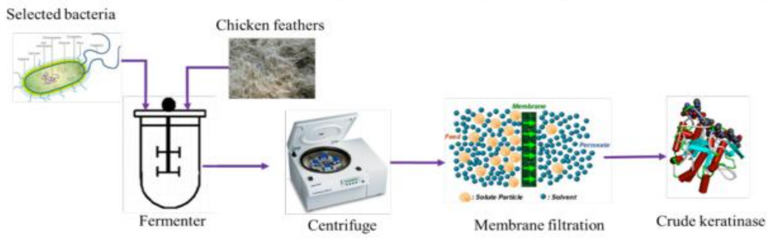

Figure 7. Schematic diagram of keratinase production from chicken feather

5. CONCLUSIONS

Chicken feathers are produced in large quantities as a by-product at poultry processing plants. Their disposal by incineration or landfilling is fraught with problems, e.g., environmental pollution and transmission of diseases due to microbial contamination. However, chicken feathers are composed of materials and components (protein and keratin fibres) that can be valorised into a large and diverse variety of valuable products and materials. Using waste chicken feathers to extract high-value materials such as keratin proteins and fibres will minimise environmental pollution as well as reduce reliance on the use of petroleum based products. Extensive research and development work is required to develop appropriate technologies for their full utilisation as a resource for the proposed applications mentioned in this review.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the South African Department of Science and Technology, UKZN Thermodynamics research unit, and the Biorefinery Industry Development Facility at the CSIR for support of this research.

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APPENDIX B

OTHER POPULAR PUBLICATIONS

CSIR CELEBRATING 70 Years Ideas that work
our future through science

The Council for Scientific and Industrial Research (CSIR) in South Africa is one of the leading scientific and technology research, development and implementation organisations in Africa. It undertakes directed research and development for socio-economic growth.

Making smart use of the world's excess of chicken feather waste

The CSIR is looking at extracting keratin from chicken feathers for the production of various high-value products such as nanostructure materials for biomedical applications, regenerated fibres for textiles, production of composite materials or technical textiles and as ingredients for use in the cosmetic industries.

Tamrat Tesfaye holds untreated chicken feathers in his right hand, and the treated, pure white feathers in his left hand.

Due to the high rate of consumption of chicken worldwide, more than five billion tonnes of chicken feathers are generated each year around the world. Unfortunately, the demand for the reuse or recycling of feathers is very low. As a result most of the world's chicken feathers are burned as waste, buried or grounded and fed to livestock. In South Africa, the situation is much the same with most feathers either burnt or processed into fertiliser meal. Until now, hardly any attention has been paid to valorisation of this waste material.

"Currently, chicken feathers are mainly viewed as useless waste," says Tamrat Tesfaye, a University of KwaZulu-Natal (UKZN) PhD student working under the supervision of CSIR researcher, Prof. Bruce Sithole and UKZN's Prof. Deresh Ramjugernath.

"Chicken feathers, however, are actually rich sources of keratin proteins and amino acids. "My research is aimed at extracting keratin proteins from the chicken feathers for the production of various high-value products."

Using the feathers for anything is difficult because of their rigid protein structure. This led Tesfaye to question whether protein can be extracted from the feathers and used in the production of valuable products.

When an industry's by-product turns out to be as valuable as its primary products

"The extraction of usable proteins from chicken feathers will solve the disposal problem and generate additional income for the poultry industry, resulting in the creation of new industries specialising in the processing of feathers," says Tesfaye.

Feathers comprise approximately 10% of a mature chicken's body weight. For the South African poultry industry, burning the feathers or converting them into fertilisers is an energy-intensive and costly process. Chicken feathers are hazardous waste materials that pose human and environmental health risks, as they may contain viruses and bacteria. "Why can we not take this 'valueless' material and convert it into high value products?" asks Tesfaye.

Extracting keratin from chicken feathers

Pre-treated and decontaminated chicken feathers, ready for keratin protein extraction.

Upon receiving the untreated chicken feathers from the poultry industry, Tesfaye proceeds to pre-treat the feathers using a variety of methods including organic and inorganic pre-treatment techniques, until the feathers are free from any debris adhering to the surface of the feathers, and are decontaminated in respect of bacteria and viruses. Thereafter, keratin proteins are extracted and characterised for their physical and chemical properties. The extracted keratin will be used for the production of high value materials and products. Due to their moisturising properties, the keratin protein could be incorporated into shampoos and conditioners, hair-loss products and hair thickening accessories.

After regeneration of the keratin fibres via electro-spinning, the fibres can be used in various other applications such as synthetic fibres in textile production, thus leading to the development of textile materials based on environmentally sustainable materials - replacing some percentage of widely used petroleum-based synthetic fibres.

"Wool fibre is 90% keratin, so it is possible to regenerate the feathers into fibres to produce clothes," explains Tesfaye. "Thus, in the near future, we might be wearing clothes made from regenerated chicken-feather fibres."

Natural fibre-reinforced polymer composites have attracted a great deal of attention and interest among materials scientists and engineers due to the considerations of developing environmentally friendly materials and partly replacing currently used glass or carbon fibres in fibre-reinforced composites. Natural fibres such as those extracted from feathers have huge potential in this market. Being lightweight and strong, they can be used to make natural fibre-reinforced polymer composites with applications in the military, automotive industry and space engineering industries.

Waste chicken feathers should be viewed as a valuable resource that can increase the viability of the country's farming industry. "Their valorisation will also have a positive environmental impact," says Tesfaye.

The chicken feathers are dispensed into different chemicals for pre-treatment and decontamination.

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THE MERCURY

ANIMAL FEED TRADER ACCUSED OF FLEECING SARS

R800m fraud exposed

Tania Broughton

A "SHAMELESS" R800 million tax fraud committed by a trader in animal feed has been exposed in a case before the high court in which a Durban businessman is accused by Sars of being a "co-wrongdoer", who should be made to repay the R41 million he allegedly got out of the deal.

But the businessman – Jacques Sassin, owner of Trojan Seeds Pty Ltd and former co-owner and employee of Benietha Veevoere Pty Ltd – has denied playing any role in what Durban High Court Judge Rishi Seegobin labelled "an extraordinary grand-scale fraud".

In a recent judgment, Judge Seegobin said Sassin's denials could not be rejected as being "far-fetched".

He also slammed Sars for attempting to get a money judgment against Sassin through hearsay evidence from a confidential inquiry which he said could not be used as it would give Sars an "unfair advantage".

He referred the matter to trial where he said Sassin would get an opportunity to cross-examine his accusers and give evidence to clear his name.

"Whilst I have no difficulty in principle regarding the important public function Sars is required to perform in collecting taxes, I do have a difficulty when it sets out to achieve its aims in an unfair, unconstitutional and prejudicial manner," the judge said.

Insolvent

The main player in the fraud, the judge said, was one Petrus Johannes Uys Badenhorst who traded as SA Global Trading. He owed Sars more than R800 million but was "insolvent" and there was no hope of recovering anything from him.

So the revenue service turned its sights on Sassin, alleging he was a party to Badenhorst's VAT fraud scheme which he perpetrated through the use of a valid certificate entitling him to buy feed at a zero VAT rate for his own use, but not for trading.

Sassin worked as a trader for Benietha, buying and selling animal feed products, and occasionally did business with Badenhorst's "small one-man enterprise".

"The volume of trade was low … but things changed in 2012 and, after a meeting in a restaurant, the volume of trade escalated with both dealers buying and selling the same quantities of feed from each other during the same periods," the Judge said. "Sars said this was strange. Firstly because Benietha sold the feed to SA Global and then bought it back at a lower price, causing SA Global to make a loss."

The transactions, which involved the use of the zero VAT rate certificate by SA Global when it bought the feed, led to Benietha being able to claim back huge refunds from Sars calculated on "artificial volumes". Sars alleged Sassin paid these tax refunds to Badenhorst and in return got "sizeable rewards" paid into the account of Trojan Feeds to avoid detection by the co-owners of Benietha.

When Sars caught up with Badenhorst, he claimed he had paid Sassin about R65 million. Sassin agreed to pay back Badenhorst so he could pay Sars, but after Sassin repaid R24 million, Sars froze Badenhorst's bank accounts, preventing further repayment. This left R41 million still owing which, Sars alleged, was "secret profits" and claimable.

Sassin, through his legal team, said the application was an abuse of the court process because Sars was attempting to rely on untested evidence obtained in the (section 50) inquiry probing the fraud.

He said the legal route taken by Sars in this matter – to ventilate via court papers rather than oral evidence – was not suitable in deciding a disputed issue of whether fraud was committed.

Having A Whale Of A Time

This photograph from last month, provided by the US National Oceanic and Atmospheric Administration Fisheries, shows a female orca and her two offspring in the Puget Sound along the north-west coast of the US.

State biologists flying a drone have taken thousands of images of endangered Puget Sound orcas, showing that the whales are in good condition this year and several appear to be pregnant. The fisheries are responsible for stewardship of US ocean resources and habitats. They oversee the maintenance of productive and sustainable fisheries, safe sources of seafood, conservation of protected resources, and healthy ecosystems. PICTURE: AP

UKZN 'Chickenman' could be on to new uses for feathers

Tony Carnie

DOUBLE, double toil and trouble; fire burn, and cauldron bubble …

There are no eyes of newts, toes of frogs or poisoned entrails being tossed into chemical beakers in this University of KwaZulu-Natal chemical laboratory.

Nor any Shakespearean witches or thunder.

Instead, dressed in a clean white lab coat, Durban chemical engineering student Tamrat Tesfaye is busy disinfecting and dissolving piles of old chicken feathers as part of an experiment to produce chicken-feather shirts and socks, chicken-feather automotive parts, chicken-feather shampoos and chicken-feather who knows what.

Tesfaye, who is also a lecturer at the Institute of Textile and Fashion Technology at Bahirdar University in Ethiopia, is studying for his PhD at UKZN under the supervision of CSIR researcher Professor Bruce Sithole and UKZN's Professor Deresh Ramjugernath.

Worldwide, the chicken industry generates more than five billion tons of feathers each year – most of which are burnt, buried or crushed up into fertiliser.

"Currently chicken feathers are mainly seen as useless waste. So why not try to turn this 'waste' into something of value?" Tesfaye asks.

Things like chicken-feather suits, chicken-feather cosmetics or chicken-feather biofuels.

"Chicken feathers are actually rich sources of keratin proteins and amino acids, and my research is aimed at extracting keratin proteins and turning them into high-value products."

Because of their moisturising properties, the keratin proteins could also be incorporated into shampoos and conditioners and hair-loss products. Chicken feathers, much like woollen fibres which are 90% keratin, could also be spun into fibre.

"Thus in the near future we might be wearing clothes made from regenerated chicken-feather fibres," he declares.

Being lightweight and strong, Tesfaye believes, the fibres could also be useful in making fibre-reinforced polymers for aircraft, cars or the space engineering industry.

But when the feathers arrive from the chicken broilers they are contaminated with viruses and bacteria and must be decontaminated before keratin proteins can be extracted.

Tesfaye also thinks they could be used as substitutes in the paper and filter industry.

● Tesfaye can be reached at tamrat_tsfy@yahoo.com.

Lecturer and chemical engineering student Tamrat Tesfaye has big plans to turn chicken feathers into a variety of new products, including chicken-feather suits and aircraft industry components. PICTURE: GCINA NDWALANE

School graft 'often involves principals'

Leanne Jansen

OF MORE than 1 000 complaints of corruption at schools lodged with Corruption Watch since 2012, principals were implicated in wrong-doing in 54% of the cases.

In a report released yesterday, the anti-graft organisation said that from the cases reported to it a pattern of collusion between school governing body members and teachers had also emerged.

The province with the second-highest number of complaints of corruption at schools (17%) was KwaZulu-Natal, behind the Free State with 18%.

David Lewis, executive director of Corruption Watch, said that, while the individual amounts of money involved seemed small, the impact on the lives of disadvantaged pupils was immense.

"(It is) the difference between an extra classroom and overcrowded classrooms.

"And it is in these acts of petty corruption that ordinary people form their impressions of the public sector and democratic institutions – whether they are to be trusted or not," he said.

The types of corruption ranged from withdrawing money from the school bank account without consulting the school governing body and inflating the number of pupils at the school to get a bigger government subsidy to demanding fees at a no-fee school.

The most common type of tender corruption perpetrated was awarding contracts to friends and family members of the principal, or members of the school governing body.

The Corruption Watch report said it was important that parents insist on knowing:

● How much money the school had been allocated by the Education Department to the school.

● Who had been appointed to independently audit the school's financial statements.

● The school budget, and the school's expenditure at the end of the year.

Anthony Pierce, provincial head of the National Professional Teachers Organisation of SA, said he believed the figures provided by Corruption Watch were on the mark.

He estimated that one in four KZN schools was battling financial mismanagement and urged all parents to become involved in running schools.

Dates for matric marking and results released

Leanne Jansen

FOR 1 882 KwaZulu-Natal matrics, today marks the end of the first week of the final exams for Independent Examinations Board pupils.

This year 10 228 IEB full-time candidates are writing the final exams, compared with 9 976 last year.

Anne Oberholzer, the IEB chief executive, said yesterday that marking of exam scripts would begin on December 6, and results were expected to be released on December 31.

The official exam calendar for all other matrics begins on Monday with English, consumer studies, and hospitality studies, and concludes with visual arts and music comprehension on November 27.

Basic Education Minister Angie Motshekga will reveal the national matric pass rate and results of the provinces on January 5. Results will be available to pupils on January 6.

The KwaZulu-Natal Education Department said last week that it was attempting to reach an 83% matric pass mark.

However, there are more KZN pupils (171 820) writing matric this year than there were last year (148 925).

The list of more than 8 000 exam script markers was audited twice this year, by exam quality watchdog Umalusi, then by the Basic Education Department. Marking will begin on December 2.

The National Professional Teachers Organisation of South Africa (Naptosa) issued a statement yesterday to wish the class of 2015 good luck. Its president, Basil Manuel, said it was important to acknowledge contributions of teachers of every grade, particularly Grade 12. He said the preparations of education authorities for the matric exams had been "exemplary".

"Naptosa wishes to encourage all learners and officials to act with integrity and not compromise the credibility of the National Senior Certificate examination," he said.

Zuma welcomes Nyusi

PRESIDENT Jacob Zuma welcomed Mozambican President Filipe Nyusi to the country yesterday and announced the launch of the South Africa-Mozambique Binational Commission.

Addressing Nyusi, Zuma expressed his delight that the Mozambican president was able to come to the country on his first state visit, and gave him a warm welcome.

Zuma spoke of the rich history both countries shared in terms of history, geography, culture, people and family ties. He recalled the words of former Mozambique president Samora Machel: "We are one people."

He said that Mozamibique was one South Africa's top trading partners, and noted how trade and investment between the two countries over the past decade had "grown exponentially" with a 50% increase.

Zuma said: "Today we launched the South Africa-Mozambique Binational Commission chaired by the two heads of state, a strategic mechanism through which we will structure our relations going forward". ANA

Converting chicken feathers into high-value materials

The CSIR, in conjunction with University of KwaZulu-Natal PhD student **Tamrat Tesfaye**, is conducting research into turning feather waste from chicken production into useful materials.

A total of 96 million tons of chicken meat were produced worldwide in 2014, an 1,6% increase over 2013, according to the Food and Agriculture Organisation (FAO). This chicken consumption generates vast quantities of feathers – more than five million tons a year. Unfortunately, the demand for recovery, reuse or recycling of feathers is low, and most end up being burned, buried or ground up as feed for livestock.

The CSIR is currently conducting research into extracting keratin protein from chicken feathers for the production of various high-value products such as nanostructure materials for biomedical applications, regenerated fibres for textiles, production of composite materials, production of technical textiles, and ingredients for the cosmetics industry.

In South Africa, the feathers are simply burnt, with some parts processed into fertiliser meal, an energy-intensive and costly process. Until now, little attention had been paid to converting this waste material into useful products.

ABOVE: Chicken feathers are immersed in various chemicals for pre-treatment and decon-tamination. PHOTOS COURTESY OF CSIR

"Currently, chicken feathers are mainly viewed as useless waste. However, they're a rich source of keratin protein and amino acids," says Tamrat Tesfaye, a PhD student at the University of KwaZulu-Natal (UKZN), working under the supervision of CSIR researcher Prof Bruce Sithole and UKZN professor Deresh Ramjugernath.

"My research is aimed at extracting keratin proteins from the chicken feathers for the production of high-value products."

The current uses for chicken feathers have only marginal economic value and disposal of the rest presents a challenge. Furthermore, the feathers' rigid protein structure makes them difficult to use. Extracting keratin proteins from the feathers and using them in the production of high-value materials will solve the disposal problem and generate additional income for the poultry industry, while creating new industries that specialise in processing feathers, Tesfaye explains.

FEATHER PROCESSING

One disadvantage of chicken feathers is that they can harbour viruses and bacteria that pose serious human and environmental health risks. They are therefore regarded as hazardous waste materials and careful disposal is required.

When Tesfaye receives the untreated chicken feathers from the poultry industry, he pre-treats them using organic and inorganic pre-treatment techniques to remove debris adhering to their surfaces. He then decontaminates them to remove any bacteria and viruses. Finally, he extracts the keratin proteins and characterises them according their physical and chemical properties.

KERATIN APPLICATIONS

Due to its moisturising properties, the extracted keratin protein could be incorporated into shampoo and conditioner, hair loss concealing products, or hair thickening accessories.

After the keratin fibres are regenerated through electro-spinning, the fibres can then be used in applications such as synthetic fibres in textile production. This could result in the development of environmentally sustainable textiles that could replace petroleum-based synthetic fibres.

"Wool fibre is 90% keratin, so I can regenerate the feathers into fibres to produce clothing," explains Tesfaye, who is based at the CSIR biorefinery centre in Durban. "Thus, in the near future, we'll be wearing clothes made from regenerated feather fibres."

TAMRAT TESFAYE

CHICKEN FEATHERS CAN BE USED TO MANUFACTURE NATURAL FIBRE-REINFORCED POLYMER COMPOSITES

Natural fibre produced from reinforced polymer composites have attracted a great deal of interest from materials' scientists and engineers in their quest to develop environmentally friendly materials. These could in future partly replace the glass or carbon fibres currently used in fibre reinforced composites.

Natural fibres such as those extracted from feathers have great potential in this market. Being lightweight and strong, they can be used to manufacture natural fibre-reinforced polymer composites with applications in the military, automotive and space engineering industries.

Chicken feathers, currently merely a by-product of poultry production, could therefore become a valuable resource that could extend the viability of South Africa's poultry industry.

• *Email Ryhana Mahomed at the CSIR at RMahomed@csir.co.za.* **FW**

ABOVE: Pre-treated and decontaminated chicken feathers ready for keratin protein extraction.

FW

Valorisation of chicken feathers into high-value materials

The consumption of chicken worldwide is very high. All this chicken consumption results in the generation of large amounts of chicken feathers – more than five billion tonnes each year around the world. Unfortunately, the demand for recovery, reuse or recycling of feathers is very low – most of them are burned, buried or grounded and fed to livestock. The CSIR is looking at extracting keratin from chicken feathers for the production of various high-value products such as nanostructure materials for biomedical applications, regenerated fibres for textiles, composite materials, technical textiles and as ingredients for cosmetic industries.

In South Africa, the feathers are simply burnt and some parts are processed into fertiliser meal. Until now, hardly any attention has been paid to valorisation of this waste material. 'Currently, chicken feathers are mainly viewed as useless waste,' says Tamrat Tesfaye, 'However, they are rich sources of keratin proteins and amino acids'.

'My research project is aimed at extracting keratin proteins from the chicken feathers for the production of high-value products'. Tesfaye is a University of KwaZulu-Natal (UKZN) PhD student, under the supervision of CSIR researcher, Professor Bruce Sithole and UKZN Professor Deresh Ramjugernath.

Worldwide, chicken feathers are considered to be waste. Their current uses are marginally economic and their disposal difficult. Furthermore, using the feathers for anything is difficult because of their rigid protein structure. This led Tesfaye to question whether protein can be extracted from the feathers and used in the production of valuable products.

What happens when an industry's by-product turns out to be as valuable as its primary products?

'Such conversion will solve the disposal problem and generate additional income for the poultry industry and the creation of new industries specialising in the processing of feathers,' says Tesfaye. Feather comprises approximately 10% of a mature chicken's body weight. The South African poultry industry either burns the feathers or converts them into fertilisers – the latter being energy intensive and a very costly process.

Chicken feathers are hazardous waste materials as they may contain viruses and bacteria, thus they require proper and careful disposal as they pose serious human and environmental health risks. 'Why can we not take this "valueless" material and convert it into high-value products?' asks Tesfaye.

Extracting keratin from chicken feathers

After receiving the untreated chicken feathers from the poultry industry, Tesfaye pre-treats the feathers using a variety of methods including organic and inorganic pre-treatment techniques, until the feathers are free from any debris adhering to the surfaces of the feathers and decontaminated from bacteria and viruses. Thereafter, keratin proteins are extracted and characterised for their physical and chemical properties. Finally, the extracted keratin will be used for the production of high-value materials and products. Because it has moisturising properties, the keratin protein could be incorporated into shampoo and conditioner, hair-loss concealing products and hair-thickening accessories.

After regeneration of the keratin fibres via electro-spinning, the fibres can be used in various applications such as synthetic fibres in textile production, leading to the development of textile materials based on environmentally sustainable materials and replacing some part of petroleum-based synthetic fibres. 'Wool fibre is 90% keratin, so I can regenerate the feathers into fibres to produce clothes,' explains Tesfaye, who is based at the CSIR biorefinery centre in Durban. 'Thus, in the near future, we will be wearing clothes made from regenerated feather fibres.'

Natural fibre-reinforced polymer composites have attracted a great deal of attention and interest among materials scientists and engineers due to the considerations of developing environmentally friendly materials and partly replacing currently used glass or carbon fibres in fibre-reinforced composites. Natural fibres such as those extracted from feathers have huge potential in this market. Being lightweight and strong, they can be used to make natural fibre-reinforced polymer composites that can have applications in the military, automotive industry and space engineering industries.

Waste feathers should be viewed as a valuable resource that can increase the viability of the country's farming industry. Their valorisation will have a positive environmental impact.

Issued by Reyhana Mohamed, CSIR

The chicken feathers are dispensed into different chemicals for pre-treatment and decontamination. Image: CSIR

Tamrat Tesfaye holds untreated chicken feathers in his right hand, and the treated, pure white feathers in his left hand. Image: CSIR

Pre-treated and decontaminated chicken feathers, ready for keratin protein extraction. Image: CSIR

CAPE TIMES

IOL

Seeking good uses for chicken feathers

NEWS / 26 OCTOBER 2015, 07:00AM / TONY CARNIE

Tony Carnie

DURBAN: Double, double toil and trouble; fire burn and cauldron bubble…

There are no eyes of newts, toes of frogs or poisoned entrails being tossed into chemical beakers in this University of KwaZulu-Natal chemical laboratory.

Nor any Shakespearean witches or thunder.

Instead, dressed in a clean white lab coat, Durban chemical engineering student Tamrat Tesfaye is busy disinfecting and dissolving piles of old chicken feathers as part of an experiment to produce chicken feather shirts and socks, chicken feather automotive parts, chicken feather shampoos and chicken feather who knows what.

Tesfaye, who is also a lecturer at the Institute of Textile and Fashion Technology at Bahirdar University in Ethiopia, is studying for his PhD at UKZN under the supervision of CSIR researcher Professor Bruce Sithole and UKZN's Professor Deresh Ramjugernath.

Worldwide, the chicken industry generates more than 5 billion tons of feathers each year – most of which are burnt, buried or crushed up into fertiliser.

“Currently, chicken feathers are mainly seen as useless waste. So why not try to turn this ‘waste’ into something of value?” Tesfaye asks.

Things like chicken feather suits, chicken feather cosmetics or chicken feather biofuels.

“Chicken feathers are actually rich sources of keratin proteins and amino acids, and my research is aimed at extracting keratin proteins and turning them into high-value products.”

Because of their moisturising properties, the keratin proteins could also be incorporated into shampoos and conditioners and hair-loss products. Chicken feathers, much like woollen fibres which are 90 percent keratin, could also be spun into fibre.

“Thus in the near future, we might be wearing clothes made from regenerated chicken feather fibres,” he declares.

Being lightweight and strong, Tesfaye believes, the fibres could also be useful in making fibre-reinforced polymers for aircraft, cars or the space engineering industry.

But when the feathers arrive from the chicken broilers, they are contaminated with viruses and bacteria and must be decontaminated before keratin proteins can be extracted.

Tesfaye also thinks they could be used as substitutes in the paper and filter industry.

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UNIVERSITY OF KWAZULU-NATAL INYUVESI YAKWAZULU-NATALI

UKZNDABAonline
Your Campus Electronic Newsletter

19 November 2015 Volume: 3 Issue: 52

Mr Tamrat Tesfaye in the lab.

Chemical Engineering PhD Student Discovers Innovative Solutions to Poultry Waste

BY: .

A PhD candidate in UKZN's School of Engineering and a Lecturer at the Ethiopian Institute of Textile and Fashion Technology at Bahir Dar University (EiTEX/BDU) in Ethiopia, Mr Tamrat Tesfaye, is researching innovative ways to turn billions of tons of feather waste from the poultry industry into useful products through the extraction of keratin.

Chicken feathers discarded during the production of poultry for human consumption is a big problem, since chicken feathers can pose hazards to human and environmental health as they often contain viruses and bacteria.

There is little demand for waste chicken feathers and most poultry producers dispose of more than five billion tons of feathers produced annually worldwide by burying or burning the feathers, or grinding them up for addition to livestock feed. Burning is the most common disposal technique, and can result in the release of 50 times more carbon dioxide than the coal industry.

Tesfaye, realising that feathers are a rich source of amino acids and keratin proteins, decided there had to be a better, more effective way of valorising these by-products.

He explained that proteins could be extracted from the feathers through a process involving (1) organic and inorganic chemical pre-treatment techniques to decontaminate the feathers, (2) extraction and characterisation of the keratin proteins, and (3) regeneration of keratin polymer for the production of valuable products using nanotechnology.

In This Issue

'We plan to transform chicken feathers into valuable products to be used in the automobile and aeroplane industries, textile and clothing industries, cosmetics, biomedical engineering applications, construction, plastics and packaging, geotextiles, biofuels and hydrogen storage,' said Tesfaye.

Keratin extracted from the feathers could be used as an ingredient in hair products due to its moisturising properties as well as being the source of synthetic fibres for the production of textiles, a more sustainable alternative to petroleum-based synthetic fibres.

According to Tesfaye, some textile fibres, like wool, are manufactured predominantly from keratin, making this use highly feasible.

'In the near future, we might find ourselves wearing clothes made from regenerated chicken feather fibres, or driving cars made from chicken feathers,' said Tesfaye.

He says scientists are also looking for lightweight, cheap and strong materials for use in the construction of the body and interior parts of automobiles and aeroplanes, to reduce energy consumption.

Aside from solving a considerable disposal problem, Tesfaye's research could generate additional income for the poultry industry alone. This process could also open up new opportunities for entrepreneurs to process the raw product into these valuable components.

Tesfaye's research is being undertaken with the Council for Scientific and Industrial Research (CSIR), and is being supervised by Dr Bruce Sithole of the CSIR and Professor Deresh Ramjugernath of Chemical Engineering at UKZN.

Christine Cuénod

Multilingual Communities

- UKZN co-hosts Workshop with the Competition Commission and CRESSE
- Writing Place awards for College of Humanities Students

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Making smart use of the world's excess chicken feather waste

Making smart use
of the world's excess chicken feather waste

The Council for Scientific and Industrial Research (CSIR) is looking at extracting keratin from chicken feathers for the production of various high value products such as nanostructure materials for biomedical applications, regenerated fibres for textiles, production of composite materials, or technical textiles, and as ingredients for use in the cosmetic industries.

Due to the high rate of consumption of chicken worldwide, more than five billion tonnes of chicken feathers are generated each year. Unfortu- nately, the demand for the reuse or recycling of feathers is very low. As a result, most of the world's chicken feathers are burned as waste, buried or grounded and fed to live- stock. In South Africa, the situation is much the same with most feathers either burnt or processed into fertiliser meal. Until now, hardly any atten- tion has been paid to processing this waste material.

'Currently, chicken feathers are mainly viewed as useless waste,' says Tamrat Tesfaye, a University of KwaZulu-Natal (UKZN) PhD student working under

Tamrat Tesfaye holds untreated chicken feathers in his right hand, and the treated, pure white feathers in his left hand.

the supervision of CSIR researcher, Prof Bruce Sithole and UKZN's Prof Deresh Ramjugernath. 'Chicken feathers, however, are actually rich sources of keratin pro- teins and amino acids. My research is aimed at extracting keratin proteins from the chicken feathers for the production of various high-value products,' he says.

Using the feathers for anything is difficult because of their rigid pro- tein structure. This led Tesfaye to question whether protein can be

The chicken feathers are dispensed into different chemicals for pretreatment and decontamination.

extracted from the feathers and used in the production of valuable products.

Industry's by-product as valuable as primary products

'The extraction of usable proteins from chicken feathers will solve the disposal problem and generate additional income for the poultry industry, resulting in the creation of new industries specialising in the processing of feathers,' says Tesfaye. Feathers comprise approx- imately 10% of a mature chicken's body weight. For the South African poultry industry, burning the feathers or converting them into fertil- isers is an energy-intensive and costly process. Chicken feathers are hazardous waste material that poses human and environmental health risks, as they may contain viruses and bacteria. So why not take this 'worthless' material and convert it into high value products?

Extracting keratin from chicken feathers

Upon receiving the untreated chicken feathers from the poultry industry, Tesfaye pretreats the feathers using a variety of methods including organic and inorganic techniques, until the feathers are free from any debris adhering to the surface of the feathers, and

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THE POLUTRY SITE - PLUCKY IDEA

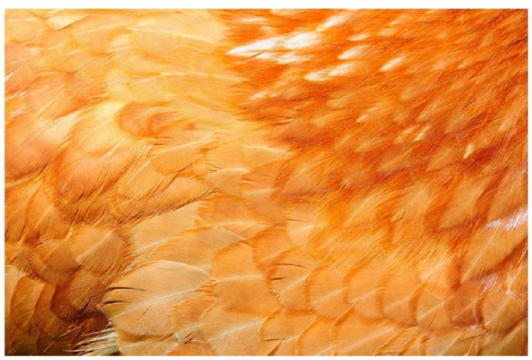
Featured Articles

Plucky Idea – Turning Waste Feathers into Sustainable Opportunities

22 November 2016

The extraction of keratin protein from chicken feathers poses an environmentally friendly and cost-effective way to rid the poultry industry of waste. Glenneis Kriel reports.

Poultry consumption generates more than five million tons of feathers a year. Demand for this by-product is unfortunately low, with most of it ending up being burned, buried or ground up as feed for livestock. The Council for Scientific and Industrial Research (CSIR) in South Africa, along with the University of KwaZulu-Natal, is however researching cost-effective ways to extract keratin protein from chicken feathers for the manufacture of high-value products.



Professor Bruce Sithole, lead researcher on the project, said that the primary method of feather-waste management in South Africa was through its conversion into feather meal to be used as stock feed. “Feather meal contains about 70 to 80 per cent crude protein, but the digestibility of the protein is poor,” explains Sithole, “because of the presence of disulphide bonds which are refractory to digestive enzymes present in chicken. It is rich in cysteine, threonine and arginine, but it is deficient in four essential amino acids, lysine, methionine, histidine and tryptophan.”

The practical level for use of feather meal in a diet is also low at just 0.5 to 1.5 per cent. “Ruminants will use the feather meal better when supplemented with urea. Utilisation is however poor when excess amounts are fed,” says Sithole.

Feathers are excellent for fertiliser purposes, since they have a 15 per cent nitrogen content, but they are difficult to degrade. The availability of nitrogen from feathers as fertiliser is therefore considerably low, unless it is mixed with manure to break it down and supplied as a compost to the soil, according to Sithole.

The problem with the disposal of feathers through incineration and burial is that these methods are energy intensive, they are not very environmentally friendly and they present biohazards. “Research by the North Carolina Department of Environment and Natural Resources found that a 57-megawatt poultry-waste combustion plant emitted more carbon monoxide and carbon dioxide per unit of power generated than new coal plants. The burial of chicken feathers on farms also has to be strictly monitored to avoid groundwater contamination," says Sithole.

Feathers, in their natural state, are also used for decorative purposes, traditional medical applications, religion and cultural ceremonies, sporting items, feather dusters and bedding. These applications are comparatively small in scale, though – which is why more uses for waste chicken feathers need to be found to solve the problem of disposal.

Keratin extraction

The extraction of keratin protein might create a whole new market opportunity for feathers. In doing so, it might also create a viable method of getting rid of this poultry industry waste product in a scalable, sustainable way.

As Professor Sithole explains, chicken feathers contain about 91 per cent keratin, 1 per cent lipids and 8 per cent water: "Keratin is in high demand in a variety of high-value industries, resulting in it selling for more than 2,400 South African rand per kilogram (about 140 GBP per kilogram). By extracting keratin from feathers you might, in effect, be able to make this by-product just as valuable as poultry meat."

While this research is a first for South Africa, international studies and patents on extraction of keratin and other products from feathers are available. The aim of the CSIR study is to develop new extraction procedures – by using a combination of unique solvents and microwave extraction techniques – to significantly reduce extraction costs.

The chicken feathers are pre-treated to remove debris and decontaminated to remove any bacteria and viruses, before the keratin is extracted. Once extracted the keratin proteins are characterised according to their physical and chemical properties. According to Prof Sithole, the extracted keratin protein could be incorporated into all kinds of hair products, due to its moisturising properties.

The harvested proteins could also be made useful in the form of keratin bio-fibres or keratin protein based products. Electrospinning could, for example, be used to regenerate keratin bio-fibres that could in turn be used to replace synthetic petroleum-based fibres in the textile industry.

Keratin proteins, on the other hand, could be converted into high-value chemicals. "In recent years, natural-fibre-reinforced polymer composites have attracted a great deal of attention and interest, as environmentally friendly replacements for glass or carbon fibres in fibre-reinforced composites," says Sithole.

You might also like

APPENDIX C

SELECTED CONFERENCE ABSTRACTS AND EXTENDED ABSTRACTS

EVENT: ETHEKWINI-UNIVERSITY RESEARCH SYMPOSIUM (MILE), DURBAN, SOUTH AFRICA, APRIL 08/2016

VALORISATION OF CHICKEN FEATHERS FOR THE PRODUCTION OF HIGH VALUE MATERIALS

Tamrat Tesfaye, PhD student, UKZN, University of KwaZulu-Natal, South Africa

Bruce Sithole, Professor, Biorefinery Industry Development Facility, NRE, CSIR, South Africa

Deresh Ramjugernath, Professor, UKZN, University of KwaZulu-Natal, South Africa

Abstract

Statement of the Problem: Worldwide, the poultry–processing industry generates large quantities of feather by-products that amount to $40*10^9$ kilograms annually. The feathers are considered wastes although small amounts are often processed into valuable products such as feather meal and fertilisers. The remaining waste is disposed of by incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases. Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. Methodology & Theoretical Orientation: The chicken feathers were thoroughly characterised by the physical, morphological, mechanical, electrical, chemical and thermal properties to find potential valorisation routes of the waste. Findings: A closer look at the structure and composition of feathers shows that the whole part of a chicken feather (rachis and barb) can be used as a source of a pure structural protein called keratin which can be exploited for conversion into a number of high-value bio products. Additionally, a number of technologies can be used to convert other biological components of feathers into high value-added products. In this paper, possible applications of chicken feathers in a variety of technologies and products are discussed. Conclusion & Significance: using waste feathers as a valuable resource can help the poultry industry to dispose of the waste feathers in an environmentally sustainable manner that also generates extra income for the industry. Their valorisation can result in their sustainable conversion into high value materials and products on the proviso of existence or development of cost effective technologies for converting this waste into the useful products.

Keyword: feather, barb, rachis, valorisation, slaughterhouse

EVENT: 66th CANADIAN CHEMICAL ENGINEERING CONFERENCE, CANADA, OCT 23/2016

VALORISATION OF CHICKEN FEATHERS BARB IN YARN PRODUCTION AND TECHNICAL TEXTILE APPLICATION

Tamrat Tesfaye[1, 2], Bruce Sithole[1, 3], and Deresh Ramjugernath[1]

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[2]Ethiopian Institute of Textile and Fashion Technology, Bahir Dar, Ethiopia

[3]Forestry and Forest Products Research Centre, Natural Resources and the Environment, Council for Scientific and Industrial Research, Durban, South Africa

Corresponding author. E-mail address: tamrat_tsfy@yahoo.com (Tamrat T.)

Abstract

Natural fibres have recently attracted material scientists' attention because of their advantages from the environmental perspective. However, research has been directed towards cellulose from plant sources without taking into account other potentially interesting raw materials. Chicken feather are considered as a waste product of poultry slaughterhouse. This paper reports the physiochemical properties of proteinous fibre obtained from chicken feather barb in a view to assess the possibilities of using barb for yarn production and technical textile application. The presence of hollow honeycomb structures, their low density, high slenderness ratio, spinnable length and fineness, high flexibility and possible structural interaction with other natural or synthetic fibres to made into a product such as textiles, provides them unique properties unlike any other natural or synthetic fibres. Using the cheap and abundant chicken feathers based biofibre that have the composition, properties and structure similar to proteinous fibres (wool and silk) in application such as composite, yarn production, technical textile, nonwoven production and paper and pulp manufacture will conserve land usage, energy, benefit the environment and also make the fibre industry more sustainable.

Keywords: - barb, characterisation, chicken feathers, technical textile, yarn

EVENT: THE SOUTH AFRICAN INSTITUTION OF CHEMICAL ENGINEERS (SAICHE), DURBAN, SOUTH AFRICA, AUGUST 30/2017

VALORISATION OF CHICKEN FEATHER: NEEDLE PUNCHED SUPERABSORBENT NONWOVEN FABRIC FOR DIAPER PRODUCTION

Grace Kakonke[1], Bruce Sithole[1,3], Tamrat Tesfaye[1,2], Germain Ntunka[1] and Viren Chunilall[3]

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Abstract

Various environmental studies suggested that non-biodegradable poultry waste, like feathers, pose a serious burden to the environment. The question is how to utilise the mountains of chicken feathers generated from poultry industry more effective and environmentally. There is a high demand of superabsorbent fabric in the world. But the production of these superabsorbent materials from waste biomass is not a well-developed technology. The aim of the present study is to investigate the possibilities of using waste chicken feather in the production of superabsorbent nonwoven fabric. Theoretical considerations on the paper-making method, also similar to the wet-laid technique used in web forming, led to a conclusion that nonwovens cannot be prepared from feathers alone. After extracting the fibre from the whole feather, the nonwoven fabric is produced using needle punched technique. Then the fabric will be treated using acrylate super absorbent polymer. The characteristics of the novel super-absorbent material will then be studied and the optimum production conditions will be investigated by systematically varying the orientation of fibres in the web, the penetration depth of needles as well as the needling density.

Keywords: Chicken feather, fibre, Non-woven technology, needle-punched fibrous mat, Super-Absorbent Polymers (SAPs)

EVENT: THE SOUTH AFRICAN INSTITUTION OF CHEMICAL ENGINEERS (SAICHE), DURBAN, SOUTH AFRICA, AUGUST 30/2017

VALORISATION OF CHICKEN FEATHERS: UTILISATION OF CHICKEN FEATHERS AS A BINDER IN THE FOREST PRODUCTS INDUSTRY

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Worldwide poultry consumption has led to the generation of large amounts of chicken feathers from poultry slaughterhouses; this is because about seven percent of chicken body weight is feathers. At present, the feathers from both small and large-scale poultry industries in most countries are disposed off in landfill, burned or processed to make a low-grade animal feedstock. Meanwhile, feathers are bio-resources with high protein content, which is a good source of natural adhesive. Feathers consists of about 91% keratin; a hard protein which can be chemically synthesized to produce a protein–based adhesive for use in wood composites industries. In this project, studies will be carried out to utilize chicken feathers for adhesive production. Feather keratin will be extracted using different extraction methods. The keratin will be modified using urea and phenol, also using different formulations, the binder will be characterised and the production process will be optimized. The binder properties will be characterised and the performances of the binder will be tested. The adhesive will be used as binder for medium density fiberboard(MDF), particleboard and plywood productions the physical and mechanical properties of the wood composites bonded with feather protein–based adhesives will be determined and compared to those using conventional resins like phenol and urea formaldehyde for their production.

Keywords: chicken feather, keratin, adhesive, wood composite

EVENT: 16th INTERNATIONAL WASTE MANAGEMENT AND LAND FILL SYMPOSIUM/SARDINIA/2017, FORTE VILLAGE CA/ITALY, OCT 2-6/2017

VALORISATION OF CHICKEN FEATHERS: CURRENT STATUS AND FUTURE PROSPECTS

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Worldwide, the poultry–processing industry generates large quantities of feather by-products that amount to $40*10^9$ kilogrammes annually. The feathers are considered wastes although small amounts are often processed into valuable products such as feather meal and fertilisers. The remaining waste is disposed of by incineration or by burial in controlled landfills. Improper disposal of these biological wastes contributes to environmental damage and transmission of diseases. Economic pressures, environmental pressures, increasing interest in using renewable and sustainable raw materials, and the need to decrease reliance on non-renewable petroleum resources behove the industry to find better ways of dealing with waste feathers. A closer look at the structure and composition of feathers shows that the whole part of a chicken feather (rachis and barb) can be used as a source of a pure structural protein called keratin which can be exploited for conversion into a number of high-value bioproducts. Additionally, several technologies can be used to convert other biological components of feathers into high value-added products. Thus, conversion of the waste into valuable products can make feathers an attractive raw material for the production of bioproducts. In this review, possible applications of chicken feathers in a variety of technologies and products are discussed. Thus, using waste feathers as a valuable resource can help the poultry industry to dispose of the waste feathers in an environmentally sustainable manner that also generates extra income for the industry. Their valorisation can result in their sustainable

conversion into high-value materials and products on the proviso of existence or development of cost-effective technologies for converting this waste into the useful products.

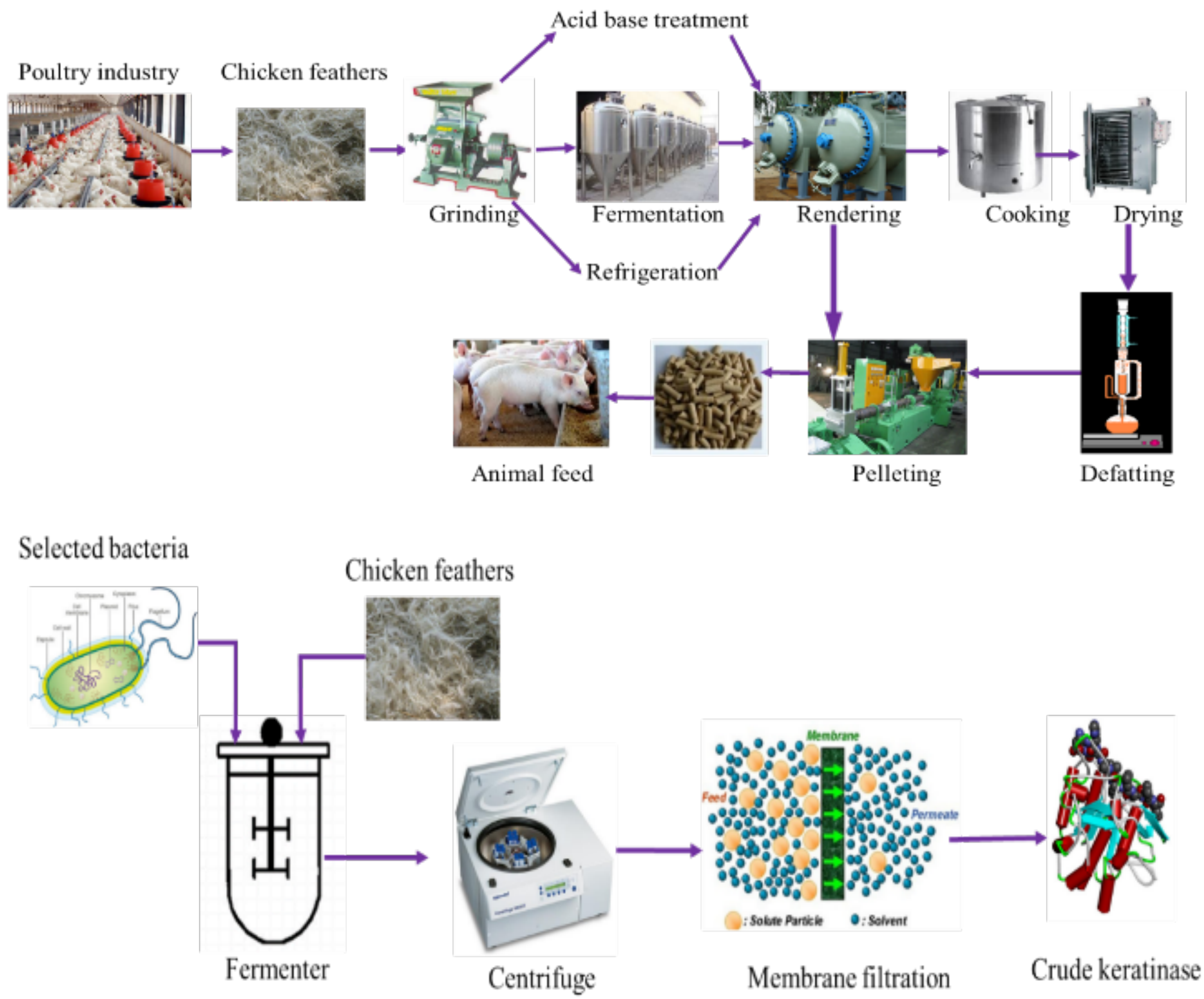

Fig. 1. a. Schematic diagram of animal feed production **b.** keratinase production from chicken feather

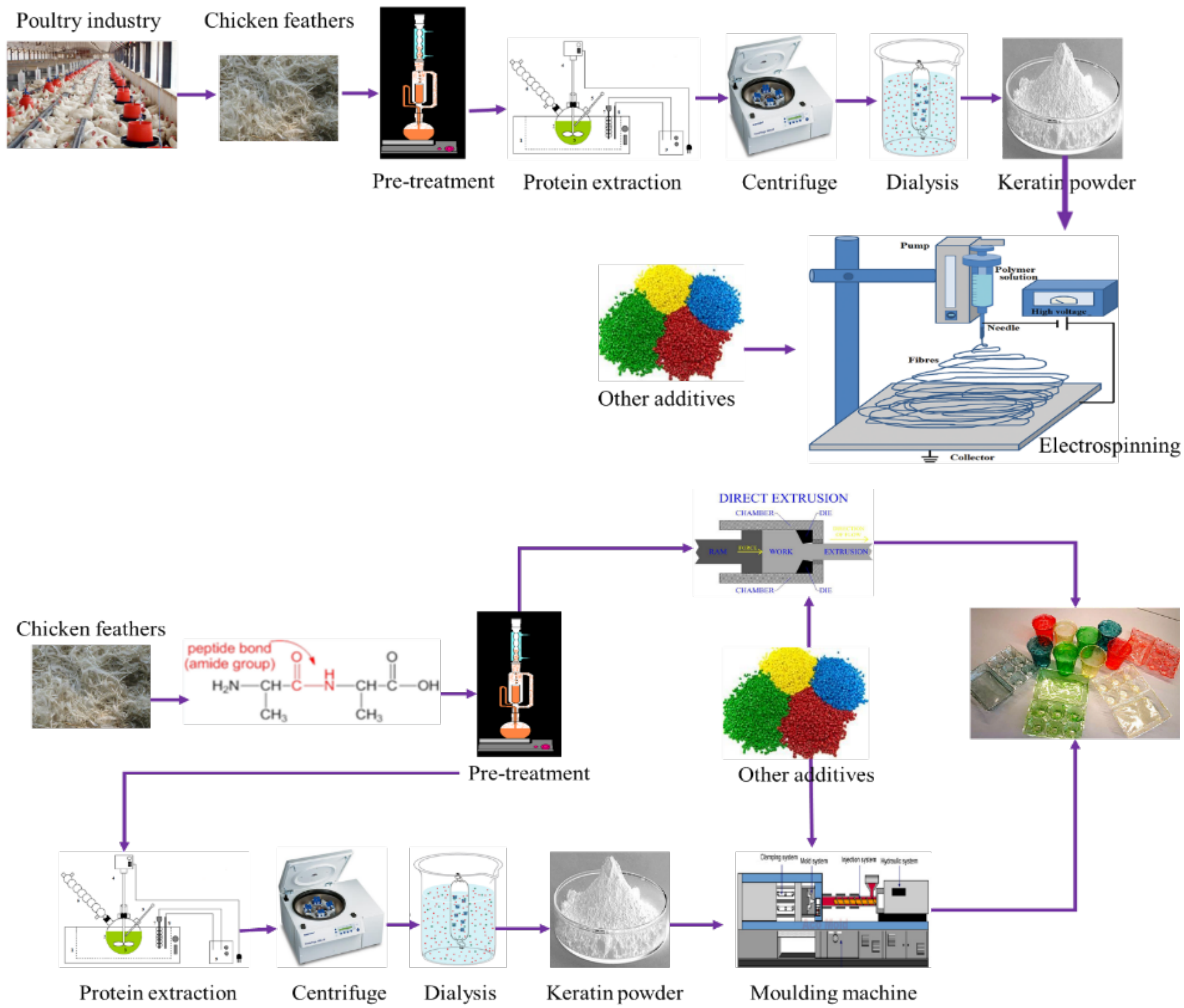

Fig. 2. a. Schematic diagram of regenerated fibre production **b.** Schematic diagram of bioplastic production from chicken feather

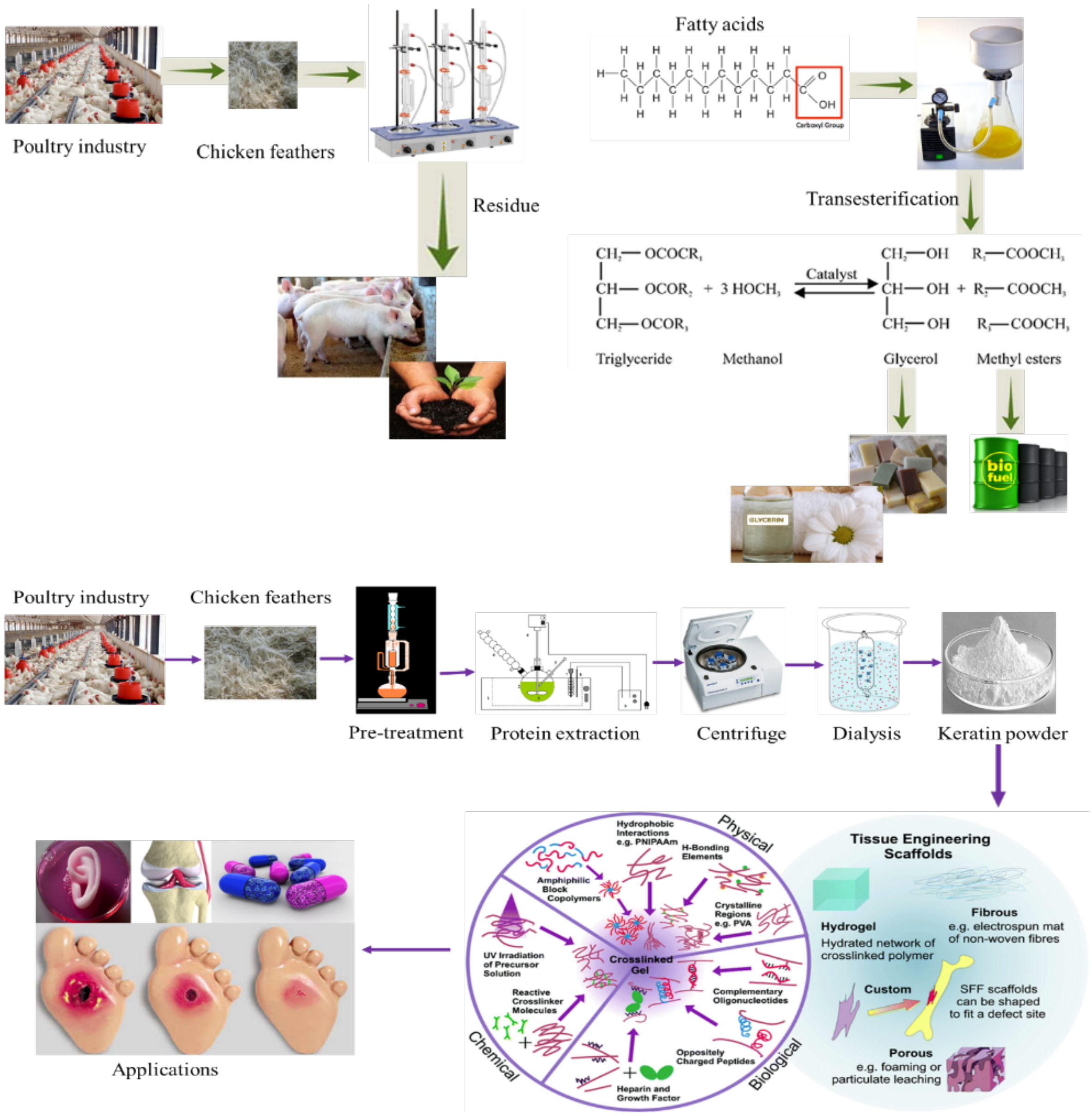

Fig. 3. The schematic process flow of production of biofuel **b.** biomedical products production from chicken feather

Their disposal by incineration or land filling is fraught with problems, e.g., environmental pollution and transmission of diseases due to microbial contamination. However, chicken feathers are composed of materials and components that can be valorised into valuable products and materials. Thus they should be regarded as a valuable resource for extraction of fibres for conversion into fabrics and composite materials; for extraction of composites that can be converted into high value products that are normally sourced from petroleum based products. Thus using waste chicken feathers for such purposes will minimise environmental pollution as well as reduce reliance on use of petroleum based products. Extensive research and development work is required to develop appropriate technologies for their full utilization as a source of some of the proposed applications mentioned in this review.

EVENT: COLLEGE OF AGRICULTURE, ENGINEERING AND SCIENCE RESEARCH DAY (CES), UNIVERSITY OF KWAZULU-NATAL, DURBAN, SOUTH AFRICA, OCT 26/2017

VALORISATION OF CHICKEN FEATHER: NEEDLE PUNCHED SUPERABSORBENT NONWOVEN FABRIC FOR DIAPER PRODUCTION

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Abstract

Numerous environmental studies suggest that non-biodegradable wastes, such as waste chicken feathers, pose a serious burden to the environment. The question is how can we beneficiate the mountains of chicken feathers generated from poultry industry more effectively and environmentally. There is a high demand of superabsorbent fabrics in the world. However, the production of these superabsorbent materials from waste biomass is not a well-developed technology. The aim of the present study is to investigate the possibilities of using waste chicken feathers in the production of superabsorbent nonwoven fabric. Theoretical analysis of paper-making operations, whereby, superabsorbent products (e.g., for use in the manufacture of diapers) are produced using wet-laid technique used in web forming, led to a conclusion that nonwovens cannot be prepared from 100% feathers – modification of the surface chemistry of the feathers will be required. Hence, this project will entail using a needle punching technique to produce chicken feather based nonwoven material that will then be treated with an acrylate polymer to impart super absorbent properties on the material. Characteristics of the novel super-absorbent material will be studied and the optimum production conditions will be investigated by systematically varying parameters such as orientation of fibres in the web, the penetration depth of needles, as well as the needling density. The produced fabric will be investigated for suitability to

replace the current superabsorbent fabrics used in diaper production. Successful use of waste chicken feather for such an application will result in beneficiation of the feathers.

Keywords: Chicken feathers, fibres, non-woven technology, needle-punched fibrous mat, super-absorbent polymers, acrylate polymers