DRYING OF SWEET POTATO TUBERS USING A NATURALLY-VENTILATED SOLAR-VENTURI DRYER AND A HOT-AIR DRYER

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Submitted in fulfilment of the requirements
for the degree of MScEng

Bioresources Engineering
School of Engineering
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June 2020

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PREFACE

The research work contained in this dissertation was undertaken at the University of KwaZulu-Natal, Pietermaritzburg Campus, South Africa, under the discipline of Agricultural Engineering, School of Engineering, in the College of Agriculture, Engineering and Science. The research was fully funded by the Agricultural Research Council. The research sought to use the abundant solar radiation, to improve the processing and storage facilities used by plant breeders in South Africa.

ABSTRACT

In South Africa, there is lack of research on hot-air drying methods, as well as their performance when drying sweet potato slices (SPS). With the current shift in use of renewable energy for drying operations, research is focusing on improving the development of a small-scale naturally-ventilated solar-venturi dryer (SD) that is suitable for Southern African agro-climatic conditions. This is seen as one of the options that can be adopted to help alleviate food insecurity. A comparative study of drying SPS using a SD and a hot-air oven dryer (HAD) was undertaken. This was meant to analyse the temperature and relative humidity (RH) in SD; model drying behaviour of SPS; evaluate the effect of drying method (SD and HAD) and SPS thickness size and effect of pre-treatment on the quality of dried SPS slices.

The SD was developed and the effects of solar radiation, drying air temperature and relative humidity in September 2018 were monitored to analyse their effect on the performance of the SD. The study showed that solar radiation had a significant ($P<0.05$) influence on the air temperature. The average difference between the outside and inside drying chamber temperature and the relative humidity was found to be 12.4°C and 19.2%, respectively for an empty dryer. The temperature and relative humidity inside SD with drying samples were found to be 18.3°C and 18.4%, respectively. There was a significant ($P<0.05$) difference between the air temperature at the exit of the solar collector and the air temperature inside the drying chamber. The maximum temperature inside the solar-venturi dryer was observed to vary at midday (12:00-13:00) on different days. The maximum mean temperature was 44.4°C (12:00 pm) in an empty (unloaded) dryer and 34.1°C (13:00 pm) in a fully-loaded (with drying samples inside) dryer. The minimum relative humidity in an empty dryer was 13.5% and 15.1% for a fully-loaded SD. The SD was able to raise the drying air temperature and the reduce relative humidity.

The drying time was relatively longer for SPS dried in HAD compared to slices dried in SD. The pre-treatments used did not have significant influence on the drying rate (DR), however thickness size had influence on the drying time and the DR. The drying time was relatively low for the 3 mm thick slices as compared to 5 and 7 mm thickness size. During the study, drying took place at falling-rate period for most of the samples indicating that diffusion was the driving mechanism in the drying process. The empirical model that was the best fit for the drying data was Midilli and Kucuk because of higher coefficient of relation (R^2), a lower root mean square error (RMSE) and a lower sum of squared errors (SSE) obtained from linear regression analysis. The Midilli and Kucuk models fitted well to the experimental data with the correlation coefficient (R^2) of 0.9996 and 0.9946 in HAD and SD, respectively. The RMSE value was 0.0339 for SD and 0.0074 for HAD. The SSE values were 0.0115 and 0.0016for HAD and SD, respectively. The D_{eff} ranged between $3.32x10^{-9}$- $6.31x10^{-9}$ $m.s^{-1}$ for a solar dryer and $1.02x10^{-8}$ - $2.19x10^{-8}$ $m.s^{-1}$ for the HAD.

The quality parameters that were evaluated were colour and microstructure changes. SPS pre-treated with lemon juice and dried in SD were lighter in colour with the lightness (L*) of 75.7, yellowness of 11.7 and redness of 1.3. On the other hand, HAD salted SPS were light in colour with lightness of 73.7, redness 2.4 and yellowness 15.8. Blanched samples had the lowest lightness values and the highest redness and yellowness values. Lemon juice was found to be the best pre-treatment method followed by salting, with a reduced drying time among control, blanching in SD. It was observed that samples pre-treated with lemon juice after drying were more clear imagery and were able to retain the natural starch morphology of SPS. The findings showed that the application of solar-venturi drying is a feasible solution for small- to medium-scale farmers who have limited access to electricity. This drying method is a renewable energy dependant alternative that can solve energy-based challenges of drying.

DECLARATION ON PLAGIARISM

I, Gasa Siyabonga, declare that:

a) The research reported in this dissertation, except where otherwise indicated, is my original work.

b) This dissertation has not been submitted for any degree or examination at any other university.

c) This dissertation does not contain other persons' writing, unless specifically acknowledged as being sourced from other persons;

d) 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:

   i. their words have been re-written, but the general information attributed to them has been referenced;

   ii. where their exact words have been used, their writing has been placed inside quotation marks and referenced.

e) Where I have reproduced a publication of which I am an author, co-author or editor, I have indicated, in detail, which part of the publication was written by myself alone and have fully referenced such publications;

f) 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 thesis and the References sections.

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DECLARATION ON PUBLICATIONS

This section provides an outline of the work submitted and presented to conferences and symposia. I designed the prototype, and I tested and evaluated the performance and the final product of the dried sweet potato slices. The work was done under supervision of Prof. TS Workneh, Prof. M Laing, Dr A Kassim and Dr. S Sibanda. The [1] indicates the corresponding author:

Chapter 3

SR Gasa[1], TS Workneh, M Laing, A Kassim and S Sibanda (2018). The effects of a solar-venturi dryer on the drying air temperature and relative humidity. Oral presentation at the South African Institute for Agricultural Engineers (SAIAE) Biennial Symposium and CPD event (17th to 20th of September 2018, North Coast, KwaZulu-Natal, South Africa).

SR Gasa[1], TS Workneh, M Laing, A Kassim and S Sibanda (2018). The effects of a solar-venturi dryer on the drying air temperature and relative humidity. Poster presentation at the Postgraduate Research and Innovation Symposium (25th of October 2018, University of KwaZulu-Natal, Westville, South Africa).

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ACKNOWLEDGEMENTS

I would like to thank God Almighty for His guidance and for giving me strength and energy through the course of this study. I would also like to thank my family and friends for the love, support and sacrifice that they have given me along in my journey to this MScEng.

I would like to thank Agricultural Research Council for funding this research and I also appreciate my supervisors (Prof TS Workneh, Prof M Laing, Dr A Kassim and Dr S Sibanda) for their endless support and guidance in the completion of my research project.

To my mother, Mrs B Gasa, and my father, Mr E Gasa, thank you all for the moral support and strength that you gave me, regardless of the distance during the study, I am truly grateful.

I am grateful to Simphiwe Mdlalose, Siboniso Nkambule and Francis Muga for their valuable assistance during the experimental work and the evaluation of the research, as well as Mr Nxumalo (Technician), for his technical support during the construction of the prototype.

Lastly, I would like to dedicate this dissertation to my late grandmother, Mrs I Gasa, who believed in me from Day One and gave me the name "*Mlungu*"; this is for you.

SUPERVISORS’ APPROVAL

Subject to the regulations of the School of Engineering, we the supervisors of the candidate, consent to the submission of this dissertation for examination.

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Co-supervisor: Dr S Sibanda…………………………………… Date …../..06../2020

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LIST OF ABBREVIATIONS AND SYMBOLS

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DAFF	Department of Agriculture, Forestry and Fisheries	13
DR	Drying rate (kg.min^{-1})	5
EHT	Extra high tension	103
FAO	Food and Agricultural Organization	46
HAD	Hot-air oven dryer	76
K	Logarithmic model constant	34
K_1	is the slope of Arrhenius plot [dimensionless]	82
K_o	is the slope of ln(MR) [dimensionless]	82
m_f	Final moisture content	79
m_i	Initial moisture content	79
mm	Millimetres	45
MR	Moisture Ratio	25
$MR_{exp,i}$	Experimental dimensionless moisture ratio	34
$MR_{pre,i}$	Predicted dimensionless moisture ratio by Page model	34
M_t	Moisture content at time, t [%]	33
N	Number of experimental data points	34
OFSP	Orange-Fleshed Sweet Potatoes	44
OSD	Open-air Sun Drying	13
PHL	Post-Harvest Losses	12

Abbreviation/Symbol	Meaning	Page
R^2	Coefficient of determination	33
RH	Relative Humidity	17
RMSE	Root mean square	33
SD	Naturally-ventilated solar-venturi dryer	3
STAT SA	Statistics South Africa	38
T	Time (min)	49
T_a	Absolute temperature	82
T_{db}	Dry-bulb temperature	17
T_{dp}	Dew point temperature	17
T_{wb}	Wet-bulb temperature	17
W_1	Original weight of a crop [kg]	12
W_2	Crop weight after transportation and storage [kg]	12
M_{db}	Moisture in dry-basis.	16
$M_{t+\Delta t}$	Moisture content at $t+\Delta t$, (% d.b),	49
M_{wb}	Moisture content in wet-basis	15
W_d	Dry matter of the product	15
W_w	Weight of water	15
a_w	Water activity in a product or sample	15
p	Vapour pressure of water	15
p_w	Partial pressure of water on the product	15

1. INTRODUCTION

The availability and access to electricity is a challenge in developing countries (Tiwari, 2016; Vijayan *et al.*, 2016). Qase *et al.*, (2015) reported that South Africa (SA) will soon have electrical energy problems and Tiwari (2016) reported that there is depletion of conventional fossil fuels. The integrated resources plan of the Department of Energy shows that South Africa needs to increase its electricity generation capacity by more than 50 GW by 2030 and predicted that by 2050 energy needs will be more than double. Therefore, harnessing renewable energy for agro-processing is of prime importance (Kumar *et al.*, 2016; Lingayat *et al.*, 2017).

The reported challenges in energy production have a huge impact in developing countries as almost 80% of the food they produce is cultivated by small-scale farmers (Phadke *et al.*, 2015). Small-scale farmers lack access to electricity, proper storage and processing facilities as energy is required in all steps of agricultural-food chain, both directly and indirectly (Mustayen *et al.*, 2014; Dubois *et al.*, 2017). As a result, there is subsequent loss in food production which is estimated to be up to 50% of the fruits and vegetables produced and 25% of the grains that are harvested each season (Sanni *et al.*, 2012; Bala, 2017).

Small-scale farmers in sub-Saharan Africa produces almost 95 % of roots and tuber crops annually for human consumption (Mustayen *et al.*, 2014; Naderinezhad *et al.*, 2016). In this part of the world root and tubers such as cassava, potatoes, sweet potatoes and yam are categorized as the most important produce for human consumption and survival (Xu *et al.*, 2012; Caetano *et al.*, 2018). These are produced annually by small-scale farmers on small parcels of marginal land (Sanginga, 2015). Among these root and tuber crops, sweet potato tubers are the most common produce mainly because of their resistance to drought and high nutritional value. However, they have a high moisture content which creates an environment for water activities and micro-organism activities.

Drying has been reported to be the most common form of food preservation method which enhances the stability of food materials by reducing the moisture content (El-Sebaii and Shalaby, 2012; Hande *et al.*, 2016; Onu *et al.*, 2017). Hence, drying is an essential method that is used for food preservation, where the moisture content of a food has to be reduced to a specific level (Sanni *et al.*, 2012; Pirasteh *et al.*, 2014; Yılmaz *et al.*, 2017). Drying uses different techniques, depending on the properties of the material to be dried (Bala, 2017; Wang *et al.*, 2018). It can be accomplished by osmotic dehydration, where the moisture content of the product is reduced through chemical decomposition, through the freeze-drying of solids and liquids, mechanically (hot air circulation), by using centrifugal force, compression or gravity (Chouicha *et al.*, 2013).

The most commonly-used method is thermal drying (Pirasteh *et al.*, 2014; Phadke *et al.*, 2015; Onu *et al.*, 2017). However, this method has the inherent limitations of high-energy requirements and capital costs (initial and continuous) as the most common thermal dryers depend on electricity-grid connection and burning of fossil fuels (Beigi, 2016; Nwakuba *et al.*, 2016; Onwude *et al.*, 2016). These energy sources are not easily accessible by rural farmers in developing countries (Maia *et al.*, 2011; Okudoh *et al.*, 2014; Lingayat *et al.*, 2017). As a result, solar drying technology is the most promising and attractive energy source, as the sun is the most abundant and non-polluting source energy (Bolaji and Olalusi, 2008; Fudholi *et al.*, 2014; Pirasteh *et al.*, 2014; Nasri and Belhamri, 2018).

Solar drying is the simplest and the most low cost method of food preservation, especially, for small-scale farmers in rural areas (Ferreira *et al.*, 2008; Mustayen *et al.*, 2014; Nasri and Belhamri, 2018). This method can reduce large amount of water through the application of heat, and limit water activities responsible for food deterioration (Luther *et al.*, 2004; Ertekin and Ziya, 2017). Although solar drying has been used in the past (Belessiotis and Delyannis, 2011; Timilsina *et al.*, 2012; Nasri and Belhamri, 2018) research has shown that inefficiencies are linked to the most common traditional methods of solar drying, such as the prolonged drying time and the poor quality of the final dried product (Dina *et al.*, 2015; Fudholi *et al.*, 2015; Kumar *et al.*, 2016). There is evidence that, if solar drying is optimized, the shelf-life of food can be extended to at least one year (Rodríguez, 2012; Onu *et al.*, 2017).

Several studies have been conducted on solar drying for agro-processing using direct and indirect type of solar dryers. However, Mustayen *et al.*, (2014) and Phadke *et al.*, (2015) reported that there is a need to optimize the existing methods of drying and dryers for the post-harvest handling of agricultural produce using, thin-layer drying models. The tray-drying method is the most common technique in agriculture because of it has potential to dry high volumes of produce. However, a limitation of this technology is the uneven drying, as a result of the uneven distribution of the air inside the drying chamber (Misha *et al.*, 2015). A combination of tray solar drying technology, with an improved hot air distribution inside the existing farm storage and processing houses, could be an advantage for small-scale farmers in the processing and extending shelf-life of their produce. Hence, several attempts have been carried out to improve the efficiency of both the direct and indirect modes of drying (Abubakar *et al.*, 2018). For example, Sontakke and Salve (2015) developed an indirect solar dryer with the aim of increasing the efficiency of the dryer by optimizing the air flow-rate and distribution inside the drying chamber. The study reported that the drying efficiency was improved from 20% to 42.6% by from increasing the air flow-rate of 0.01 to 0.21 kg.s^{-1}. The study also reported that the use of tools, such as thin-layer drying models are of utmost importance in selecting optimal micro-environment drying conditions which are important parameters to optimize the solar dryers and improve the quality of the final dried product

Onwude *et al.*, (2016) and Onu *et al.*, (2017) reported that the construction materials of the existing drying technology are expensive, and the energy requirements are high. Hence, it is of outmost importance to construct a low-cost and effective solar-venturi dryer that is fossil fuel-free, reliable and easy to use. It is reported that the use of solar chimneys as stack ventilation in buildings with the existing corrugated iron roof sheets can improve natural ventilation in the development of new solar dryers (Maia *et al.*, 2011; Phadke *et al.*, 2015). In this system, a solar chimney can be used to improve natural ventilation in buildings by encouraging upward air movement and the system totally depends on pressure differences without any mechanical components.

Nwofe (2015) studied the efficiency of open sun-drying and a solar dryer, using sweet potatoes as a test crop. The study reported an increase in the drying efficiency of the solar dryer, compared to open sun drying. The drying rate (DR) of the solar dryers was 0.75 kg.h^{-1}, with an efficiency of 68.5%. Silayo *et al*. (2003) studied the use of alternative drying surfaces, such as corrugated iron roof sheets, ground floor and raised perforated surface by drying potato slices, at different thickness sizes on different surfaces. In the study, raised perforated surfaces and corrugated iron sheets were found to be superior to the ground floor drying of potatoes slices in-terms of drying performance. However, as a result of higher prices of corrugated iron sheet, the study recommended the use of raised perforated surfaces unless corrugated iron roof house already exists, since they are replacing thatched roofs. Literature suggests modification and adaptation of existing corrugated iron roof houses to solar energy-assisted storage houses. However the modification and adaptation of existing corrugated iron-roofed houses to solar dryers has not been reported. Hence, extensive research is required in South Africa on the utilization and feasibility of such technologies for smallholder farmers. This will ensure the preservation of sweet potato slices and other perishable food produce and it will also improve the marketability of the produce.

This study has identified a need for investigating an innovative naturally-ventilated solar-venturi dryer (SD) that uses solar energy to preserve sweet potato slices and to reduce the post-harvest losses experienced by the smallholder farmers in South Africa. Considering that the majority of South African provinces receive an average of 5.5 kWh.m^2 of solar irradiation, the use of solar energy, as a source of energy is feasible in the country (Fluri, 2009). However, extensive research needs to be undertaken on the utilization of solar energy in the South African food industry. The aim of this study is to comparatively evaluate the effect of pre-drying treatments and drying conditions (relative humidity, temperature and air flow velocity) on drying characteristics of sweet potato (*Ipomoea batatas* L.). The output of this study could potentially result in the reduction of post-harvest losses, an increase in the shelf-life of agricultural produce and increased food security for small-scale producers in South Africa. The SD will be a cost-effective drying method that does not require electricity to drive an accelerated drying technology. This will help to generate income for rural farmers, to meet the present and future demands for food, and to sustain the agricultural economy of most developing countries. The research questions of the study are as follows:

(a) Is the airflow uniformly distributed inside the drying chamber of the naturally-ventilated solar-venturi dryer?
(b) How will the external environmental conditions (wind velocity, air temperature and relative humidity) affect the performance of the naturally-ventilated solar-venturi dryer?
(c) Which heat and mass transfer models can best describe the performance of the naturally-ventilated solar-venturi dryer and hot-air oven dryer?

The aim of the project is to optimize and evaluate a small- to medium-scale solar-venturi tray dryer with a heat storage cabinet and a solar chimney. The objectives of this research are:

(a) to evaluate the effect of a solar-venturi dryer on the thermal drying air conditions of the constructed solar dryer;
(b) to evaluate and compare the thin-layer drying characteristics and model heat and mass transfer of SPS using a naturally-ventilated, solar-venturi dryer and a hot-air dryer; and
(c) to evaluate and compare the effects of the SD dryer and a hot-air dryer on the changes in quality of SPS.

The hypothesis of this study are as follows:

(a) air flow is uniformly distributed inside the drying chamber of the SD;
(b) performance of the S is affected by the air velocity and temperature and humidity;

(c) the air velocity and temperature of the thin-layer model will best describe the drying of SPS; and that slices with a shorter drying time will have less changes in quality.

1.1 Outline of the Dissertation Structure

The dissertation is divided into six chapters, namely:

Chapter 1	This chapter provides the rationale of the study and an overview of the study objectives.
Chapter 2	This chapter provides an overview of sweet potatoes. It entails a critical literature review of the tubers, in terms of their production, processing and storage on global scale, concentrating mainly on dehydration, to minimise the loss of quality and to add value to the produce of rural farmers.
Chapter 3	This chapter focuses on the performance evaluation of a solar chimney dryer that was constructed and evaluated under Pietermaritzburg conditions at two different loading intensities.
Chapter 4	This chapter studies the thin-layer drying characteristics of SPS and models heat and mass transfer during drying, under a naturally-ventilated, solar-venturi dryer and a hot-air oven drying system.
Chapter 5	This focuses on the changes in quality of the final SPS that are dried in both a naturally-ventilated solar-venturi dryer and a hot air oven drying systems.
Chapter 6	This chapter presents the conclusions of the study by highlighting its findings and recommendations for further research.

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2. A REVIEW OF SWEET POTATO TUBER PRODUCTION AND PROCESSING

This chapter contains a critical review of tuber crops, and focuses mainly on the production, processing and storage of sweet potato tubers. Sweet potato tubers are amongst the group of root and tuber crops that are considered major staples, because they produce large quantities of dietary energy for a significant number of the population in the developing world (Morgan and Choct, 2016).

2.1 Production and Consumption of Sweet Potato

Sweet potato (*Ipomoea Batatas* L.) is a starchy tuber root crop ranked as the fourth most important crop that feed the world the other four in the top five are rice, sorghum, wheat and corn (Antonio *et al.*, 2008; Seidu *et al.*, 2012). Sweet potatoes are grown in more than 110 countries of the world and account for about 12% of the world's root and tuber crop production. In 2013 the total production of sweet potatoes was about 103 million tonnes (Latif and Müller, 2015; Abong *et al.*, 2016). Sweet potatoes are important for food security with the world per capita consumption (kg) of 8.22 (in 2009), 8.01 (in 2010) and 7.97 (in 2011) (Antonio *et al.*, 2008; Oke and Workneh, 2013). The main advantage of growing sweet potatoes is their tolerance to drought conditions and easy to cultivate (Antonio *et al.*, 2011). However, the potential of sweet potato is underexploited as its production is regarded as a poor man's food. Fresh sweet potatoes can be processed at home for human consumption, as a ready-to-eat vegetable that is boiled or baked, or through industrial processing through fermentation into food and beverages (Antonio *et al.*, 2008; Seidu *et al.*, 2012; Titus and Lawrence, 2015). Fresh sweet potatoes are perishable and bulky which makes them difficult to transport and limit distance of transportation unless they are processed (Akinwande *et al.*, 2013; Oke and Workneh, 2013). Developing countries, such as the northern central and Volta regions of Ghana, grow sweet potatoes to generate income; however, growers face high post-harvest losses, which reduces their income and standard of living (Seidu *et al.*, 2012; Sanginga, 2015). Seidu *et al* (2012) suggested that a knowledge of sweet potato drying could add more value to the produce.

2.2 Postharvest Losses of Fruits and Vegetables

The food produced for human consumption is almost 1.3 billion tonnes each year and literature shows that one-third of this is lost due to postharvest losses (PHL) and marketing systems

(Sawicka, B. 2019). Literature shows that food losses in the production chain occur at the production level, or in the post-harvest processing and consumer stages (Abass *et al.*, 2014; Kasso and Bekele, 2016). The food losses in the production chain of industrialized Asia, developed and developing countries vary and are summarised in Figure 2.1. Reducing PHL is the first major step to food safety, security and sustainability; however, technology and current methodologies are inefficient in the reduction of these losses (Affognon *et al.*, 2015; Kasso and Bekele, 2016).

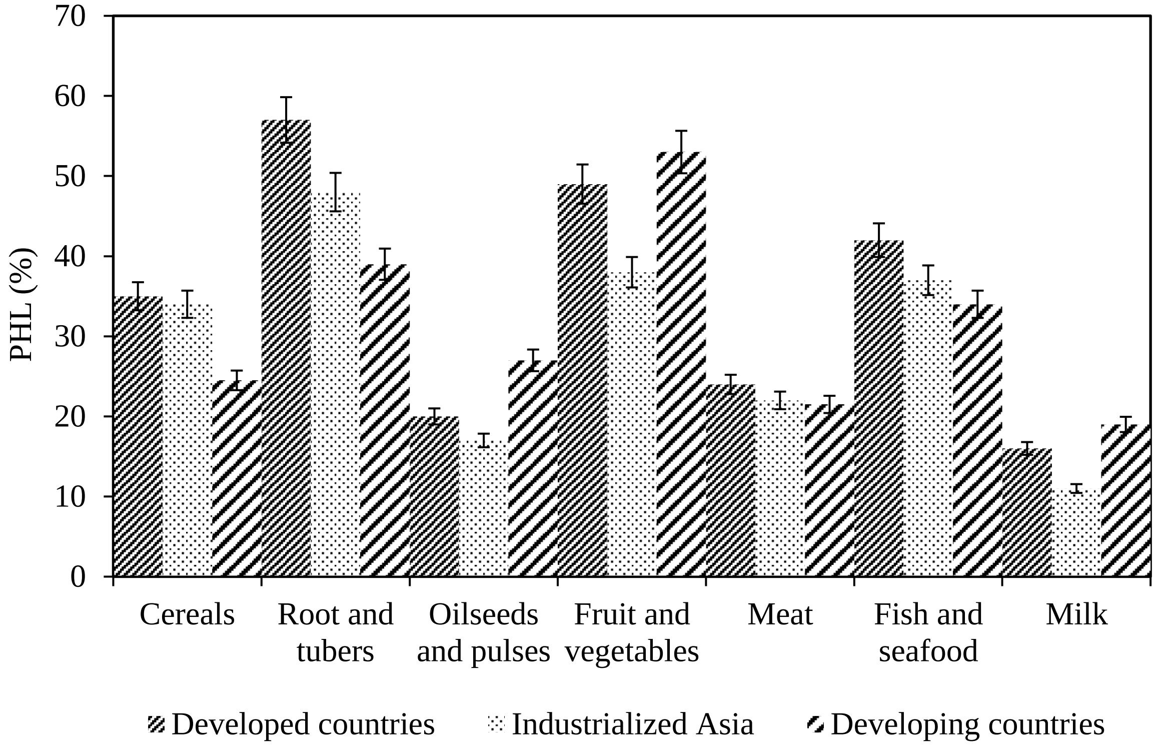

Figure 2.1 Global food loss variations by commodity across countries (after Gustavsson et al., 2011)

Food safety and security is a global concern, especially in developing countries, due to the increasing population (Abass *et al.*, 2014; Kiaya, 2014). The world population is expected to reach 9.1 billion by 2050 and in order to meet the expected demand, food production should be increased by 50 to70% (Affognon *et al.*, 2015). Approximately 20-40% of all PHL in developing countries are caused by mechanical damage during harvesting, transportation and storage, as well as, decay, and physiological disorders (Olayemi *et al.*, 2011; Abass *et al.*, 2014). Quality deterioration and PHL can be determined by using a modified PHL equation (Abong *et al.*, 2016; Kasso and Bekele, 2016) as expressed as Eq. (2.1).

$$\text{PHL}\ (\%) = \frac{w_1 - w_2}{w_1} \times 100 \tag{2.1}$$

Where

w_1 = is the original weight of a crop [kg], and

w_2= is the crop weight after transportation and storage [kg].

The shortage of storage and poor processing techniques are the main cause of the PHL of fresh produce (Kiaya, 2014; Mustayen *et al.*, 2014; Kasso and Bekele, 2016). Post-harvest losses relate to losses in the quality and quantity of the food. Quantitative losses occur when there is a loss of weight of food, while quality losses occur when there is a loss in nutrients or when there is food contamination (Kiaya, 2014). Literature reports that food loss and waste in sub-Saharan Africa occur from the farmer's field after harvest to the consumers' plate (Sheahan and Barrett, 2017). Kasso and Bekele (2016) conducted a study on PHL in the Dire Dawa region of Ethiopia. The study reported that severe PHL of horticultural crops occurred during harvesting, marketing, transportation and storage. These losses were recorded to be between 20% and 50%, from marketing to consumption (Kasso and Bekele, 2016). The study then recommended that there is a need to develop proper handling strategies along the supply chain. It is therefore of outmost importance to reduce PHL by preservation of fruit and vegetables, such as sweet potatoes as a complementary alternative for improving agricultural productivity.

2.3 Storage and Processing of Sweet Potato Tubers

Typically, sweet potatoes are stored and eaten fresh, however, some simple processing methods together with storage methods can be used to increase their storability (Ajala *et al.*, 2012). Storage of sweet potato in dried slices and crushed form has become a practice of increasing importance (Abong *et al.*, 2016). Sweet potato stored as slices can stay up to six months and when in crushed form can stay even longer; however, there is a risk of pest's infestation (Allen *et al.*, 2016). Stored sweet potatoes can be processed to brew alcoholic beverages or to produce products like crisps, chips flakes, granules and starch (Akinwande *et al.*, 2013). The high moisture content of roots and tubers makes storage for long periods difficult, hence, drying before storage is necessary (Andres *et al.*, 2004; Akinwande *et al.*, 2013; Titus and Lawrence, 2015). Drying of tubers is done to store them fresh to keep the edible material on them. Dried sweet potatoes are produced around the world as a cheap source of carbohydrates, especially in sub-Saharan Africa, with Nigeria producing the highest quantities of sweet potatoes in the region (Andres *et al.*, 2004; Bradbury and Denton, 2011; Ajala *et al.*, 2012; Akinwande *et al.*, 2013).

Oyengbal et al. (2013) reported that there is a need for the rapid processing of sweet potatoes immediately after harvesting to reduce moisture content to levels that minimise enzymatic activity and increase shelf life. Slicing is of sweet potatoes is one method that enhance the reduction of the high moisture content (Chouicha *et al*., 2013). Peeled tubers are sliced mainly to reduce the drying time and increase the drying rate (Bolaji *et al*., 2008; Meisami-asl *et al*., 2010; Hashim *et al*., 2014).The drying of the sliced potatoes can be achieved through direct and indirect sun drying, or through artificial drying, using hot air ovens (Beigi, 2016). The shape and size of the slices have an effect on the rate of drying and the final product quality; hence, the samples to be dried need to be cut specifically according to the required final product and its use (Meisami-asl et al., 2010; Akinwande *et al*., 2013; Naderinezhad *et al*., 2015). The study conducted by Naderinezhad *et al*. (2015) reported that square slices of sweet potatoes dried faster than circular slices. Small thickness sizes generally dry quicker but while thicker slices allow the easy compaction of chips during process making flour (Titus and Lawrence, 2015). Akinwande (2013) reported that the production of dried slices is the cheapest postharvest handling method that both reduces microbial activity and is less labour intensive. The production process is comprised of a simple unit that can be operated at a low cost (Aliyu and Jibril, 2009; DAFF, 2010; Oyebanji *et al.*, 2013).

2.4 Drying as a Method of Processing and Preservation

Over the years, the drying of food has been a standout method of preservation that is used to prolong the shelf-life (Sobukola *et al.*, 2007; Pirasteh *et al.*, 2014; Phadke *et al.*, 2015; Beigi, 2016). There are different drying methods which are used based on the agricultural products to be dried and different purposes for drying (Luther *et al.*, 2004). Sun drying, freeze drying and convective drying are the most common methods used in the drying of agricultural products; however, freeze-drying use is limited by high energy input and costs (Zotarelli *et al.*, 2012). Freeze-drying is regarded as the best dehydration batch process and is characterised by long dehydration period with a low dehydration temperature (Samsalee N and R, 2012; Zotarelli *et al.*, 2012). Beigi (2016) reported that convective dryers are mostly used to dry agricultural products.

Drying is regarded as the most important method that can reduce moisture by the total removal of water to produce a solid product known as dehydration or the partial removal of water, which will produce a moisture-concentrated product under evaporation (Luther *et al.*, 2004; Kiaya, 2014; Kumar *et al.*, 2016). Traditional methods of drying, such as shade and open-air sun drying on flat surfaces, bare ground, and mats have been used in a number of countries over the years (Oyebanji *et al.*, 2013; Rabha and Muthukumar, 2017). The drawbacks of these traditional methods include microbial contamination, dust and prolonged drying time (Doymaz, 2011; Seidu *et al.*, 2012; Beigi, 2016). To solve these problems, traditional methods should be replaced with artificial methods of drying, such as hot air and solar drying (Andres *et al.*, 2004; Demiray and Tulek, 2012; Chouicha *et al.*, 2013; Pirasteh *et al.*, 2014; Kumar *et al.*, 2016). In an experiment performed by Aliyi and Jibril (2009) using an indirect passive solar dryer, it was found that this type of drying can save over 30% of drying time, compared to open-air sun drying and also reduce the dust contamination. Therefore, drying can be used as a method of processing and preservation for agricultural produce.

2.5 Principles of Drying

Drying is defined as a method used to remove water from moist products through the evaporation of water via the application of heat (Mujumdar, 2012; Parikh, 2014; Ertekin and Ziya, 2017). During drying, energy consumption ranging between 0.43 to 20.35 MJ.kg^{-1} occurs when moisture from the food is evaporated (Barat and Grau, 2016). The amount of heat required is equal to the latent heat of vaporisation of water (2260 kJ.kg^{-1}). The drying rate is dependent on the product, as well as the relative humidity of the surrounding air, product type and maturity and its moisture content.

2.5.1 Mechanism of dying

Heat and mass transfer are important in drying processes (Parikh, 2014). When heat is transferred to a drying product, mass transfer occurs to the surrounding environment in a vapour form. This transfer occurs in two stages, the first one being the moisture transfer from the interior of a drying product to the surface, and the second phase is the vapour evaporation from the surface of a product to the air (Pirasteh *et al.*, 2014; Tiwari, 2016). The rate of drying during the early stage of wet product drying is influenced by external factors, which affects the mass and heat transfer, such as the humidity, the temperature, and the air velocity on the exposed surface area of the product. The drying of the product occurs in two phases, namely, the constant rate and the falling rate drying periods (Bala, 2017). The constant drying rate period occurs when the surface moisture is removed and the evaporation rate per unit area is constant during this period (Mujumdar, 2012; Miraei *et al.*, 2017). The falling rate period occurs when the rate of drying falls continuously in time (Ertekin and Ziya, 2017). In a study by Doymaz (2011) the drying process of SPS at various temperatures (50, 60 and 70°C) occurred at the falling rate period. In this study, it was concluded that moisture diffusion was a dominant physical mechanism governing the moisture movement. Sobukola *et al.* (2008) reported similar findings.

2.5.2 Water activity and moisture content

Agricultural and food products have a limit below which micro-organisms stop growing. The control of water activity of fruits and vegetables is essential to minimize microbial deterioration (Akinwande *et al.,* 2013). Water activity is defined as a measure of the energy status of water in a system (Decagon Devices, 2009; Tiwari, 2016). Water activity provides information on the chemical and physical stability and microbial spoilage of a product. It can be expressed as a ratio of the vapour pressure of water in a sample, to the equilibrium vapour pressure of pure water at the same temperature, as shown in Eq. (2.2). According to Beuchat (1981), bacterial growth is at $\mathrm{a_w} = 0.85$, mould and yeast $\mathrm{a_w} = 0.61$, fungi is at $\mathrm{a_w} < 0.70$. Therefore, it is of vital importance for dried fruits and vegetable to have water activity levels that will not allow for micro-organisms to grow.

$$\mathrm{a_w} = \frac{\mathrm{p}}{\mathrm{p_w}} \tag{2.2}$$

Where

$\mathrm{a_w}$ = is the water activity in a product [dimensionless],

p = is the vapour pressure of water [kPa], and

$\mathrm{p_w}$ = is the partial pressure of water on the product [kPa].

The moisture content represents the amount of water present in a product and can be expressed as a percentage of wet and dry basis. The wet basis can be defined as a ratio of the mass of water in a product to the mass of the total sample, which can be expressed by using Eq. (2.3) (Bala, 2017):

$$\mathrm{M_w} = \frac{\mathrm{M_w}}{\mathrm{M_w+M_d}} \tag{2.3}$$

Where

M_w = moisture content in the wet-basis [%],

M_w = is the mass of water [kg], and

M_d = is the mass of dry matter of the product [kg].

The moisture content in dry-basis is the ratio that compares the weight of moisture present in a product to the weight of dry matter. It can be expressed by using Eq. (2.4) (Bala, 2017):

$$M_{db} = \frac{M_w}{M_d} \tag{2.4}$$

Where

M_{db} = is the moisture in dry-basis.

However, it may be necessary for some applications to convert from a dry basis to a wet basis, or vice versa, using Eq. (2.5).

$$M_d = \frac{M_w}{1 - M_w} \tag{2.5}$$

2.5.3 Psychrometrics moist air properties

Psychrometrics principles apply to any physical system consisting of gas-vapour mixtures and Psychrometrics is a tool that is used to measure heat and vapour properties of air, and it is shown in a simplified chart form in Figure 2.2 (Mittal and Zhang, 2003). Psychometric and drying involve several terms used to measure psychometrics variables, as summarised in Table 2.1.

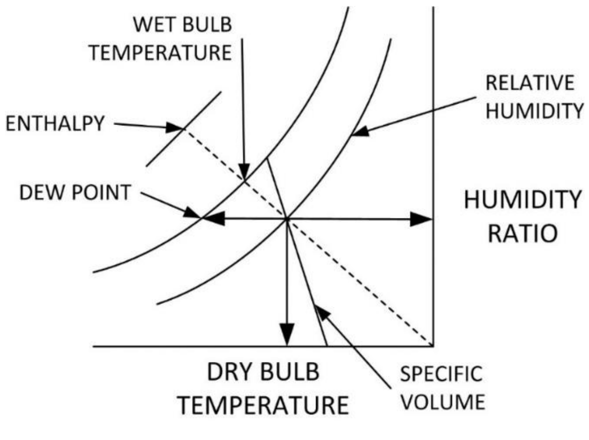

Figure 2.2 Psychrometric chart showing properties of moist air

Table 2.1 Definitions of psychometrics properties of moist-air

Variable	Psychometrics definition
(a) Dry-bulb temperature (T_{db})	Is a Psychrometric property (temperature) that can be defined as the average kinetic energy or heat content of particles in the air and that can be referred to as a primary force for heat transfer (Mittal and Zhang, 2003). It is measured using a normal thermometer exposed to the air in a place sheltered from direct solar radiation (actual air temperature). The vapour pressure at this temperature is defined as the saturated partial pressure of water vapour and gives an indication of the sensible heat (Chukwunonye *et al.*, 2016).
(b) Wet-bulb temperature (T_{wb})	Is the temperature of air, if the energy required to bring air to saturation is taken from the thermal energy of the air (Devres, 1994; Mittal and Zhang, 2003). Practically, this temperature can be obtained by sticking your thermometer into a wet cotton wick and the resulting temperature is the wet bulb temperature (Chukwunonye *et al.*, 2016). Hence, this temperature indicates the quantity of the latent heat.
(c) Dew point temperature (T_{db})	Is the temperature at which water begins to condense out of the air, also known as the saturation point (Mittal and Zhang, 2003).
(d) Relative humidity (RH)	Is the ratio of the partial pressure of moisture to the partial pressure of water, if air is saturated with water (Mittal and Zhang, 2003).

2.5.4 Drying methods

Several drying methods that are used for drying agricultural produce. These include; microwave drying, freeze drying, vacuum drying and hot-air drying.

(a) **Microwave drying** is described as the type of drying that expose the produce to high frequency electronic waves. The main advantage of microwave drying is that it reduces the drying time four to eight times compared to other drying methods because of the dielectric heating, which results in energy coupling into the water, leading to fast heating and drying (Motevali and Minaei, 2012). However, this method cannot be used in this study and by small-scale farmers because of high capital and running costs.

(b) **Freeze drying** is known as a two-stage process which involves (i) the freezing of water in the food materials and (ii) the application of heat so as to directly convert the ice into vapour (Wang *et al.*, 2018). Literature shows that this method has preference over other drying methods as it reserves the product structure. However, Pawel *et al.*, (2011) reported that the costs of freeze-drying are 4 - 8 times higher than other methods of drying. Hence, its application is limited for small-scale operations as it is relatively expensive. Therefore, it cannot be considered for small-scale farmers and this study.

(c) **Vacuum drying** is a method used for drying heat-sensitive fruits and vegetables. The process is done at a pressure less than 100 kPa, at different temperature (Alibas 2012). A lower drying temperature causes a lower rate of oxidation, which results in an improvement of produce quality (Lui *et al.*, 2015). This method however requires high capital and running costs, to ensure that the pumping system for the vacuum runs smoothly. Therefore, not feasible for small-scale farmers.

(d) **Hot-air drying** is the most common method of drying where the heated air is circulated by natural or forced ventilation through the moisture-filled product. The operation temperature ranges from ambient temperature to 100^{o}C (Hashim *et al.,* 2014; Ismal *et al.,* 2015). In this type of drying, solar, electricity or geothermal are used as energy sources. Hot-air drying methods includes, kiln dryers, fluidized bed dryers, cabinet tray dryers, tunnel dryers, pneumatic dryers, spray dryers and rotary dryers (Mihindukulasuriya and Jayasuriya, 2013). SDS will be used because of its abundant energy source (solar energy) and popular use and applicability. This method will be tested and evaluated against the HAD.

2.6 Energy Requirements for Drying

Roots and tuber crops are harvested as fresh produce with a moisture content of over 80% and has high latent heat of vaporization (Onu *et al.*, 2017). To decrease such high moisture content levels requires a high-energy input to heat the drying air (Motevali and Minaei, 2012; Akoy, 2014; Rabha and Muthukumar, 2017). The high latent heat of vaporization has longer drying time, resulting in high-energy requirements. The drying time is determined by factors such as the initial moisture content of the drying product and the required final moisture content. Nwakuba *et al.* (2016) reviewed the energy requirements for drying sliced agricultural products, such as carrots, potatoes, garlic, onions, tomatoes, mangos and bananas. The study reported that slice thickness, the initial and desired final moisture content, the air temperature, the air velocity, the specific heat capacity and relative humidity, are major parameters that affect the energy requirements of drying of crops. A minimum energy requirement of 4.22 MJ.kg^{-1} and maximum of 24.99 MJ.kg^{-1} was reported in drying crops with a high moisture content, such as mangoes, apples, cucumbers and carrots slices. Furthermore, Nwakuba *et al.* (2017) reported that microwave dryers save about 70% of energy when, compared to other official dryers due to their low energy consumption at high power densities; however, they are cost-effective when operated at the recommended 500 W power densities for sliced products. The study recommended improving reviewed dryers efficiency at optimal operating conditions during drying. However, small-scale farmers have limited access to proper processing and storage facilities, such as microwaves and commercial dryers.

2.7 Solar as a Source of Energy for Drying

The energy requirements for drying can be supplied from various sources such as electricity, natural gas, fossil fuels, wood and solar. However, considering the rapid depletion of natural fuel resources and the rising fossil fuels cost, solar is the most attractive solution because of its abundant availability and cost-effectiveness. The earth receives a small portion of 70 000 to 80 000 kW.m^{-2} solar radiation intensity from the 6000^{o}C solar surface temperature of the sun (Tiwari, 2016). However, the use of solar radiation for drying has not been widely commercialized especially in the industrial sector (Bal *et al.*, 2010; Chouicha *et al.*, 2013; Shalaby *et al.*, 2014). Pirasteh *et al.*, (2014) conducted a review study on the feasibility of harvesting and using solar energy as a primary source for agriculture and other industries (Pirasteh *et al.*, 2014). The study reported small-scale farmers for open-air sun drying have successfully harnessed solar energy. However, the limitations of this method resulted in a need to develop solar dryers (Vaibhav and Sanjay, 2016; Rabha and Muthukumar, 2017).

Researchers and other scientists have been trying to find solutions to overcome the limitations of open-air sun drying (Belessiotis and Delyannis, 2011; Mustayen *et al.*, 2014; Vaibhav and Sanjay, 2016). As a result, Everitt and Stanley (1976) developed a solar dryer with a transparent sunlight cover in a box-shaped housing (Kumar *et al.*, 2016). Other researchers have developed new drying technologies, such as forced air circulation to improve on the initial design. The drying mechanism process for food materials is a complex process involving the transient mechanism of heat, mass and momentum transfer, accompanied by chemical, physical and phase change transformation (Sabarez, 2016). These systems have been reported as promising applications for environmentally-friendly and renewable technology, as they can remove both bound and unbound moisture from solid food products (Chouicha *et al.*, 2013; Fudholi *et al.*, 2015; Kumar *et al.*, 2016). Bound moisture is defined as the moisture held in the microstructure of the solid and exerting a vapour pressure less than that of the pure liquid. The unbound moisture is the moisture in excess of the bound moisture (Tiwari, 2016). The transfer of the internal moisture to the surface of the drying material and heat transfer from the surrounding environment occurs simultaneously to evaporate surface moisture during drying. Its potential application in the agricultural sector for drying systems to preserving fruits, vegetables, grains and warming buildings in the winter season has been reported to be feasible, especially for small-scale farmers in developing countries (El-Sebaii and Shalaby, 2012; Mustayen *et al.*, 2014; Pirasteh *et al.*, 2014; Shalaby *et al.*, 2014).

2.8 Availability of Solar Energy in South Africa

Solar energy is a source of renewable energy, which is attributed to sunlight. It is the energy emitted is from the sun’s radiation at rate of 3.8×10^{23} kW. Of this energy 1.8×10^{4} kW is intercepted by the earth. Solar energy is the most readily-available renewable energy source in South Africa for both heating and electricity (Qase *et al.*, 2015). Solar energy has a number of benefits, such as tax credits, feed-in-tariff, preferential interest rates and green power programs; however, some technical and financial barriers, like low efficiency and high capital costs, need to be overcome (Timilsina *et al.*, 2012). Solar energy represents the largest source of renewable energy, compared to biomass, biogas, wind and geothermal sources. Solar energy is environmental-friendly and is viewed as a promising heat source that meets the high-energy demands, without having an adverse impact on the environment (Tyagi *et al.*, 2012).

Fluri (2009) studied the availability of solar energy and the potential for implementing solar power plants in all the provinces of South Africa, which can be identified by using Geographical Information System (GIS). The total nominal capacity of the country was found to be 547.6 GW, with the identified areas able to accommodate solar power plants with a nominal capacity of 510.3 GW in the Northern Cape Province, 10.5 GW in Western Cape, 25.3 GW in the Free State and 1.6 GW in the Eastern Cape Province (Fluri, 2009). The study implies that there is enough solar energy in South Africa, as shown in Figure 2.3 that can be converted to heat, or electricity for thermal and electrical applications. The potential for the application of solar energy for preservation of horticultural commodities, such as fruits and vegetable through cool storage and drying exists.

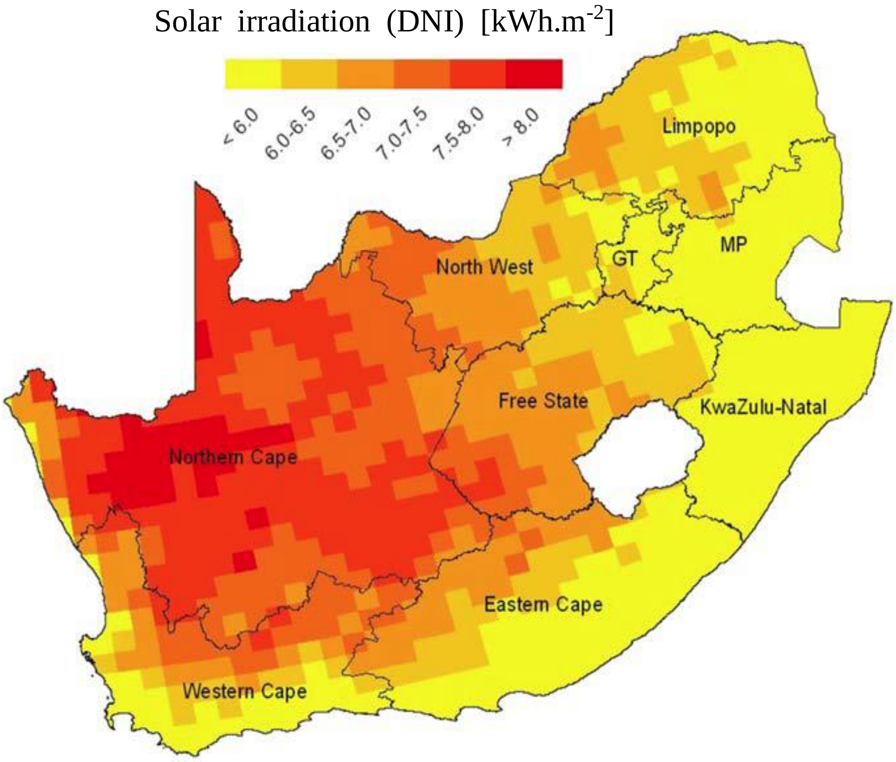

Figure 2.3 Average annual solar radiation of South African provinces (adopted from Fluri, 2009)

2.9 Solar Drying

2.9.1 Solar chimney drying

The first stack solar chimney was developed between the 19th and the 20th century by the introduction of the Trombe-Michel wall, which was then further modified as the Trombe wall and roof collector (Tan and Wong, 2013). The stack solar chimney is a passive ventilation system, which uses the temperature difference to drive air. Solar chimney is another way of improving ventilation rate in naturally-ventilated dryer (Khanal and Lei, 2011; Tan and Wong, 2013). It consists of an internal absorber wall, which uses radiant energy to heat up the air in the chimney. Solar chimney technologies were developed to produce hot air that can be used in various applications, such as power generation, solar chimney drying systems and air ventilation (Belfuguais and Larbi, 2011). It operates by increasing the buoyancy force, which is directly proportional to the difference between the mean air density within the chimney and the density of the outside air. In addition, the airflow, temperature and velocity at the outlet of the chimney also increases. Studies indicates that solar chimneys have shown success in areas where the heated air is between 10-30^{O}C. Solar chimneys are applicable to forced ventilation dryers because of the pressure difference, which improves their performance. Hence, they are amongst the most attractive and promising technologies for the future, as they contribute to the reduction of the greenhouse effect, global warming and climate change (Belfuguais and Larbi, 2011; Tan and Wong, 2013).The observations from different research studies on solar chimney driers are summarised in Table 2.2.

Table 2.2 Summary of observations on a solar chimney drying

Crop dried	Observations	References
Grains	The solar chimney dryer was found to be technically feasible for the drying of agricultural food; however, the device required modifications and improvements.	Ferreia *et al.,* 2008
Tomatoes, peppers and bitter leaves	Solar dryer reduced drying losses, compared to sun drying with good-quality dried products (colour and flavour) and free from microbial contamination.	Medugu 2010
Chillies	The solar dryer was able to reduce microbial contamination, and to protect from direct solar radiation and insect infestation	Chevli *et al* 2016
Seaweed	The solar dryer was able to reduce the moisture content and to obtain a better selling price at the market	Phang *et al.,* 2018

2.9.2 Open-air sun drying

Open-air Sun Drying (OSD) is a traditional drying method used to preserve agricultural products in sub-tropical and tropical countries (İsmail *et al.*, 2015; Hande *et al.*, 2016). This type of drying depends on weather conditions (temperature and relative humidity) (Seidu *et al.*, 2012; Meher and Nayak, 2016). In this type of system the drying product is usually spread on the ground, floors, roofs or flat surfaces and usually turned once, or twice daily (Lingayat *et al.*, 2017). Its working principle is that the short wavelengths of solar radiation falls directly on the drying product surface and is converted to thermal energy, as shown in Figure 2.4 (Jabeen *et al.*, 2015; Lingayat *et al.*, 2017). In this way, part of the solar radiation is absorbed, while another part of it is reflected by the surface of the drying product, with the reflected and absorbed amount being dependent on the surface colour of the drying product (Phadke *et al.*, 2015; Lingayat *et al.*, 2017). The increase in temperature results in increased moisture evaporation from the drying product which results in drying. The drying rate in OSD is relatively low; as a result, has longer drying time. Therefore, OSD drying drawbacks, includes: (a) the slow drying rate, (b) inability to control over drying rate and time, and (c) the direct exposure of the product to uneven solar conditions and dust (Phadke *et al.*, 2015; Rabha and Muthukumar, 2017). New technologies can solve such drawbacks by introducing cabinets, or drying chambers, for the product (Beigi, 2016). Table 2.3 shows observations of other researchers on OSD.

Table 2.3 Summary of observations on open-air sun drying

Sample dried	Observations	References
Sweet potato chips	Drying on ground floor resulted in poor final dried products, compared to perforated surface and iron sheet drying.	Silayo (2003)
Potato slices	Potato slices that are dried using solar dryer had a shorter drying time, a faster drying rate and yielded a better product, compared to open-air sun drying.	Nwofe 2015
Ginger	The colour and nutrient retention attributes were improved and improved the rehydration ratio of the dried product with microwave vacuum method, while open-air sun drying had a poor final dried product.	Valarmithi *et al.,* 2017

2.9.3 Indirect solar drying

Indirect solar dryers are systems in which the product to be dried is not directly exposed to sunlight, as shown in Figure 2.4 (Vaibhav and Sanjay, 2016). Indirect solar dryers have two main components, namely, a drying chamber, where the product is kept during drying, and a manifold, which heats up the cool air (solar collector) (Finck-Pastrana, 2014) and a solar collector, which absorbs solar radiation and converts it into heat energy that heats a drying air (Bakari *et al.*, 2014). However, poor thermal conductivity and the low heat capacity of air are major drawbacks, as it results in a low heat transfer coefficient between the air stream and absorber plate. The performance of the solar collector depends on the glazing material used, the thermal insulation and the absorber plate.

Indirect solar drying is used to produce good quality products in terms of colour, texture, flavour and marketability (Varun *et al.*, 2012; Phadke *et al.*, 2015). Indirect solar drying systems are categorized as natural and forced convection dryers (El-Sebaii and Shalaby, 2013). Indirect solar drying systems also reduce the drying time and maintain good quality products compared to OSD (Lingayat *et al.*, 2017). They are therefore, regarded as the best alternative solution to problems reported in OSD and other traditional drying methods (Beigi, 2016; Lingayat *et al.*, 2017).Table 2.5 shows the findings on indirect solar dryers.

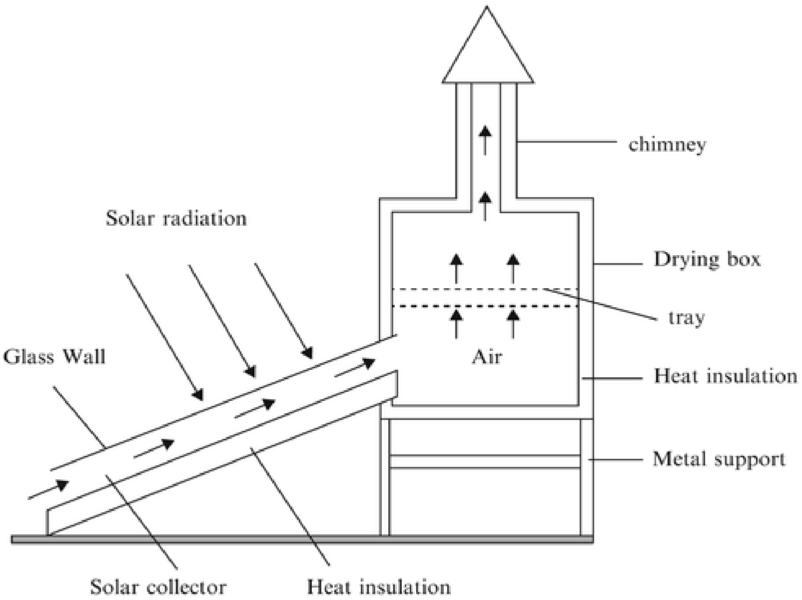

Figure 2.4 Illustration of the working principle of an indirect solar dryer (After Vaibhav and Sanjay, 2016)

Table 2.4 Summary of observations on indirect solar drying

Crop dried	Observations	References
Grapes and figs	Scalded and sulfurized samples had a lower amount of Vitamin C as a result of oxidation. Colour and texture showed a high level of acceptance, compared to sun dried samples in both grapes and figs.	Gallali *et al.*, 2000
Olives leaf	The lightness (L^*) of the final dried leaves increased more than fresh leaves, and the greenness decreased, while the luminance of the leaves improved.	Bahloul *et al.*, 2009
Lemon slices	Less browning was obtained in a solar dryer, compared to a hot air dryer, drying at 60°C.	Chen *et al.*, 2005

2.9.4 Hybrid solar drying

Hybrid solar dryers have a conventional source of heat energy or storage in order to continue drying during non-sunshine hours (Reyes *et al.*, 2014; Rabha and Muthukumar, 2017). Hybrid solar drying does not only depend on weather conditions for energy source, hence, drying can take place even during non-sunshine hours, resulting in continuous drying to minimise chance of deterioration of the product by microbial activity (Hossain *et al.*, 2008; López-Vidaña *et al.*, 2013). Hybrid solar dryers are made of three main components namely: (a) a solar collector, (b) an energy accumulator and (c) a drying chamber. Literature reviewed reports studies that have been conducted on solar dryers, with and without the solar accumulator, and results show that such systems use between 10% - 25% of solar energy (Reyes *et al.*, 2014). The working principle of Hybrid solar dyers is as shown in Figure 2.5

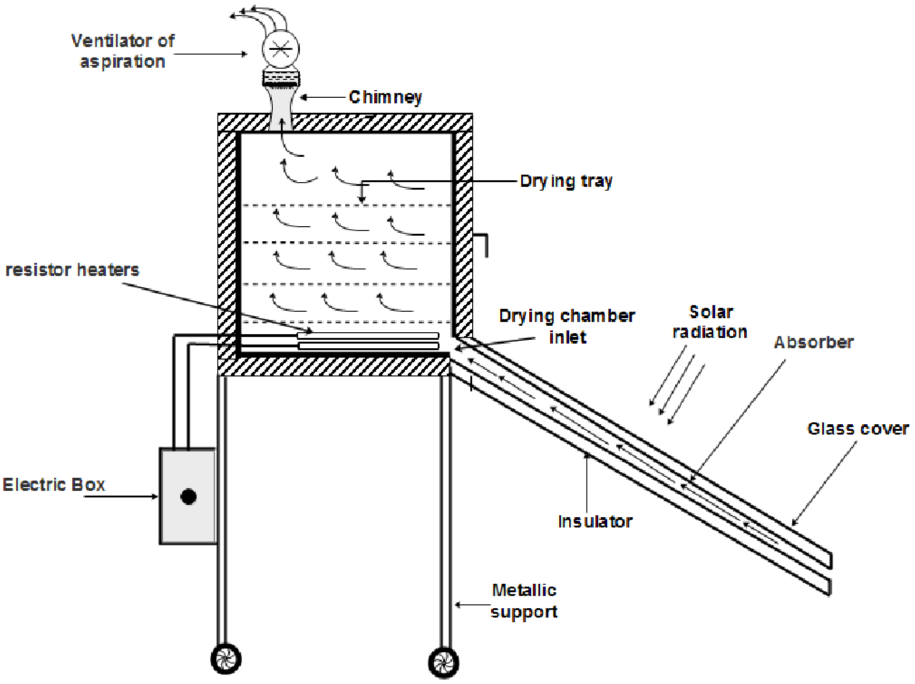

Figure 2.5 Illustration of the working principle of a hybrid solar dryer (After Reyes et al., 2014)

Table 2.5 Summary of observations on hybrid solar dryers

Crop dried	Observations	References
Tomato	Dryer performance was evaluated, in terms of drying rate, total flavonoids, colour, ascorbic acid and lycopene, to compare with the open sun drying findings. The drying process reduced the ascorbic acid, colour, lycopene and total flavonoids significantly.	Hossain *et al.,* 2008
Potato	An improved final dried product was obtained by increasing the number of solar panels from one panel to two panels, which also reduced the drying time from 3 hours to 2h.45 min.	Chouicha *et al.*, 2013
Onions and Potatoes	The dryer was able to increase the air temperature, using solar energy and, heating elements, which improved the temperature control inside the drying chamber	Singh and Verma 2015

2.9.5 Solar dryers compared to other drying methods

Preservation of agricultural food preservation has been practised all over the world for thousands of years, using various methods (Aravindh and Sreekumar 2015; Bala, 2017). Drying has been the most common method of preservation in developed and developing countries. A number of studies on various drying methods have identified the most feasible method of obtaining a specific final dried product (Costa *et al.*, 2011; Bhargava and Bansal, 2018). Table 2.7 shows a comparison between solar drying and other methods. However, solar drying is highly affected by the environmental conditions of a specific location (Dina *et al.*, 2015). Some key indicators of suitability for solar drying applications include:

(a) the amount of sunshine received in a particular location and duration;
(b) the amount of available solar energy;
(c) the quality of the final dried product; and
(d) introducing solar energy has no negative impact.

Table 2.6 Advantages and disadvantages of a solar dryer over traditional and fuelled drying methods

Drying method	Advantages (+) and disadvantages of solar drying (-)
Solar drying versus other common drying methods (open-sun drying and fuelled)	Almost zero operating costs (+)
	Zero dependence on fuel or conventional energy sources (+)
	Little or no environmental impact (+)
	Preferably hot and dry weather conditions (-)
	Reduction of food losses and contamination (+)
	Good quality products (+)
	Less labour, drying area and time (+)
	Ability to reduce moisture content to safe level for longer storage (+)
	Sometimes food quality is not significantly improved (-)
	Sometimes market value is not improved (-)
	Enough solar radiation is required (-)

*(-) = Disadvantage and (+) = Advantage

2.10 Drying Models

Drying is a process comprising of simultaneous heat and mass transfer within the material and between the surfaces of the material the surrounding. Drying models describe the drying process for different agricultural products. Drying models can be classified as either empirical, semi-theoretical or theoretical and they have been developed and used over decades to design and select the optimum drying conditions and to accurately predict the simultaneous heat and mass transfer during the drying process (Aktaş *et al.*, 2008; Mercali *et al.*, 2010; Kucuk *et al.*, 2014; Onwude *et al.*, 2016). These models are used to estimate drying several products under different drying conditions, and how to increase the drying process efficiency and also generalize drying curves, for the design and operation of dryers. Empirical and semi-theoretical models only account for external resistance to moisture transfer between the air and the product, while theoretical models account only for internal resistance to moisture transfer (Asiru *et al.*, 2013). Empirical models are widely since they constitute of direct relationship between moisture content and the drying time (da Silva *et al.*, 2014; Naderinezhad *et al.*, 2016). Semi-theoretical models are derived from simplifying general Fick's second law. To accurately predict heat and mass transfer during the drying process, the drying time as a function of the moisture content is required (Silva *et al.*, 2012; Kucuk *et al.*, 2014).

2.10.1 Thin-layer drying theories and modelling

A thin-layer drying model is used to design and optimize efficiency of drying systems (Hashim *et al.*, 2014; Ertekin and Ziya, 2017). It is used to determine the drying kinetics of food materials and involves simultaneous heat and mass transfer operations (Olawale and Omole, 2012; Onwude *et al.*, 2016). Thin-layer drying models are classified into distributed models, lumped models, theoretical models, and semi-theoretical models (Demiray and Tulek, 2012). Distributed models consider simultaneous mass and heat transfer (both internal and external) and they also predict moisture gradient and predict temperature of the product better (Erbay and Icier, 2010). The thin-layer models work on the Luikov equation derived from Fick's Second Law of Diffusion, as shown in Eq. (2.6) and Eq. (2.7):

$$\frac{\partial \mathrm{M}}{\partial \mathrm{t}} = \nabla^2 \mathrm{K}_{11}\mathrm{M} + \nabla^2 \mathrm{K}_{12}\mathrm{T} \qquad (2.6)$$

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \nabla^2 \mathrm{K}_{21}\mathrm{M} + \nabla^2 \mathrm{K}_{22}\mathrm{T} \qquad (2.7)$$

Where

$\mathrm{K}_{11}, \mathrm{K}_{22}$ = phenomenological coefficients,

$\mathrm{K}_{12}, \mathrm{K}_{21}$ = coupling coefficients,

$\frac{\partial \mathrm{M}}{\partial \mathrm{t}}$ = mass transfer, and

$\frac{\partial \mathrm{T}}{\partial \mathrm{t}}$ = heat transfer.

Theoretical and semi-theoretical models do not only describe partial removal of water but also heat penetration during water removal when hot air is used (Asiru *et al.*, 2013; da Silva *et al.*, 2014). Theoretical and semi-theoretical models accounts for the transport of moisture between the atmospheric air and the material (Ajala *et al.*, 2012).

i. Theoretical models

   Theoretical models account for both the external and internal moisture transfer, making them more reliable (Erbay Z and Icier, 2010; Onwude *et al.*, 2016). Both the internal and external resistances can be calculated using equations that describe heat and mass transfer (Erbay Z and Icier, 2010). However, theoretical models make too many assumptions leading to a considerable number of errors, thus limiting their utilization in the design of dryers (Onwude *et al.*, 2016).

ii. Semi-theoretical models

The semi-theoretical models are derived from solutions of Fick's Second Law of Diffusion and modifications of its simplified forms (other semi-theoretical models are derived by analogues with Newton's Law of cooling). They are easier and need fewer assumptions as they use of experimental data (Onwude *et al.*, 2016; Ertekin and Ziya, 2017). The semi-theoretical and some empirical models provide an understanding of the transport process and demonstrate a better fit to the experimental data (Onwude *et al.*, 2016; Ertekin and Ziya, 2017). The main challenge about the empirical models is that they are dependant largely on experimental data and provide limited information about the heat and mass transfer during the drying process (Blanco-Cano *et al.*, 2016).Table 2.8 below shows studies conducted on the thin-layer drying of agricultural foods.

Table 2.7 Summary of studies conducted on thin-layer drying

Crop dried	Type of a dryer	Selected drying model	Reference
Apple slices	Oven dryer	Midilli et al. Henderson and Pabis	(Meisami-asl *et al.*, 2010; Zarein M *et al.*, 2013)
Jackfruit	Tunnel dryer	Midilli et al.	(Saxena and Dash, 2015)
Chilli	Oven dryer and fluidized bed dryer	Midilli et al.	(Mihindukulasuriya and Jayasuriya, 2013)
Apple slices	Laboratory hot-air convective dryer	Logarithmic	(Kaleta and Górnicki, 2010)
Basil leaves	Tunnel and tray dryer	Logarithmic	(Kadam *et al.*, 2011)
Beetroot	Tray and microwave dryer	Two term	(Kaur and Singh, 2014)
Onion slices	Open sun drying	Two term	(Yaldýz and Ertekýn, 2007)
Pumpkin	Laboratory hot-air convective dryer	Henderson and Pabis	(Zenoozian *et al.*, 2008)

2.10.2 Model selection and assessment

The mathematical modelling of the drying process of agricultural produce allows for the prediction of their behaviour during the drying process. Some of thin-layer models such as Henderson and Pabis, Logarithmic, Two-term and Midili *et al.* for drying are presented in Table 2.9. In these models, the moisture ratio (MR) is calculated using the Fick's law of diffusion Eq. (2.8). This equation assumes that the air velocity is high enough or the drying material is thin enough, to assume that the temperature and humidity are constant (Onwude *et al.*, 2016; Onu *et al.*, 2017).

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_e}}{\mathrm{M_i} - \mathrm{M_e}} = \mathrm{e}^{-\mathrm{kt}} \tag{2.8}$$

Where

MR = moisture ratio [dimensionless],

$\mathrm{m_t}$= moisture content at time *t* [%],

$\mathrm{m_e}$= equilibrium moisture content (dry basis) [%],

$\mathrm{m_i}$= initial moisture content (dry basis) [%],

k= drying rate constant per minute [kg.min^{-1}], and

t= drying time [min].

In the assessment of the models, drying data collected can be used to determine the applicability of the models through the use of statistical measures, such as the coefficient of determination (R^2), the coefficient of correlation (r) and the root mean square error (RMSE) (Kaur and Singh, 2014; Aregbesola *et al.*, 2015). The value of R^2 can be calculated by using Eq. (2.9) and ranges from 0 to 1, the closer it gets to 1, the better the model describes the drying behaviour (Onwude *et al.*, 2016; Ertekin and Ziya, 2017). RMSE is a measure of a standard error that can be calculated using Eq. 2.10 and the coefficient of correlation *r,* is a square root of R^2, which is a measure of a correlation between two variables ranging between -1 to +1 inclusive (Alibas, 2012; Ertekin and Ziya, 2017). The sum of the square errors (SSE) is calculated by using Eq. (2.11), which determines the differences between each observation.

$$\mathrm{R}^2 = 1 - \frac{\sum_{\mathrm{i}=1}^{\mathrm{N}} (\mathrm{MR}_{\mathrm{exp,\ i}} - \mathrm{MR}_{\mathrm{pre,\ i}})^2}{(\mathrm{MR}_{\mathrm{exp}} - \mathrm{MR}_{\mathrm{exp,\ i}})^2} \tag{2.9}$$

Where:

$\mathrm{MR_{pre,i}}$ = predicted dimensionless moisture ratio by the Page model,

$\mathrm{MR_{exp,i}}$ = experimental dimensionless moisture ratio, and

N = number of experimental data points.

$$\mathrm{RMSE} = \left(\frac{\sum_{i=1}^{N}(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}})^2}{N}\right)^{1/2} \qquad (2.10)$$

$$\mathrm{SSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(\mathrm{MR_{exp,i}} - \mathrm{MR_{pre,i}})^2} \qquad (2.11)$$

Table 2.8 Thin-layer drying models

Model name	Model	References
Henderson and Pabis	$\mathrm{MR = a\ exp(-kt)}$	Hashim *et al.*, (2014)
Logarithmic	$\mathrm{MR = a\,exp(-kt) + b}$	Kaur and Singh, (2014)
Two term	$\mathrm{MR = a\,exp(-kt) + b\ exp\ (-kt)}$	Blanco-Cano *et al.*, (2016)
Midili et al.	$\mathrm{MR = a\,exp(-(kt^n) + bt}$	Ayadi *et al.*, (2014)

$\mathrm{MR} =$ predicted moisture ratio [dimensionless], $\mathrm{a, b,}$ n = drying model coefficient, $\mathrm{k} =$ drying constant [hr^{-1}] and $\mathrm{t} =$ is the drying time [hr^{-1}].

2.11 Pre-drying Treatments

In order to improve the quality of processed fruits and vegetables there are various methods that are utilized, such methods commonly referred to as pre-treatments as they are applied prior the drying process (Abdulla *et al.*, 2014; Haile *et al.*, 2015). The most commonly used pre-treatments include blanching, salting and lemon juice.

2.11.1 Blanching

Blanching is also known as a hot-water treatment; is used as pre-treatment before drying of agricultural foods. It is uses inactivate enzymes and increase the rate of drying (fruits and vegetables) (Allen *et al.*, 2016; Wang *et al.*, 2018). The effect of blanching at various temperatures has been studied and modelled by a number of researchers, using thin-layer drying models (Oke and Workneh, 2014; Garba *et al.*, 2015). Abdulla *et al.* (2014) studied the effect of pre-treatments on moisture content, colour, and oil absorption of fried sweet potato chips. In the study, SPS were pre-dried only, blanched, or treated with 0.1% citric acid solution prior drying. The study concluded that SPS pre-dried only were darker, compared to blanched and citric acid treated chips. Fried sweet potato chips pre-treated with either citric acid or blanching and pre-dried had the best sensory scores for sensory quality attributes. On the other hand, Lui *et al*. (2014) studied the effect of steam blanching (SB), hot water blanching (HWB) and microwave blanching (MWB) on purple-flesh sweet potatoes. The study reported that the HWB- and SB-treated samples had significantly brighter final products, compared to MWB. Research revealed that blanching is an important step in preventing off flavouring and colouring, when drying fruits and vegetables (Doymaz, 2011; Dinrifo, 2012; Wang *et al.*, 2018). It is reported that blanching also reduces the primary causes of quality degradation, such as browning (Liu *et al.*, 2015).

2.11.2 Salting

Salting in the form of sodium chloride has an influence on the crispiness and taste of dried sweet potato chips. However, studies reflect that it has the potential to reduce β-carotene (Tumuhimbise *et al.*, 2013; Clifford *et al.*, 2014; Haile *et al.*, 2015). Gaston *et al.* (2013) studied the effect of salting on the sensory characteristics and quality of Orange-Fleshed Sweet Potato crisp (OFSP). The study reported that OFSP treated with 2% salt scored the highest acceptability mean scores and were reasonably stable during storage, while there was no difference between varieties (Ejumula and Kakamega). Haile *et al.* (2015) reported that salt treated SPS had the lowest moisture content and the highest ash content. The salting of SPS increases stress in the enzymes and bacteria and reduces the osmotic tension on tubers cells (Bechoff *et al.*, 2011; Gaston *et al.*, 2013).

2.11.3 Lemon juice

The moisture content reduction of agricultural foods to less than a 20% wet basis reduces microbial and enzyme activity (Antonio *et al.*, 2008; Abano *et al.*, 2013). Lemon juice has been used as a pre-treatment to inhibit microbial growth on SPS during drying and storage (Bechoff, 2010). Abano *et al.* (2013) studied the effect of ascorbic acid, lemon juice and honey treatment on the sensory characteristics and drying kinetics of dried mango slices. The results showed a high preference on sensory characteristics of final dried samples pre-treated with honey; followed by ascorbic acid, control lemon juice and salt solution, respectively. Hence, the study concluded that these pre-treatments when applied before the drying of food materials enhance sensory quality of the final product. Therefore, this study will use the salt, lemon juice and blanching pre-treatments.

2.12 Quality Assessment of Sweet Potato Slices

The quality of SPS after drying is assessed, using various quality parameters such as the physical, physiological, and structural properties.

2.12.1 Colour of sweet potato slices

The colour of the food material is an important attribute that attracts the consumer to buy (Oyedeji *et al.*, 2017; Bhargava and Bansal, 2018). The colour of the final dried food material can be used to assess the effect of drying and the pre-treatment method of the drying food (Costa *et al.*, 2011; Pathare *et al.*, 2013). Colour correlates with the physicochemical properties of food; therefore, it can be used to measure the quality of the final products, such as its nutritional and sensory attributes (Cubero *et al.*, 2011; Nisha *et al.*, 2011). The colour of any food material can be defined by three dimensional parameters, namely: Lightness (L^*), redness (a^*) and yellowness (b^*) (Tiwari *et al.*, 2009). Commission Internationale d’Eclairage (CIE) L^* a^* b^*, as shown in Figure 2.5 is the colour indicator axis that was developed in 1976 to provide more uniform colour differences. The CIELAB colour space indicates that lightness ranges between $L^*= 100$ (white) to $L^*= 0$ (dark), a^* indicates $- a^*$ (greenness) to $+ a^*$ (redness) and b^* indicates $- b^*$ (blueness) to $+ b^*$ (yellowness). From these colour parameters, the colour intensity and hue angle can be calculated by using Eq. 2.12 and Eq. 2.13, respectively (Abdulla *et al.*, 2014):

$$C = \sqrt{(a^*)^2 + (b^*)^2} \tag{2.12}$$

Where

a^* = redness,

b^* = blueness, and

C = colour intensity.

$$h_{ab} = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{2.13}$$

Where

h_{ab} = hue angle.

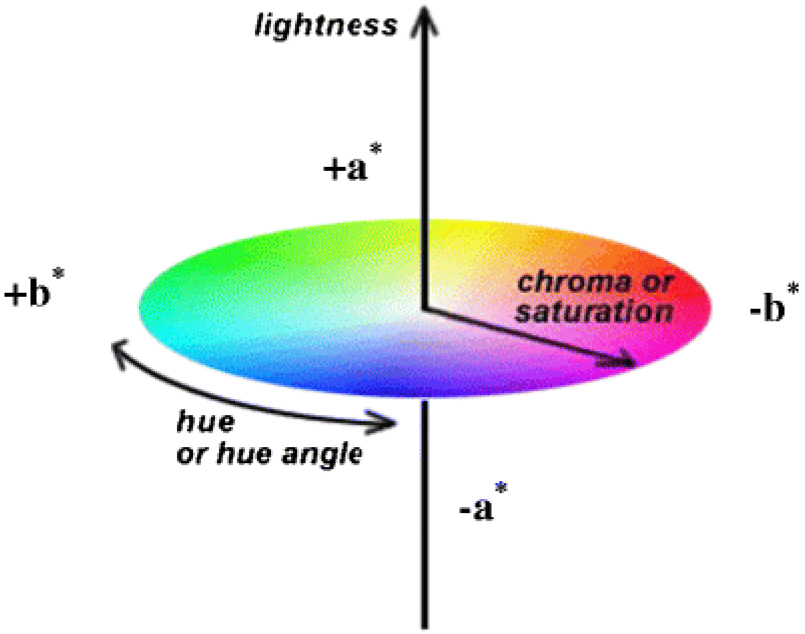

Figure 2.6 CIELAB colour space (Abdulla *et al.*, 2014)

2.12.2 Texture of sweet potato slices

Texture is an important quality attribute in determining the quality and acceptability of dehydrated products (Gao *et al.*, 2014). The common methods of assessing texture or hardness include applying of deforming forces, using compression or puncture test. These are methods, measure the force required to punch a probe to a fruit or vegetable product. It is recommended to use the puncture test and not the flat-plate compression for a fresh produce. The textural properties of the end product of dehydrated tubers are dependent on the properties of the raw material, such as starch granules, starch content, non-starch polysaccharides, polysaccharides, cell walls, pectin substances and the processing conditions (drying time and temperature) (Ishara, 2016; Oyedeji *et al.*, 2017). Chemical changes, such as the release of intracellular materials, crust formation, dehydration (water evaporation), the breakdown of adhesive force cells, tissue expansion and starch gelatinization determines hardness (Gao *et al.*, 2014; Ishara, 2016). Gao *et al.* (2014) reported that the maximum breaking force causes major fractures and determines the hardness of the dried food product. Literature reports that the maximum peak fracture force indicates less sensorial tenderness and crunchiness.

2.12.3 Starch morphological structure

Scanning Electron Microscope (SEM) is a tool used to study the morphology of starch granules and the gelatinization in SPS (Yung-Chang and Che-Lun, 2013; Wei *et al.*, 2017). The morphology of sweet potato starch changes after thermal treatment and it is related to the sensory and physicochemical characteristics of the food product (Lai *et al.*, 2013; Babu *et al.*, 2015). Studies reported that pre-treatment methods have an effect on the starch content of various sweet potato cultivars. Wei *et al.* (2017) reported that steaming reduces the starch (amylopectin and amylose) and sugar content of sweet potatoes. Babu *et al*. (2014) reported that the modification of starch with acid hydrolysis alters the physicochemical properties of starch, without affecting the starch granule structure.

2.13 Discussion

A population increase in developing countries results in the increased competition for resources and food allocation (Gustavsson *et al.*, 2011; Abass *et al.*, 2014; Kiaya, 2014). Electricity grid connection and conventional fossil fuels are the major unevenly-distributed energy resources; hence, the rural areas and in developing countries have limited access to them (Bolaji and Olalusi, 2008; Beneke *et al.*, 2016; Tiwari, 2016). STAT SA (2013) states that the South African population will increase to 80 million by 2035, which will demand an increase in agricultural food production to keep up with the growing population. Agricultural production and agro-processing require high-energy input, which is a challenge to developing countries and small-scale farmers with no access to grid electricity (Afriyie and Bart-Plange, 2012; Chouicha *et al.*, 2013; Lingayat *et al.*, 2017). Almost 80% of the food produced in developing countries is produced by small-scale farmers who lack proper storage and processing equipment because of limited energy sources (Phadke *et al.*, 2015). Kiaya, 2014 reported estimated losses of up to 50%, for fruits and vegetables, and 25% for grains (Kiaya, 2014). Therefore, extra the food required for an increasing population and can be met by reducing the postharvest losses (Sanni *et al.*, 2012). Dehydration and drying are the most common preservation technique amongst other preservation methods and the oldest methods used to reduce the moisture content of agricultural products (Doymaz, 2011; Hashim *et al.*, 2014; Ertekin and Ziya, 2017).

Solar energy is the most attractive and promising energy source usable in countries with enough available solar radiation (Kiaya, 2014; Jabeen *et al.*, 2015; Onwude *et al.*, 2016). South Africa receives enough solar radiation that can be used for energy-intensive processes, such as drying

(Qase *et al.*, 2015; Beigi, 2016). Small-scale farmers commonly use open-air solar dryers (OSD). However, it is less efficient and has a number of drawbacks such as producing low quality produce (İsmail *et al.*, 2015; Tiwari, 2016).

Solar dryers are developed to overcome these drawbacks and inefficiencies (Afriyie and Bart-Plange, 2012; Rodríguez, 2012). They consist of a drying chamber and a solar collector compartment, which is an improvement on the open-air solar dryers (OSD) (Altobelli *et al.*, 2014; Lingayat *et al.*, 2017). Innovative technologies, such as dryers with solar chimneys, thermal storage and wind-ventilators have been developed, with the aim of improving the drying process (Madhlopa and Ngwalo, 2007; Lingayat *et al.*, 2017). Studies on the improvement of traditional methods and development of improved solar drying technologies in South Africa lagged behind, specifically sweet potato drying technologies. Naturally-ventilated solar chimney dryers were found to be the most promising and beneficial drying technology for small-scale farmers and developing countries (Khanal and Lei, 2011). In solar drying, solar energy is collected via solar collectors, and the drying chamber stores the drying material (Khanal and Lei, 2011; Blanco-Cano *et al.*, 2016).

2.14 Conclusion

The literature reviewed showed that the use of naturally-ventilated solar-venturi drying is a feasible solution as it allows for the drying of larger volumes of the produce. The review of literature in this study has identified a research gap in South Africa namely: the potential for modification of the existing storage houses into a naturally-ventilated solar-venturi drying rooms by incorporating solar chimneys and drying chambers that will benefit mostly, small-scale farmers. In this system, air flow is one of the important factors influencing the performance of a solar dryer together with the relative humidity and temperature (Hegde *et al.*, 2015). The development and improvement of solar dryers will help the producers to venture into new business opportunities, such as selling both fresh and processed produce. This will also provide a new simple drying technology. Drying as a preservation method, with the use of drying pre-treatments has been proven to be the most reliable and promising technology to not only reduce food losses, but to also meet the expected increase in food demand.

2.15 References

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3. THE EFFECT OF TEMPERATURE AND RELATIVE HUMIDITY ON THE PERFORMANCE OF NATURALLY-VENTILATED SOLAR-VENTURI DRYER

Abstract

The relationships between natural-ventilated solar-venturi dryer (SD) and ambient temperature and relative humidity (RH) and their effect on the performance of a natural-ventilated solar-venturi dryer is investigated in the study. The objective of the study was to evaluate the effect of the drying conditions (temperature and RH) on the constructed naturally-ventilated solar-venturi dryer. The investigation was done using two dryer conditions (a) an empty (SD with no samples) and (b) loaded (SD with samples). Temperature inside a naturally-ventilated solar-venturi dryer were monitored using hobo-ware data loggers. The temperature and RH showed an inversely proportional relationship. As the ambient temperature increased both the SD and ambient RH decreased. There was a direct proportion between increasing ambient temperature and increased SD temperature.

The solar radiation received had a significant ($p<0.05$) influence on ambient air temperature and relative humidity. The SD was found to raise air temperature and reduce relative humidity of the ambient air. The average temperature and relative humidity difference between the ambient and inside drying chamber were found to be 12.4°C and 19.2% for an empty dryer. The variation of air temperature inside the loaded drying chamber was not significantly different ($p>0.05$) to that of the empty drying chamber. There was a significant difference between the air temperature at the exit of the solar collector and the temperature inside the drying chamber in the fully-loaded experiment. The maximum temperature inside the solar-venturi dryer was 44.4°C (12:00 pm) in an empty dryer and 34.1°C (13:00 pm) for a fully-loaded solar-venturi dryer. The minimum relative humidity in an empty dryer was 13.5% and 15.1% for a fully-loaded solar-venturi dryer. The SD was able to increase the temperature and reduce the relative humidity at a minimum and maximum efficiency of 38.5 and 84.9% in a loaded solar-venturi dryer and 35.2 and 77.6% in an empty dryer.

Keywords: solar-venturi dryer, relative humidity, solar radiation, efficiency

3.1 Introduction

Globally, there is increasing awareness of the potential for the adoption of technologies for agricultural processing including agri-processing and in value addition of agricultural products like drying (Fudholi *et al.*, 2014; Lingayat *et al.*, 2017). Literature reports that there is potential for harvesting solar energy for agricultural processing (Pirasteh *et al.*, 2014; Phadke *et al.*, 2015). Miraei *et al.*, (2017); Rabha and Muthukumar, (2017) reported that solar energy can provide the required temperature for drying. However, solar energy remains untapped in the south, mainly in the African countries (El-Sebaii and Shalaby, 2012; Chouicha *et al.*, 2013).

Developing countries with poorly-established thermal drying and processing facilities face the challenge of closing the gap between the gross food produced and the net food available, as a result of post-harvest losses (Bolaji and Olalusi, 2008; Madrid, 2011; Mustayen *et al.*, 2014). These losses include those in the field, during storage and during processing and are estimated to range between 20-50% in Africa (Abass *et al.*, 2014). The postharvest losses of the harvested cereal is estimated to be 25% and 50% of all fruits and vegetables (Kiaya, 2014). Sun drying has been predominantly used by small-scale farmers to reduce this loss. However, traditional sun drying is fraught with challenges, such as being highly dependent on the weather, as well as the threat of contamination.

On average, South Africa has 2 500 hours of sunshine per year and an average solar radiation that ranges between 4.5 and 6.5 kWh.m^{-2} per day (Qase *et al.*, 2015). Hence, there is a potential for harvesting solar energy. Disadvantages arising from traditional open-sun drying have led to the development of both active and passive conventional types of solar dryer, which can further be sub-divided into the direct, indirect and mixed mode types of a solar dryer. Direct solar dryers have prolonged drying time and to overcome this, indirect solar dryers were developed to reduce the drying time. Sontakke and Salve (2015) conducted a study on indirect solar drying of apricots using a small dish type of a solar heater which was connected to a drying chamber. The study concluded that, indirect solar dryers are able to increase the drying efficiency of a direct solar dryer from 20% at a natural flow rate of 0.01 kg.s^{-1} to 42.6% at a convective flow rate of 0.21 kg.s^{-1}. The study reported that the dehydration of apricot from 85% to 8% moisture content took 13 hours. However, these dryers are linked with high-energy prices.

Use of solar chimney dryers is gaining momentum in agriculture because of the increasing energy prices and the importance of environmental protection. This drying system uses solar energy to heat ambient air to dry agricultural products. Alam (2007) reported that increasing the chimney height of solar chimney dryers increases the dryers' efficiency. This provides free convection, which permits good air speed and the uniform distribution of the hot air inside the drying chamber (Maia *et al.*, 2011; Afriyie and Bart-Plange, 2012). The principle of solar chimney drying combines wind-driven ventilation and a solar stack. There is limited research on the use of solar-venturi drying for agricultural produce in South Africa. Therefore, the objective of this study was to characterise the air temperature and relative humidity inside the SD.

3.2 Materials and Methods

3.2.1 Study site and climatic data

The study was carried out at the Ukulinga Research Farm at the University of KwaZulu-Natal Pietermaritzburg, South Africa (30°24'S'' and 29°24'E at an altitude of 721 m above sea level). The long-term minimum and maximum temperatures of the study site ranges from 6.0 - 16.4°C and 20.6 - 27.4°C, respectively, while the relative humidity ranges from 61.1 - 75.3%. The area receives an average solar radiation of between 15.1 and 27.8 MJ.m^{-2}.day^{-1}, which is sufficient for solar drying application (Schulze and Maharaj, 2007).

The long-term minimum and maximum temperatures for the experimental month (September 2018) ranged from 10.0 - 17.1°C and 12 - 27°C respectively, while the relative humidity ranged from 61.1 – 68.1%. The average solar radiation, wind speed and average sunshine hours for the month of September ranged from 15.1 - 27.8 MJ.m^{-2}.day^{-1}, 0.8 – 9.7 m.s^{-1}, and 7 hours, respectively (Schulze and Maharaj, 2007). Temperature, relative humidity, solar radiation and wind speed data recorded during the study period were obtained from the weather station at Ukulinga research farm.

3.2.2 Sample preparation

A 50 kg batch of fresh sweet potato tubers was purchased from a local supermarket (Pick n Pay, Pietermaritzburg (Hayfields), South Africa). Sweet potato tubers with no physical damage and no sign of fungal or microbial attack were selected. The selected tubers were peeled, using a carbon steel blade potato peeler, after which they were washed, using deionized water. The tubers were dabbed using paper towels to remove the water on the surface. Thereafter, the sweet potato tubers were sliced into rectangular-shaped slices with dimensions of 50 by 20 mm, using a stainless-steel kitchen knife (Oke and Workneh, 2013). There were three thickness sizes of the SPS viz; 3, 5 and 7 mm. The slices were pre-treated by either dipping them in a salt solution (0.1% w/v concentration for 20 minutes), a lemon juice solution (1% w/v concentration for 20 minutes) or blanched in a water bath at 70°C for 10 minutes (Olawale and Omole, 2012) (Labotech water bath, Thermo Fisher Scientific, Waltham, Massachusetts, United States). The pre-treated samples were dabbed, using paper towels to remove excess water from the prepared slices surface.

3.2.3 Description of the solar-venturi dryer

The constructed SD consisted of three main parts, a solar collector, a drying chamber and a solar-chimney as shown in Figure 3.1 (Abdellatif *et al.*, 2015). The ambient air entered the lower side of the solar collectors (roof) and rose to the top side as a result of venturi effect. The solar collectors' heat ambient air as it directed up before entering the drying chamber. The heated air then flowed through the drying chamber as a result of the negative suction created by the solar chimney and the whirlybird at the bottom of the drying chamber, as shown in Figure 3.4.

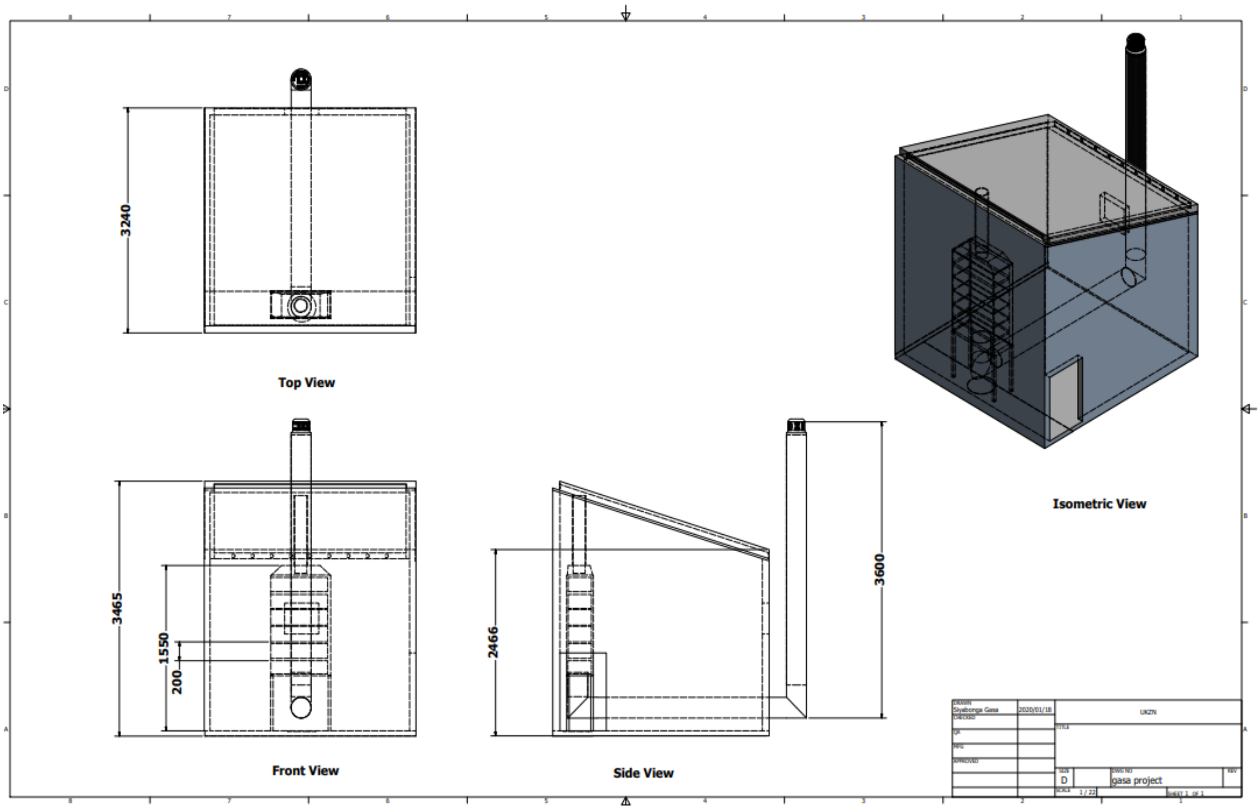

Figure 3.1 Naturally-ventilated solar-venturi dryer

i. Solar collector

The solar radiation collector was constructed, using a galvanized corrugated iron sheet (760 x 3500 x 1 mm). The emissivity and absorptivity of galvanized steel was 0.13 and 0.65, respectively. The galvanized corrugated iron sheet was painted black to increase the absorption of the available solar irradiation. Painting the galvanised corrugated iron sheet black can increase its absorptivity up to 0.90 (Sanni *et al.*, 2012; Seidu *et al.*, 2012). A clear polycarbonate sheet (750 x 3600 x 1 mm) was placed on top of the galvanized corrugated iron sheet, with a clearance of 100 mm, as shown in section A-A of Figure 3.2. The polycarbonate sheet was supported by a rectangular steel bar frame, with a cross-section of 3 x 100 mm. Polycarbonate sheeting has a transmittance of 0.80. The ambient air entered the solar collector via the circular inlet (50 mm diameter) at the lower side of the solar collector. The inlets were spaced at 100 mm from centre to centre, as shown in Section A-A and exit from a circular opening (150 mm diameter) on the elevated side of the solar collectors to the drying chamber.

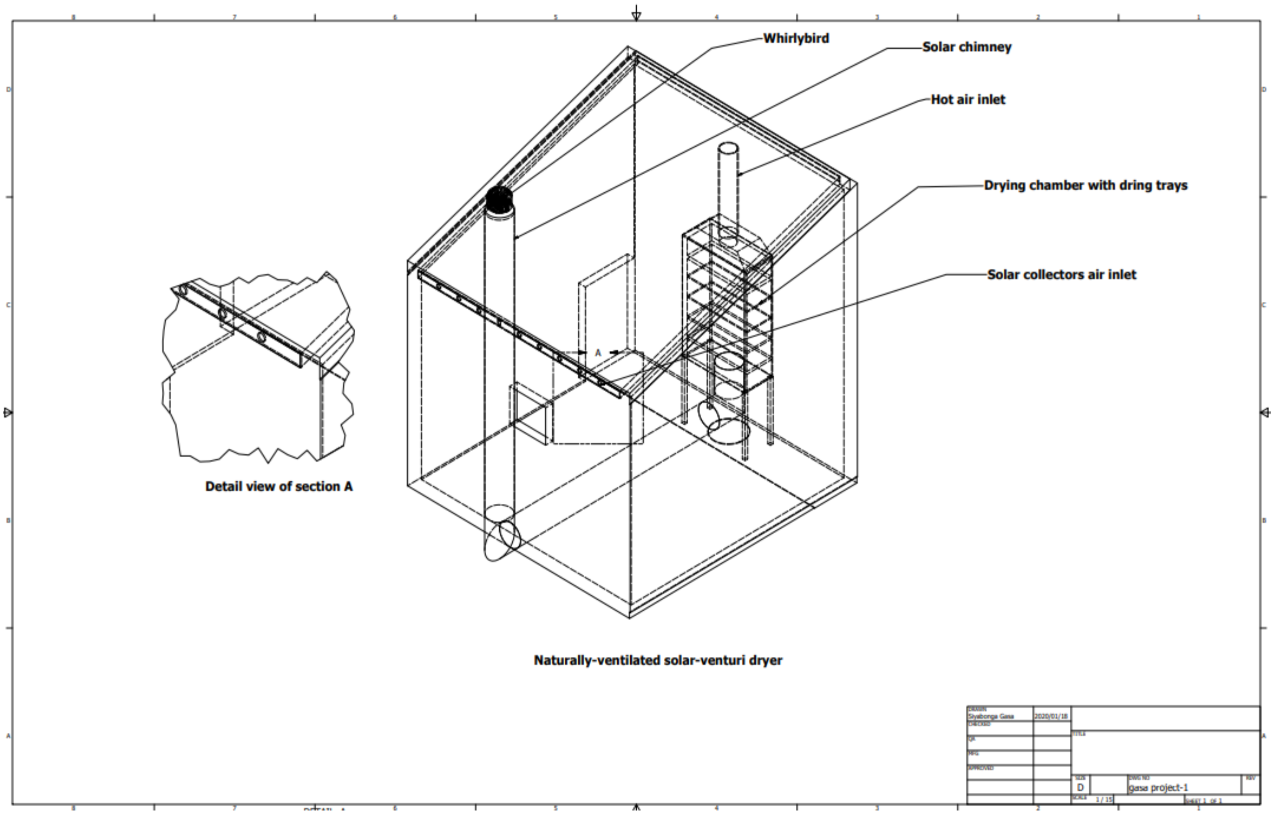

Figure 3.2 Isometric view of a naturally-ventilated solar-dryer

ii. Drying chamber

The drying chamber with the dimension of 900 x 600 x 1450 mm, was constructed using angle bars (25 x 25 x 5 mm), as shown in Figure 3.3. The steel frame was enclosed, using 9.5 mm thick plywood. The drying chamber was fitted with six (900 x 600 mm) equally-spaced trays (200 mm apart) made of wire mesh (with an aperture size of 0.23 by 0.23 mm). The drying chamber had two circular (150 mm in diameter) air inlets at the top, which were connected to the solar collector via two 1100 mm long cylindrical pipes, each with a diameter of 150 mm. The air exited the drying chamber through a 300 mm diameter hole at the bottom that was connected to the solar chimney using an L-shaped galvanised steel cylindrical pipe with a diameter of 300 mm.

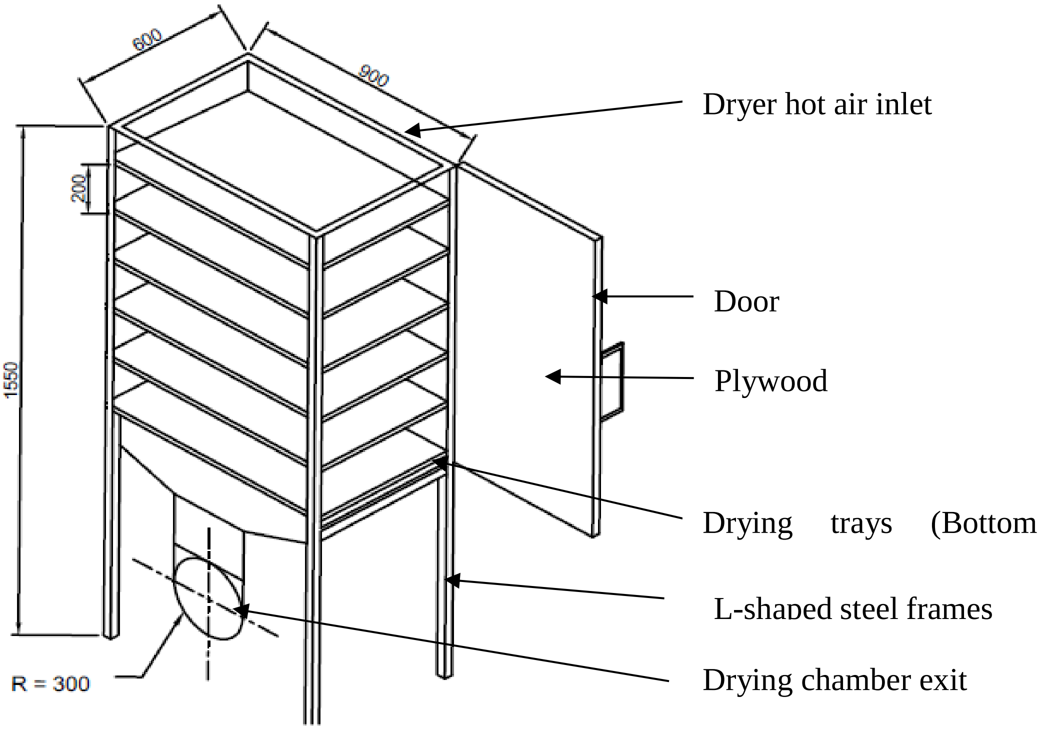

Figure 3.3 Schematic presentation of the drying chamber

iii. Solar chimney

The solar chimney was made of galvanized steel with the height of 3600 mm and a diameter of 300 mm (Figure 3.1 above). The solar chimney was painted black. A whirlybird with a diameter of 250 mm in diameter was connected by using a ducting reducer with a diameter of 300-250 mm.

3.3 Performance Evaluation of both an Empty and a Fully-Loaded Solar-venturi dryer

The performance of the solar-venturi dryer was evaluated by measuring the air velocity, temperature and the relative humidity inside the drying chamber as well as the ambient temperature and the relative humidity on sunny days. The air temperature and relative humidity inside the solar-venturi drying system were measured at four points, namely: A (at the exit of the solar collector), B (at the inlet of the drying chamber), C (at the centre of the drying chamber), and D (at the exit of the drying chamber). Hobo ware data loggers (Model U23-001, Onset, Cape Cod, USA) were used to measure the temperature and relative humidity with an accuracy of ±0.21°C and ±2.5%, respectively. The data loggers were placed (two at each measuring point A, B, C and D) as shown in Figure 3.4. The air velocity was measured at the centre of the drying chamber, using a Heavy Duty Hot Wire Thermo-Anemometer (Extech instruments, Massachusetts, United States). In a loaded drying experiment (dryer with samples) each tray was loaded with 2.7 kg of SPS in each experiment.

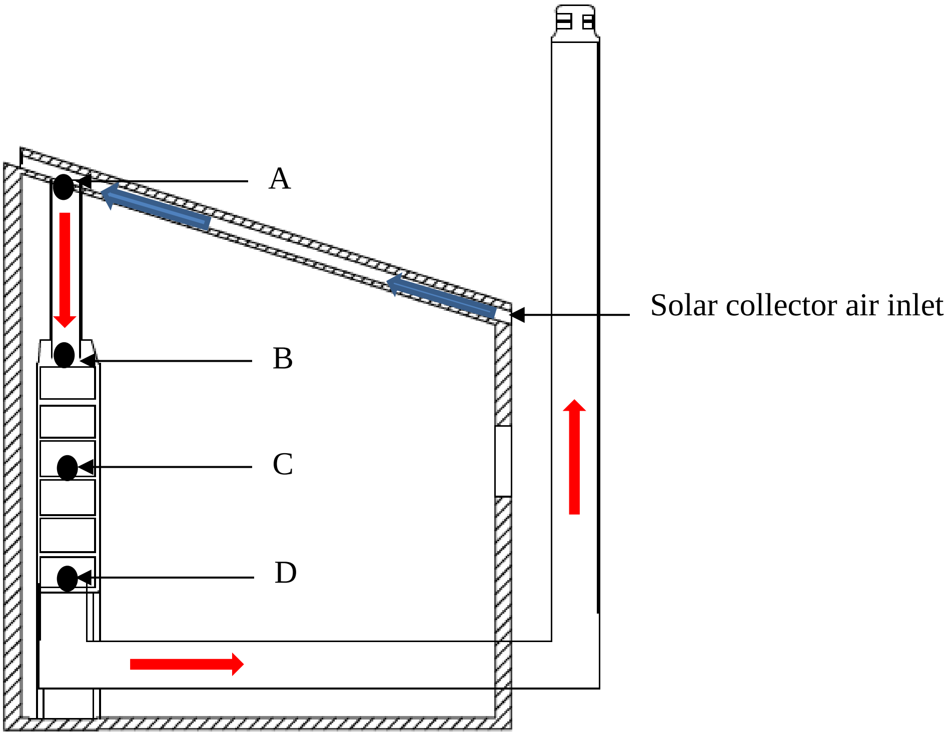

Figure 3.4 Illustration of air flow and data collection points inside the solar dryer (*A = exit of the solar collector, B = inlet of the drying chamber, C = centre of the drying chamber and D = exit of the drying chamber)

3.4 Performance Evaluation of the Solar Collector

The performance evaluation of the solar collector was done by calculating the available solar energy (Eq. 3.1) (Abdellatif,*et al.*, 2015).

$$q_a = R \times A_c \tag{3.1}$$

Where

R = solar radiation flux incident [W.m^{-2}],

A_c = area of the solar collector [m^2], and

q_a = solar energy available [W].

The useful heat gained in the solar collector was calculated using (Eq. 3.2) (Abdellatif,*et al.*, 2015).

$$q_u = \dot{m} c_p (T_e - T_i) \tag{3.2}$$

Where

q_u = heat gained by the air [W],

$\dot{m}$ = mass flow rate of air [kg.s^{-1}],

c_p = specific heat of air [=1.006 kJ.kg.^{o}C $^{-1}$],

T_i = temperature at the inlet of the solar collector [C], and

T_e = temperature at the exit of the solar collector [C].

The overall thermal efficiency of the solar collector was calculated, as shown in (Eq.3.3).

$$\eta_c = \frac{q_u}{q_a} \times 100 \tag{3.3}$$

Where

η_c = solar collector efficiency [%], and

A_c = area of the solar collector [m^2].

3.5 Results

The ambient air conditions (temperature, relative humidity and solar radiation) measurements were taken on hourly basis during the experimental month (September 2018). The experiments for the natural-ventilated solar-venturi dryer were divided into empty (dryer with no samples) and a loaded drying (dryer with drying samples).

3.5.1 Air temperature and relative humidity of an empty solar-venturi dryer

The average variation in ambient temperature and temperature inside the dryer at various locations in the solar-venturi dryer from 2-6 September 2018 is presented in Figure 3.5. The minimum and maximum ambient temperatures were 23.3°C and 26.4°C recorded at 8:00 am and 14:40 pm, respectively. The solar radiation increased from a minimum of 388.0 W.m^{-2}, recorded at 8:00 am, to a maximum of 894.3 W.m^{-2}, recorded at 12:00 pm, beyond which it gradually reduced to the 742.7 W.m^{-2} recorded at the end of the experiment (14:40 pm).

The initial and final temperatures recorded at the exit of the solar collector were 32.2°C and 29.7°C respectively. The temperature at the exit of the solar collector gradually increased from 32.2°C, recorded at the start of the experiment (8:00 am) to a maximum of 44.4°C, recorded at 12:00 am, after which it dropped sharply to a minimum of 29.7°C, recorded at the end of the experiment. The temperature recorded at the inlet, centre and exit of the drying chamber gave a similar temperature profile to that at the exit of the solar collector (Figure 3.5).

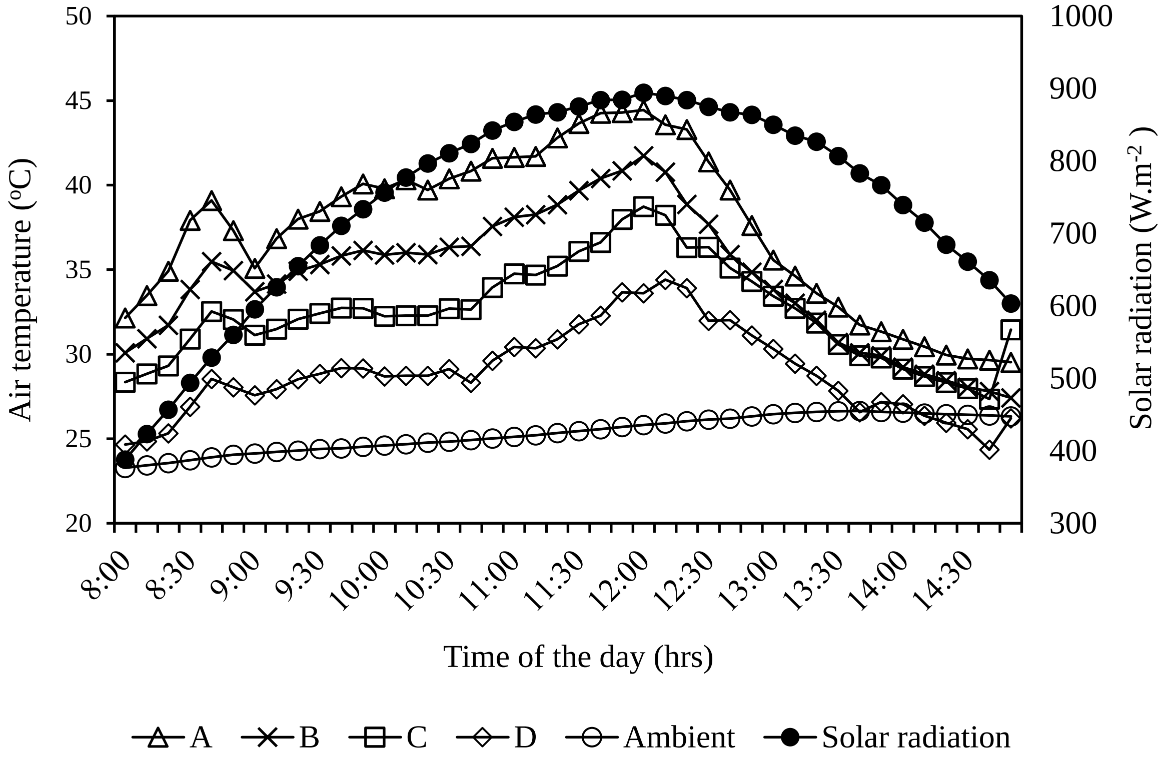

Figure 3.5 Average daily variation of air temperature and solar radiation in an empty dryer (A = exit of the solar collector, B = inlet of the drying chamber, C = centre of the drying chamber, D = exit of the drying chamber, Ambient = Ambient temperature

The maximum temperatures recorded at inlet, centre and exit of the drying chamber were 41.7, 38.7 and 34.4^{o}C, respectively. The minimum temperatures recorded at the inlet, centre and exit of the drying chamber, were 27.8, 27.4, and 24.4^{o}C, respectively. At all the points (inlet, centre and exit of the drying chamber), the maximum and minimum temperatures were recorded at 12:00 (mid-day) and 14:40 pm (the end of the experiment), respectively. The average temperature differences between the ambient temperature and the exit of the solar collector, the exit of solar collector and the inlet of the drying chamber, the inlet and centre of the drying chamber, centre and the exit of the drying chamber were 12.4, 3.0, 2.2, and 3.6^{o}C, respectively.

The ambient relative humidity and the relative humidity recorded inside the solar-venturi dryer, are shown in Figure 3.6. The initial ambient relative humidity at the start of the experiment (8:00 am) and the final ambient relative humidity at the end of the experiment (14:40 pm) were 50.2% and 61.7%, respectively. The maximum ambient relative humidity recorded was 61.7% at 14:40 pm. The minimum ambient relative humidity recorded was 31.2% at 12:20 pm and the average relative humidity was 44.5%.The initial relative humidity recorded at the exit of the solar collector inlet, at the centre and exit of the drying chamber, was 29.9, 33.8, 38.0 and 47.9% at the beginning of the experiment (8:00 am). It then decreased to a minimum relative humidity of 13.5, 15.2, 18.4 and 28.4% recorded at 12.00 pm at the exit of the solar collector, and at the inlet, centre and exit of the drying chamber. The final relative humidity (at the end of the experiment) at the exit of the solar collector, and at the inlet, centre and exit of the drying chamber were 49.5, 49.5, 49.9 and 59.9%, respectively. The final relative humidity recorded at the end of the experiment (14:40 pm) was observed to be the maximum relative humidity at all measured points. The relative humidity of the air increased as the air moved from the solar collector down to the exit of the drying chamber (Figure 3.6).

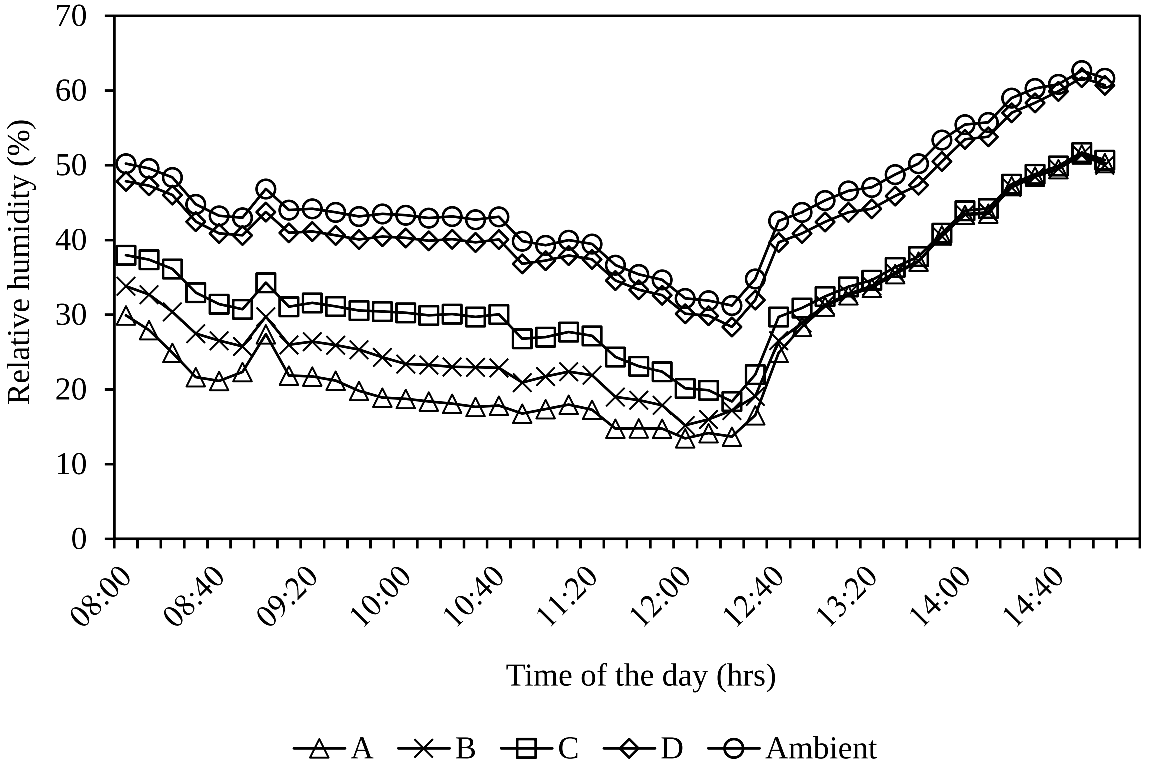

Figure 3.6 Average daily variation of air relative humidity in an empty dryer (A = exit of the solar collector, B = inlet of the drying chamber, C = centre of the drying chamber, D = exit of the drying chamber and Ambient = ambient relative humidity)

3.5.2 Air temperature and relative humidity of a fully-loaded solar-venturi dryer

The average ambient temperatures recorded at the start and end of the experiment were 20.2°C and 22.3 °C, respectively from 9-20 September 2018. The maximum, minimum and average ambient temperatures recorded were 22.4 (15:50 pm), 20.2°C and 21.2°C, respectively, as shown in Figure 3.7. The solar radiation at the start of the experiment was measured to be 546.9 $W.m^{-2}$, increasing to a maximum of 889.7 $W.m^{-2}$ recorded at 13:00 pm and thereafter, it dropped to 566.5 $W.m^{-2}$ (16:00 pm).

The temperatures inside the drying chamber (inlet, centre and exit) measured at the start of the experiment were 23.6, 22.1 and 20.9°C. The maximum temperatures recorded at the inlet, centre and exit of the drying chamber were 34.1, 29.7 and 25.9°C, respectively. At all measuring points, the maximum temperature occurred at 13:00 hours, after which it decreased until the end of the experiment. At the maximum temperature points, solar radiation was at its maximum. The final temperatures at the inlet, centre and exit were 25.3, 24.7 and 23.7°C, respectively. The temperature difference between the ambient conditions and the exit of the solar collector, the exit of the solar collector and the inlet of the drying chamber, as well as the inlet of the drying chamber and the centre of the drying chamber, centre and exit of the drying chamber were 10.7, 11.5, 3.1 and 2.2°C respectively.

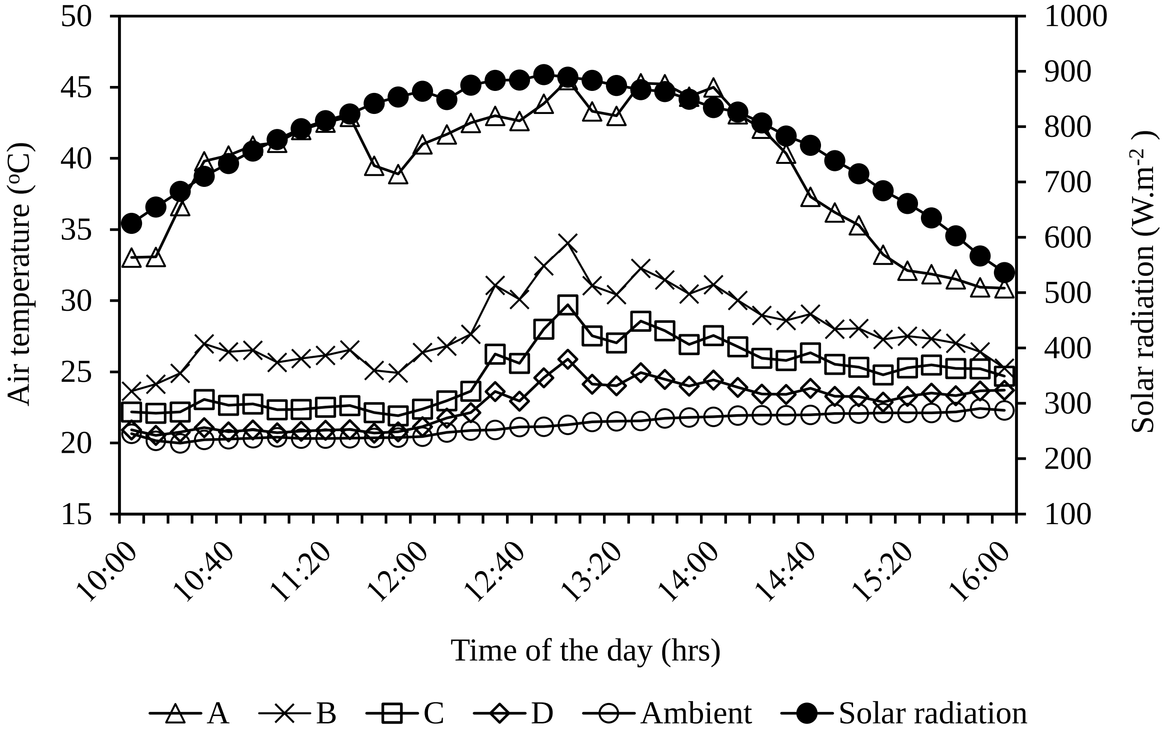

Figure 3.7 Average daily variation of air temperature and solar radiation in a fully-loaded solar dryer (A = exit of the solar collector, B = inlet of the drying chamber, C = centre of the drying chamber, D = exit of the drying chamber, Ambient = ambient temperature

The relative humidity at the exit of the solar collectors was 22.3% (at 10:00 am) initially at the start of the experiment. It then then decreased to a minimum of 10.8% (13:00 pm) during the experiment, as shown in Figure 3.8. And finally increased to 35.8% (16:00 pm) at the end of the experiment. The maximum relative humidity at the inlet, centre and exit of the drying chamber was 39.9, 39.1 and 45.7%, respectively. The initial relative humidity (RH) recorded at the inlet, centre and exit of the drying chamber was 34.3, 39.1 and 45.7 %, respectively. The final relative humidity (16:00 pm) was 39.9, 38.3 and 41.8%, respectively. The minimum RH was observed at midday in all measuring points (inlet, centre and exit of the drying chamber) and were measured to be 15.1, 18.4 and 26.6%, respectively. The average relative humidity difference between ambient and exit of the solar collectors, the exit of the solar collectors and the inlet of the drying chamber, the inlet of the drying chamber and the centre of the drying chamber, the centre and the exit of the drying chamber were measured to be 18.4, 7.4, 4.4 and 1.0% respectively. The initial ambient relative humidity outside the dryer was measured to be 46.3% (10:00 am) and the final relative humidity was 39.5% (16:00 pm). It decreased to a minimum of 27.8% (14.30 pm). The average ambient relative humidity was 35.9 % respectively.

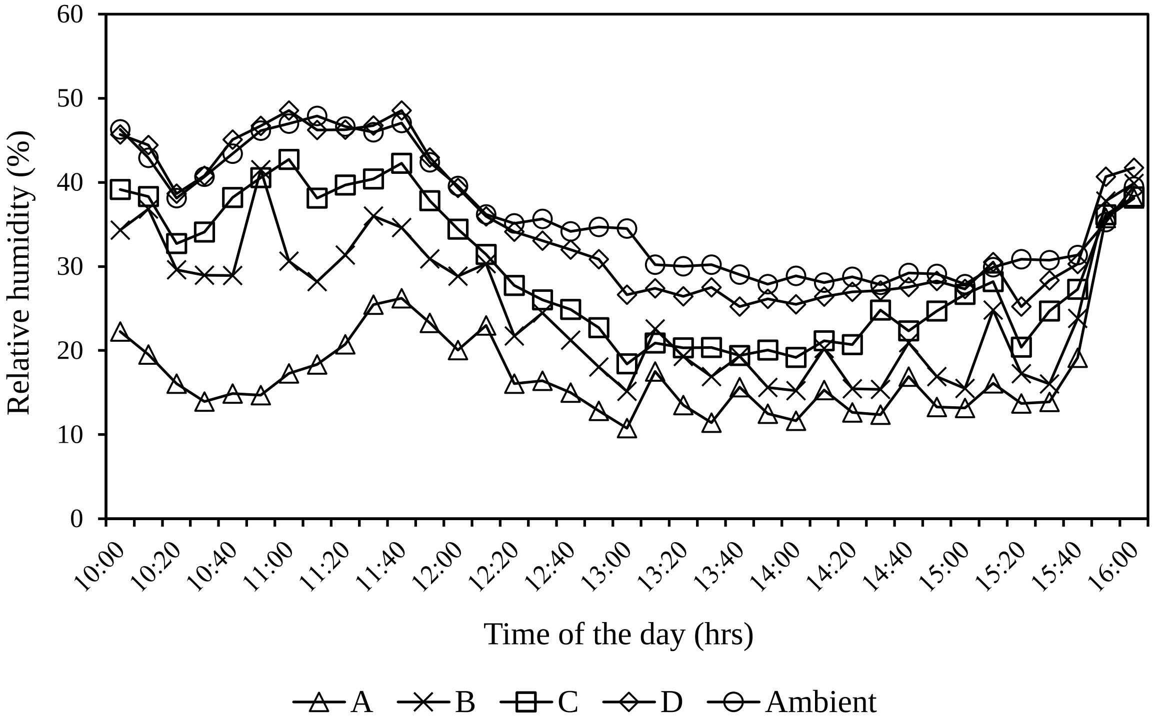

Figure 3.8 Average daily variation of air relative humidity in an fully-loaded dryer (A = exit of the solar collector, B = inlet of the drying chamber, C = centre of the drying chamber, D = exit of the drying chamber and Ambient = ambient relative humidity)

3.5.3 Evaluation of the solar collector

In unloaded drying conditions, the minimum and maximum solar energy available at the solar collector was 3984.2 W and 9184.2 W, respectively. On the other hand, the minimum and maximum useful heat gained by the air was 1131.0 W and 9486.0 W, respectively. The minimum and maximum solar energy available during loaded drying conditions was 5514.2 W and 9136.9 W, respectively. The minimum and maximum useful heat energy gain by air in the solar collector was 2072.3 W and 17217.3 W, respectively. The heat gained by the air in an empty and loaded solar-venturi dryer are presented in Figures 3.8 and 3.9, respectively.

Figure 3.11 highlights the average daily (2-20 September 2018) variation in the efficiency of the solar collector. The maximum efficiency of the solar collector for an empty dryer was 77.6% and was achieved at 12:00 pm. For a loaded solar dryer, the maximum solar collector efficiency was 84.9%, which obtained at 13:00 pm. The maximum solar energy, heat gain, and thermal efficiency occurred at maximum solar radiation for both experiments, as illustrated in Figures 3.9 and 3.10.

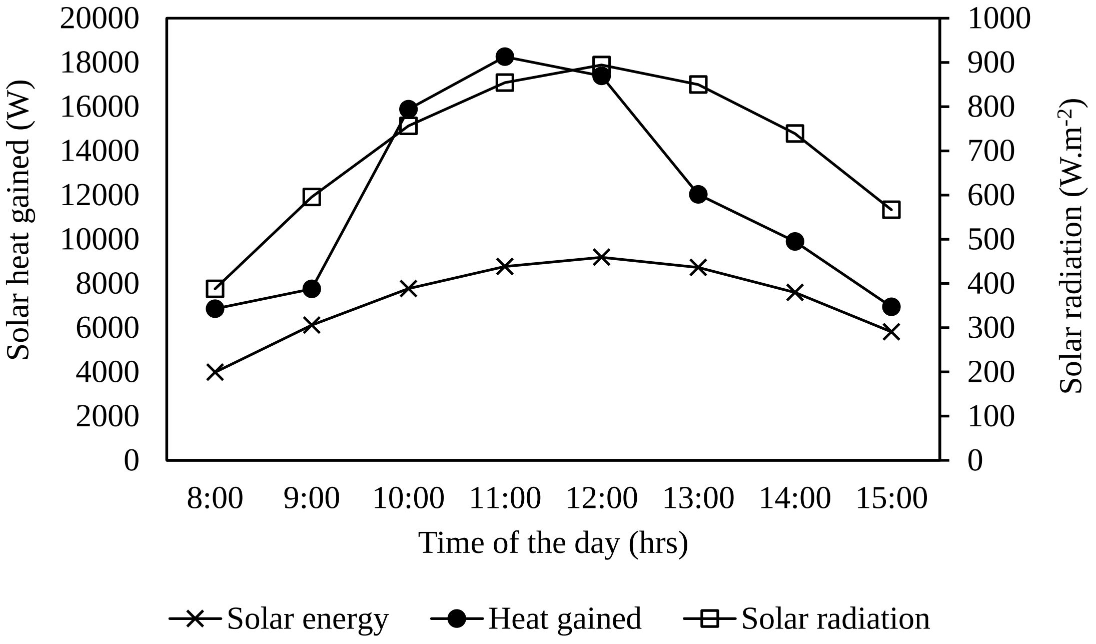

Figure 3.9 Solar collector performance in an empty solar-venturi dryer (Solar energy [W], Heat gained [W] and Solar radiation [W.m^{-2}])

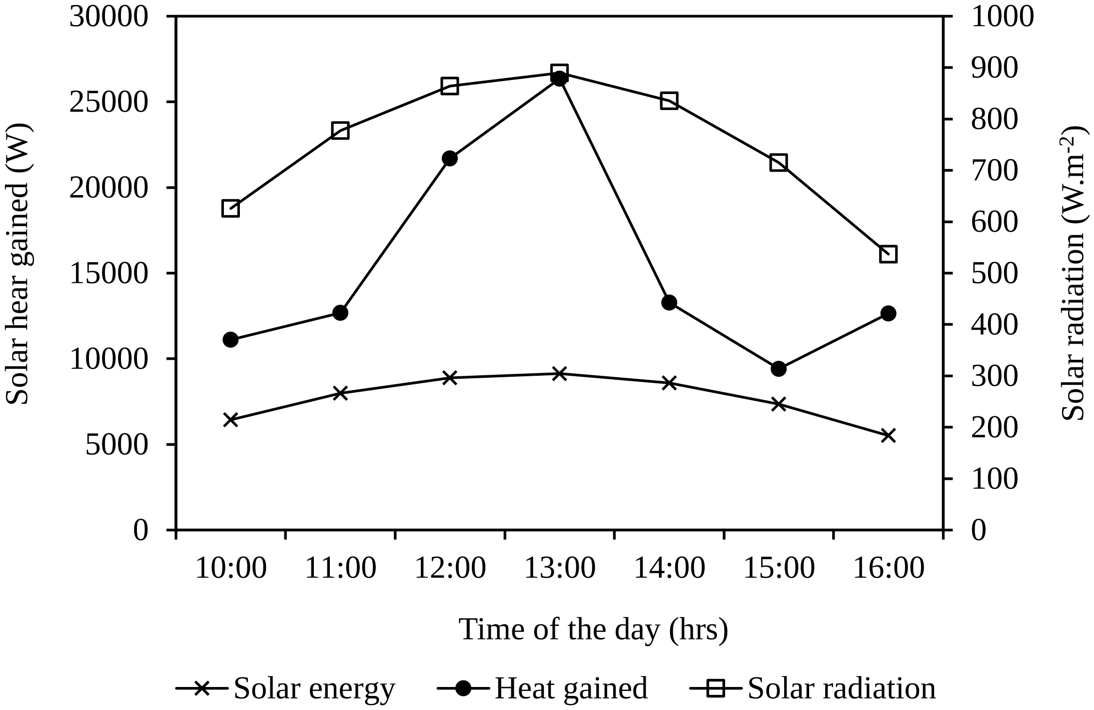

Figure 3.10 Solar collector performance in a fully-loaded solar-venturi dryer (Solar energy [W], Heat gained [W] and Solar radiation [W.m^{-2}])

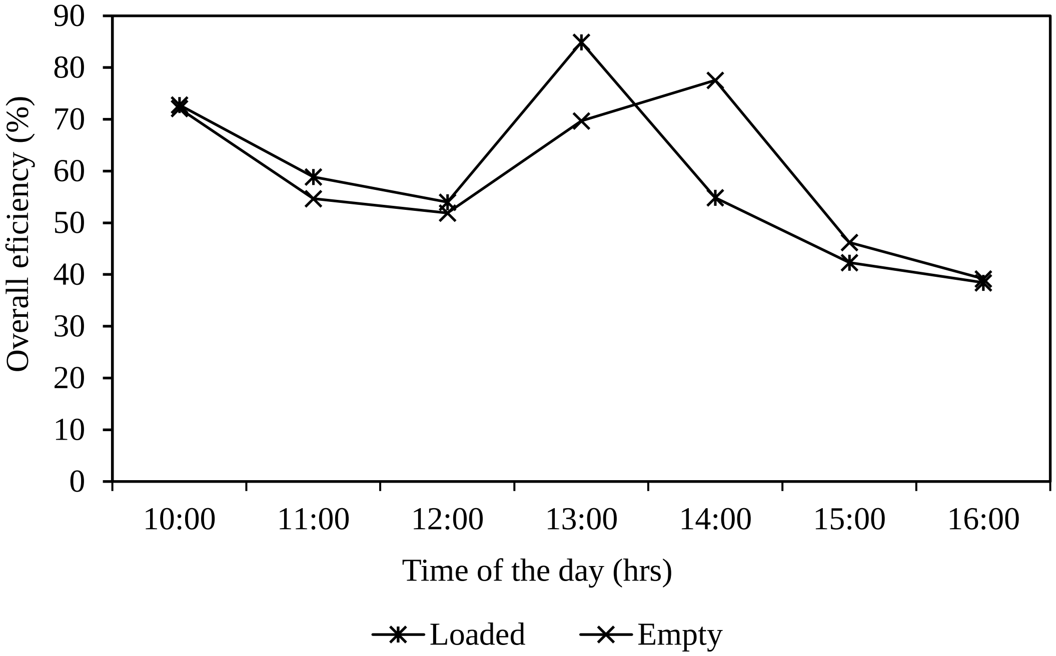

Figure 3.11 Thermal efficiency of solar collectors

3.6 Discussion

The solar radiation intensity was observed to have a bell-shape, with the maximum intensity occurring at midday (12:00-13:00 pm). This was expected as at midday the sun is overhead and its path is shortened. At midday, less solar radiation is scattered or absorbed by atmospheric mediums, and more direct radiation reaches the solar collectors compared to anytime of the day which is similar to findings of Schulze and Maharaj, 2007 and Lingayat *et al.* (2017). The variation of solar radiation and the ambient air temperature significantly affect the SD temperature positively. The ambient temperature was less than the temperature inside the drying chamber with an average temperature difference of 12.4^{o}C. This is similar to the findings by Hegde *et al.* (2015) of an average temperature difference of 11 ^{o}C in a solar dryer. The SD temperature remains higher than the ambient temperature. The maximum air temperature and minimum relative humidity inside the drying chamber was observed at the highest solar radiation intensity (Berinyuy *et al.*, 2012; Kolawole, 2013). Ekici and Teke (2018) found that factors, such as the season and time of the day, are important parameters that determine the amount of solar radiation received a location. However, it is also affected by presence of clouds and turbidity in the atmosphere.

The increase in temperature inside the solar-venturi dryer was directly proportional to the increase in ambient temperature, and it was inversely proportional to the relative humidity inside and the ambient relative humidity. The increasing ambient temperature causes a decrease in ambient relative humidity, which was accompanied by a decrease in SD relative humidity with the minimum relative humidity observed during midday (12:00-13:00). In addition, the ambient relative humidity was always higher than the SD relative humidity due to increased temperature inside the dryer. As the temperature inside the dryer increased, the heated air from the solar collectors could hold larger amount of water vapour and therefore, the relative humidity decreased. Mkhathini *et al.* (2018) reported their study findings also lowest relative humidity in the solar drying occurred during midday at high ambient temperature. There was a significantly ($p<0.05$) high temperature and relative humidity difference between the ambient conditions and the inside of the solar-venturi dryer.

The bottom tray had a lower temperature compared to the top tray, which indicates that heat was lost as the air moved inside the drying chamber and through the moist drying samples. This may have resulted from the increase in water vapour content and the relative humidity because cold air doesn't require as much moisture to be saturated as warmer air. Khiari *et al.*, (2004) reported that an optimum temperature for food water removal is 80^{o}C and if higher temperatures are used, the food will cook instead of drying. The results showed that the current study drying temperature was always less than 80 ^oC, which shows that drying is still possible below 80 ^oC, however, the time to complete drying maybe longer. However this can be improved by increasing the airflow rate. Therefore, the close relationship between the ambient and SD is very important. The relative humidity increased as the heated air flowed from the inlet of the drying chamber to the exit. This means that the solar-venturi dryer was able to raise the air temperature and reduce the air relative humidity under Pietermaritzburg conditions.

The collector efficiency indicates the utilized heat against the heat input in the form of solar insolation. The maximum efficiency of the solar collector was observed at the maximum insolation (at midday). Thermal efficiency of the solar dryer was observed to be dependent on the solar radiation intensity and wind speed and direction. Useful heat gain is dependent on the air mass flow rate and the difference in temperature between the ambient air entering and leaving the solar collectors. Thermal efficiency decreased as the solar radiation decreases.

3.7 Conclusion

SD was evaluated to illustrate its performance when loaded with sweet potato samples and empty under Pietermaritzburg conditions. It was concluded that during the day, the increase in ambient temperature increases the naturally ventilated solar-venturi dryers temperature when loaded with samples and when empty (unloaded). It was also observed that there is a positive strong relationship between ambient and the solar-venturi temperatures. Increasing temperature reduces ambient relative humidity, which results in a decrease of the relative humidity inside the SD. As ambient temperature dropped, ambient relative humidity increased and the temperature inside the SD decreased which resulted in an increase in relative humidity inside the dryer. Hence, the relative humidity increased at night when the temperature dropped and when there is no solar radiation which requires that the drying samples be removed from the dryer at night and kept in air tight containers. However the study concluded that the drying conditions in Pietermaritzburg (temperature, relative humidity and solar radiation) do allow the adoption of the SD however, there is still a need to find ways increase air flow velocity in order to reduce the drying time and optimizing the dryer to maintain low relative humidity during day light and at night.

3.8 References

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4. THIN-LAYER MODELLING OF SWEET POTATO DRYING USING SOLAR-VENTURI AND HOT AIR CIRCULATION DRYERS

Abstract

The drying of agricultural products is important in reducing the moisture content of the product to an acceptable level. However, due a lack of preservation technologies and limited access to energy sources, most farmers experience high post-harvest losses of their produce. Therefore, there is a need to develop food preservation technologies and optimize the existing methods. Thin-layer drying models are tools that can be used to optimize drying performance. In this study four mathematical models were investigated to estimate the drying coefficients, using non-linear regression method, for both drying methods to find the best fit of the moisture ration models. Sweet potato tubers were sliced at 3, 5 and 7 mm thickness sizes with (blanched, salted and lemon juice) and without (control) pre-treatments. The drying rate of the sample dried in HAD was higher than the drying rate of the samples in SD. The results show that the drying time was significantly affected by the size of sweet potato slices (SPS). The pre-treatments did not have a significant effect on drying time and rates. Most of the drying period took place at the falling rate period and a constant drying time. The Midilli et al. model was best for predicting the moisture ratio of SPS dried in HAD and SD based on statistical parameters such as coefficient of determination (R^2), reduced mean square error (RMSE) and the sum of square errors (SSE). The Midilli *et al*. model was found to be the best fitting model for both drying methods based on the statistical parameters R^2 of 0.9996 and 0.9946 in HAD and SD, respectively. The RMSE value was 0.0339 for SD and 0.0074 for HAD. The SSE values were 0.0115 and 0.0016 for HAD and SD, respectively. The D_{eff} ranged between $3.32x10^{-9}$- $6.31x10^{-9}$ $m.s^{-1}$ for a natural-ventilated solar-venturi dryer and $1.02x10^{-8}$ - $2.19x10^{-8}$ $m.s^{-1}$ for the HAD. The activation energy (E_a) was 16.53, 19.11 and 20.12 $kJ.mol^{-1}$ for 3, 5 and 7 mm thick slices

Keywords: Drying, modelling, thin-layer drying, drying kinetics, sweet potato

4.1 Introduction

Drying of food involves heat and mass transfer accompanied by changes in the structure, shape and biological quality of the product (Jabeen *et al.*, 2015; Nasri and Belhamri, 2018). Mathematical models, known as thin-layer drying models are tools used to better understand the thermal process and to develop and improve the existing drying systems (Akoy, 2014; Oke and Workneh, 2014; Miraei *et al.*, 2017). These models describe both the microscopic and macroscopic drying behaviour of the heat and mass transfer of the drying material (Doymaz, 2011; Ayadi *et al.*, 2014). Thin-layer drying models provide the basis for understanding the drying characteristics of any food material (Babiker *et al.*, 2016).

Thin-layer drying models depict the drying kinetics of the drying food material at any given time, when subjected to certain drying conditions (da Silva *et al.*, 2014; Oke and Workneh, 2014; Naderinezhad *et al.*, 2016). The drying conditions, such as the relative humidity, air temperature and air velocity have an impact on the quality of the final dried product (Meher and Nayak, 2016; Onwude *et al.*, 2016; Ertekin and Ziya, 2017). Therefore, there is need to model and analyse their effects.

Sweet potato tubers are amongst a group of crops that feed the world (Sanginga, 2015; Sanoussi *et al.*, 2016). Freshly-harvested sweet potato tubers have a moisture content that ranges between 48.0-53.3% (Titus and Lawrence, 2015). Such high moisture content makes sweet potatoes highly perishable and difficult to transport from one place to another difficult (Seidu *et al.*, 2012; Oyebanji *et al.*, 2013; Nwakuba *et al.*, 2016). Hence, appropriate preservation technologies are required that can increase shelf life. The study proposed technologies should be low cost and if to be used by small- to medium-scale farmers should require little or no energy input to run them (Afriyie and Bart-Plange, 2012).

Olawale and Omole (2012) studied eight thin-layer drying models for blanched and unblanched sweet potatoes slices drying in a tray dryer. Amongst these models, the Page model was found to be the best model for all samples. Other researchers have studied thin-layer drying models using different types of dryers. The study of thin-layer models using a naturally-ventilated, solar-venturi dryer (SD) to dry sweet potato slices (SPS) has not been investigated and reported. The aim of this study was to investigate the effect of solar-venturi drying on thin-layer drying characteristics of SPS and to model the heat and mass transfer of these samples.

4.2 Materials and Methods

4.2.1 Study site and climatic data

The study was carried out at the Ukulinga Research Farm, at University of KwaZulu-Natal, Pietermaritzburg, South Africa (30°24’S’’ and 29°24’E at an altitude of 721 m above sea level). The annual average long-term minimum and maximum temperatures of the study area range from 6.0 - 16.4°C and 20.6 - 27.4°C, respectively, while the relative humidity ranges from 61.1 - 75.3% (Schulze and Maharaj, 2007). The area receives an average solar radiation of between 15.1 and 27.8 $MJ.m^{-2}.day^{-1}$, which is enough for solar drying applications (Schulze and Maharaj, 2007).

The study was conducted during the month of September in 2018. The average long-term minimum and maximum temperatures in September range from 10.0 - 17.1°C and 12 - 27°C respectively, while the relative humidity ranges from 62.3 – 68.1%. The average solar radiation, wind speed and average sunshine hours for the month of September range from, 15.1 - 27.8 $MJ.m^{-2}.day^{-1}$, 0.8 – 9.7 $m.s^{-1}$, and 7 hours, respectively (Schulze and Maharaj, 2007). The weather data (temperature, relative humidity, solar radiation and wind speed) recorded during the study period was obtained from the weather station at Ukulinga Research Farm.

4.2.2 Sample preparation and treatments

A 50 kg batch of fresh sweet potato tubers was purchased from a local supermarket (Pick n Pay, Pietermaritzburg, South Africa). Sweet potato tubers with no physical damage and no sign of fungal or microbial attack were selected. The selected tubers were peeled, using a carbon steel blade potato peeler, after which they were washed using deionized water. The tubers were dabbed, using paper towels to partially remove the water on their surface. Thereafter, the sweet potato tubers were sliced into rectangular-shaped with the dimensions of, 50 by 20 mm, using a stainless steel kitchen knife (Oke and Workneh, 2014). The thickness size of the slices were 3, 5 and 7 mm. The slices were pre-treated by either dipping in a salt solution (0.1 % w/v concentration for 20 minutes), a lemon juice solution (1 % w/v concentration for 20 minutes), blanched in a water bath at 70°C for 10 minutes (Labotech Water Bath, Thermo Fisher Scientific, Waltham, Massachusetts, United States) and control samples was not pre-treated (control) (Olawale and Omole, 2012). The pre-treated samples were dabbed, using paper towels to remove any liquid from their surface.

4.2.3 Experimental design

The study was based on a factorial design experiment with factor A at three levels, factor B at four levels, factor C at two level and three replications. The factors studied were thickness of sweet potato slice (3, 5 and 7 mm); drying pre-treatment (salt, lemon juice, control and blanching) and drying method (SD and HAD). The drying temperature for the HAD was 70^{o}C. Figure 4.1 details treatment structure of the experimental design.

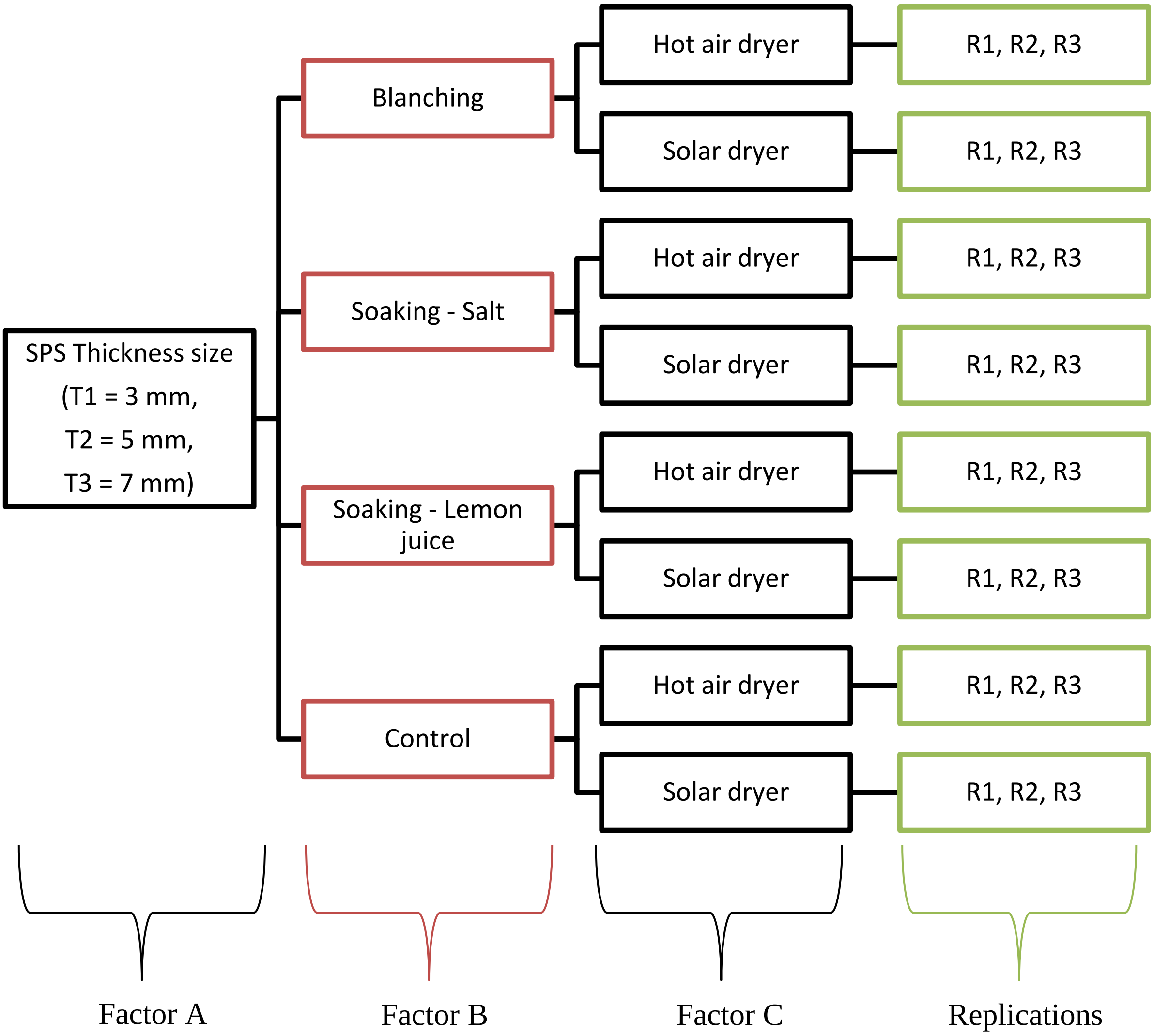


Figure 4.1 Schematic presentation of the experimental treatment structure with three factors (factor A = thickness size, factor B = drying pre-treatment, factor C = drying method)

4.2.4 Data collection

The drying air conditions were constant at 70°C in the hot-air dryer and dependent on the environmental conditions for a natural-ventilated solar-venturi dryer. The weight loss measured during drying was used to calculate different moisture contents, namely; (i) the initial moisture content (m_i), (ii) the moisture content at time, t (m_t) and (iii) the equilibrium moisture content (m_e). The weight loss of SPS dried in the SD and HAD was measured using a digital mass balance (Avery Berkel, Model TB151-C4ZA10AAR, UK) with an accuracy of ±0.1. The weight loss was monitored at fixed intervals of 5-minutes for the first 45 minutes, 15-minutes interval for the following three hours and at an hourly interval for the rest of the drying process (Oke and Workneh, 2014). The equilibrium moisture content was determined in the HAD by drying the samples for 48 hour at 105°C, using the AOAC (2005) method.

4.2.5 Drying characteristics data analysis

(a) Moisture ratio

The moisture ratio at time (*t*) was calculated using Eq. (4.1) below and drying curves were generated, by using Microsoft Office Excel (2016) (Onu *et al.*, 2017).

$$\mathrm{MR} = \frac{\mathrm{M_t - M_e}}{\mathrm{M_i - M_e}} \qquad (4.1)$$

Where

MR = moisture ratio [dimensionless],

m_t= moisture content at time [%],

m_e= equilibrium moisture content [%], and

m_i= initial moisture content [%].

(b) Drying rate

The drying rate was calculated using Eq. (4.2) (Onwude *et al.*, 2016). Drying rate curves were generated using Microsoft Office Excel (2016).

$$\mathrm{DR} = \frac{\mathrm{M_{t+dt} - M_t}}{\mathrm{d_t}} \qquad (4.2)$$

Where

DR= is the drying rate [kg.hr^{-1}],

M_{t+dt}= moisture content of the sample at time [t+dt], and

M_t= moisture content at time, *t* [hrs],

d_t = change in drying time.

(c) Modelling of sweet potato slices drying curves

Non-linear regression was carried out to determine the goodness of fit of thin-layer drying models summarised in Table 4.1 to the experimental moisture ratio. R2017b Matlab and Simulink – MathWorks was used to estimate the drying coefficients and the coefficient of determination (R^2), root mean square error (RMSE) and sum of squared errors (SSE). These statistical parameters were then used to assess goodness of fit for each model.

Table 4.1 Selected thin-layer drying models

Model name	Model	References
Henderson and Pabis	$MR = a \exp(-kt)$	(Hashim *et al.*, 2014)
Logarithmic	$MR = a \exp(-kt) + b$	(Kaur and Singh, 2014)
Two term	$MR = a \exp(-kt) + b \exp(-kt)$	(Demiray and Tulek, 2012)
Midili *et al.*,	$MR = a \exp(-(kt^n) + bt$	(Kucuk *et al.*, 2014)

*a, b, = empirical model constant (dimensionless), k = drying constant obtained from experimental data (s^{-1}), n = empirical model constant (dimensionless) and t = time (s).

4.2.6 Determination of effective moisture diffusivity and activation energy

Fick’s law of diffusion is widely used to describe drying in the falling rate, where diffusion is dominant drying mechanism of fruits and vegetables (Zhu and Jiang, 2014; Onu *et al.*, 2017). Fick’s equation solution was developed, by Crank (1975) and assumes that, in the drying period there is, uniform initial moisture distribution, moisture migration is by diffusion, negligible external resistance, negligible shrinkage, constant diffusivity and temperature. In this study, the moisture diffusion during drying and the activation energy were determined by Fick's law of diffusion and Arrhenius model for the lemon juice pre-treated SPS with 3, 5 and 7 mm thickness. Therefore, the initial moisture concentration was uniform and the average moisture ratio at time t, can be calculated using by Eq. (4.6) (Aregbesola *et al.*, 2015).

$$\mathrm{MR} = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff} t}{4H^2}\right) \tag{4.6}$$

Where:

MR = moisture ratio [dimensionless],

H^2 = is the half thickness of a thin-layer sample [m],

$\mathrm{D_{eff}}$ = effective moisture diffusivity$[\mathrm{m.s^{-1}}]$, and

t = is the drying time [s].

The slope of the ln(MR) versus time graph was used to estimate to determine the effective moisture diffusivity.

$$\mathrm{K_o} = -\frac{\pi^2 \mathrm{D_{eff}}}{4\mathrm{H}^2} \tag{4.7}$$

Where:

$\mathrm{K_o}$ = is the slope of ln(MR) [dimensionless], and

H^2 = is the half thickness of a thin-layer sample [m].

The activation energy was calculated using the slope of Arrhenius-type equation Eq. (4.8) (Lopez et al., 2000). The activation energy was calculated from the slope of the Arrhenius-type grap ln ($\mathrm{D_{eff}}$) versus$\frac{1}{\mathrm{T_a}}$ which gives a straight line of slope ($\mathrm{K_1}$) as shown in Eq. (4.10).

$$\mathrm{D_{eff}} = \mathrm{D_o} \exp\left(-\frac{E_\mathrm{a}}{\mathrm{RT_a}}\right) \tag{4.8}$$

Where:

$\mathrm{D_o}$ = is the pre-exponential factor of the Arrhenius equation $[\mathrm{m^2.s^{-1}}]$,

$\mathrm{E_a}$ = is the effective activation energy $[\mathrm{kJ.mol^{-1}}]$, R = is the universal gas constant [8.314 J.mol^{-1} K], and

T_a = is the absolute temperature [K].

From the slope of the straight line of described by the Arrhenius equation, the E_a can be calculated using Eq. (4.9).

$$K_1 = \frac{E_a}{R} \tag{4.9}$$

Where

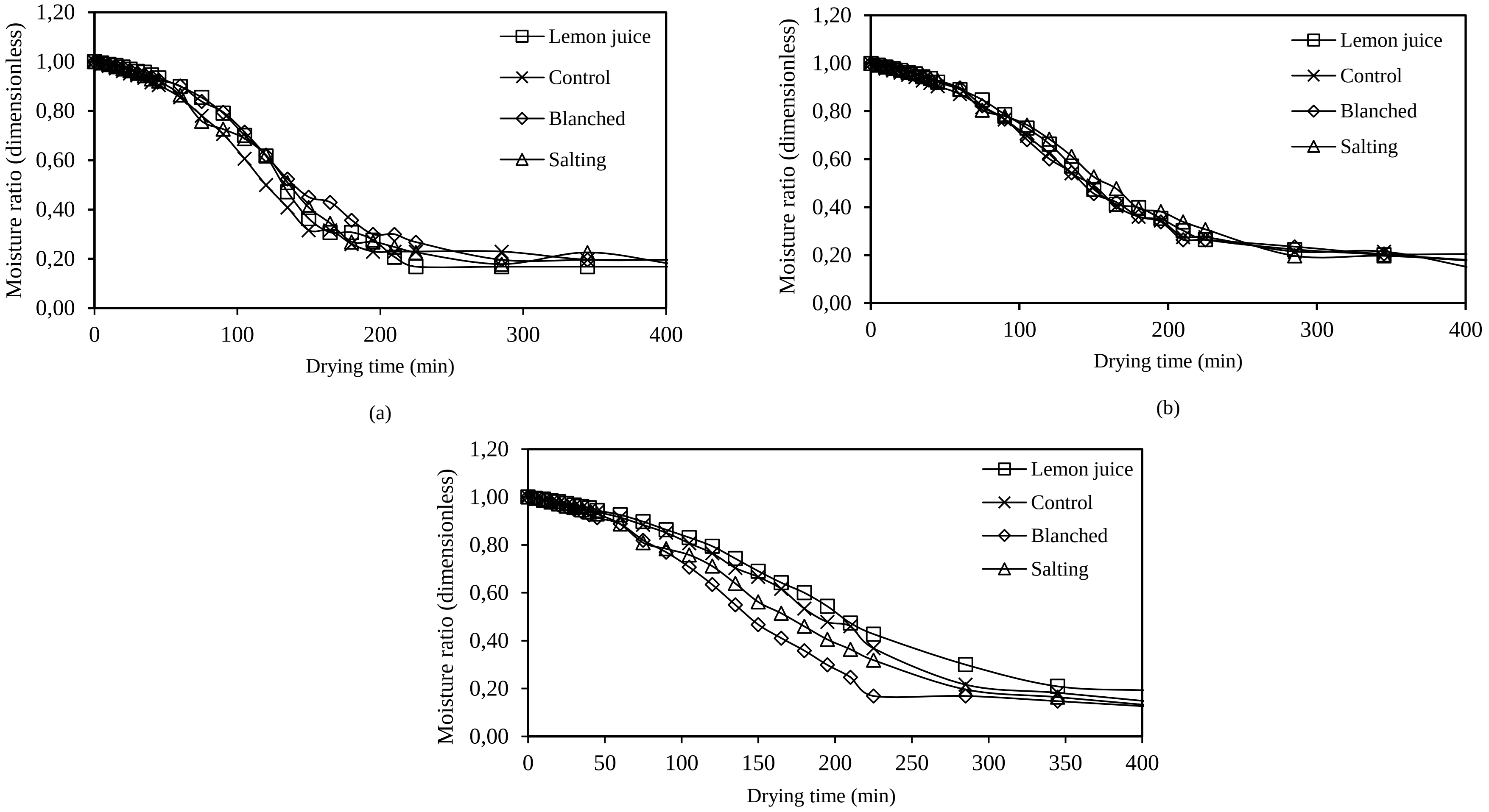
K_1 = is the slope of Arrhenius plot [dimensionless].

4.3 Results

4.3.1 The effect of pre-treatment and sweet potato slice thickness on the drying time and the drying rate

Figures 4.2 and 4.3 show the characteristics drying curves for control (samples with no-pre-treatment), blanched, salted and lemon juice pre-treated sweet potato samples sliced to 3, 5 and 7 mm thickness. Figures 4.4 and 4.5 changes in drying rate as a function of moisture content at for each thickness size for the SD and HAD. Observations in a HAD indicates that the drying time increased appreciably with the increase in thickness size (from 3 to 7 mm). The time taken to reach equilibrium moisture for a HAD to dry 3, 5 and 7 mm thick sweet potato slice was 225 min, 285 min and 345 min, respectively. Drying rate was calculated from the observed data by estimating change in moisture content observed in each consecutive interval. Initially surface of the sweet potato slice was wet and a continuous film of water existed on the drying surface. The mean drying rate of 3, 5 and 7 mm thickness SPS were 0.57, 0.55 and 0.53 g.hr^{-1}, respectively.

The observation in a SD showed that the drying time increased with the increase in thickness. For a SD, the drying time taken to reach equilibrium moisture content was 12-13 hours for all thickness size and pre-treatments. The mean drying rates for SD were 0.68, 0.61 and 0.56 g.min^{-1}, respectively. The drying rate was observed to decrease at night, hence. Drying rate versus drying time graph shows that the rate of drying decreased over time.

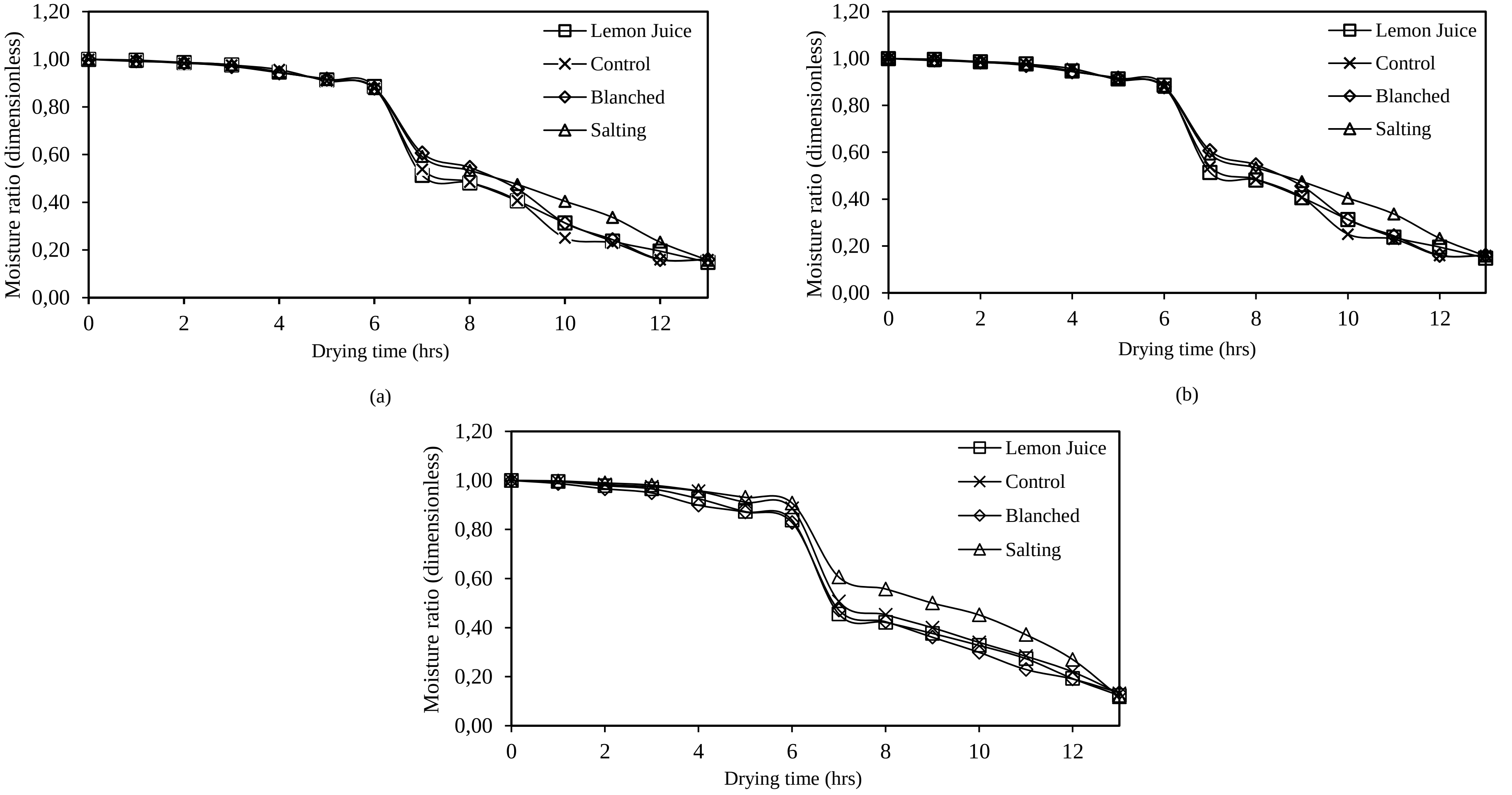


(a)

(b)

(c)

Figure 4.2 Moisture ratio of (a) = 3 mm, (b) = 5 mm and (c) = 7 mm thickness sweet potato slices drying in a hot-air oven dryer at 70^{o}C

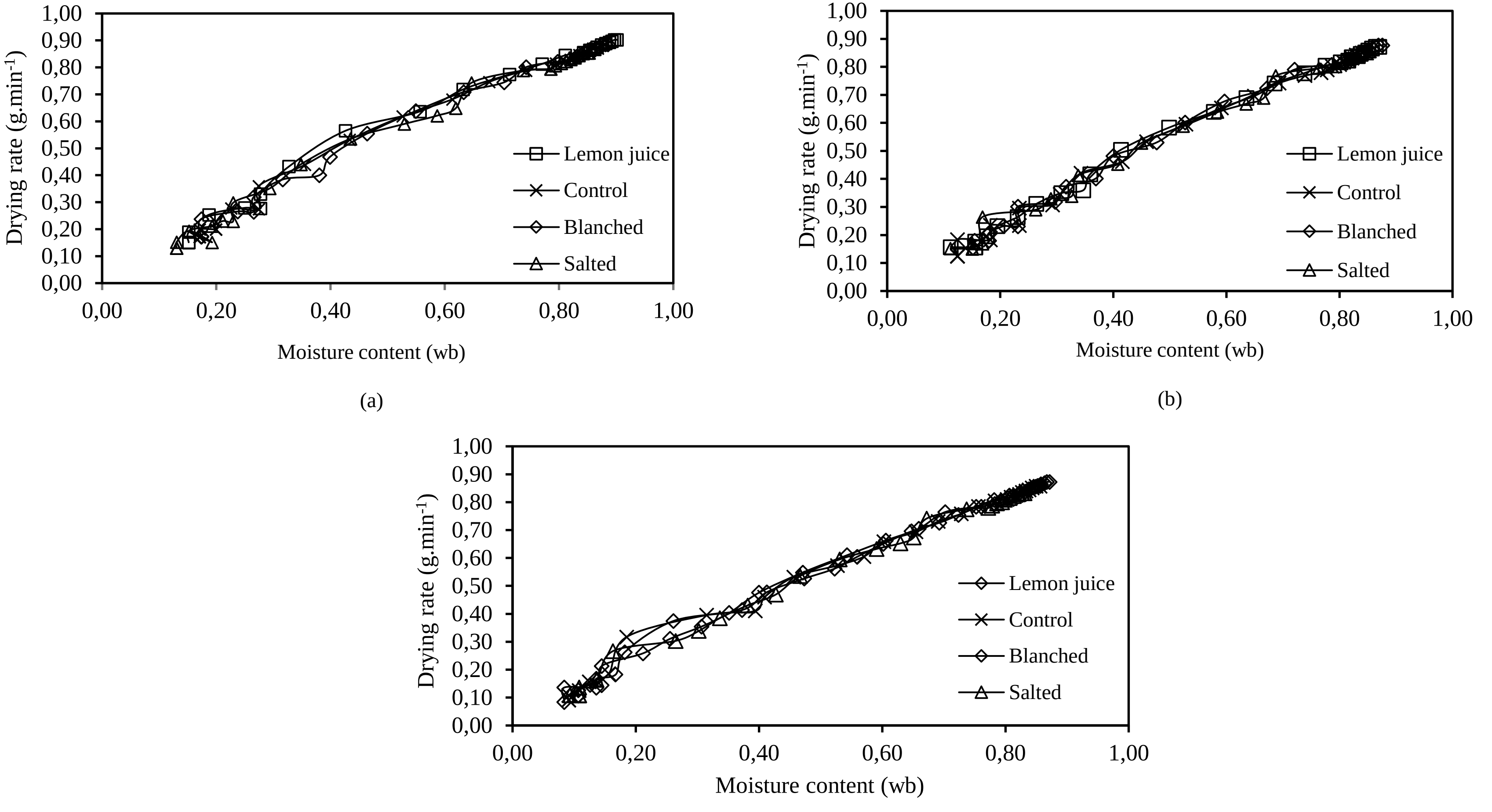


(a)

(b)

(c)

Figure 4.3 Moisture ratio of (a) = 3 mm, (b) = 5 mm and (c) = 7 mm thickness sweet potato slices drying in a naturally-ventilated solar-venturi dryer

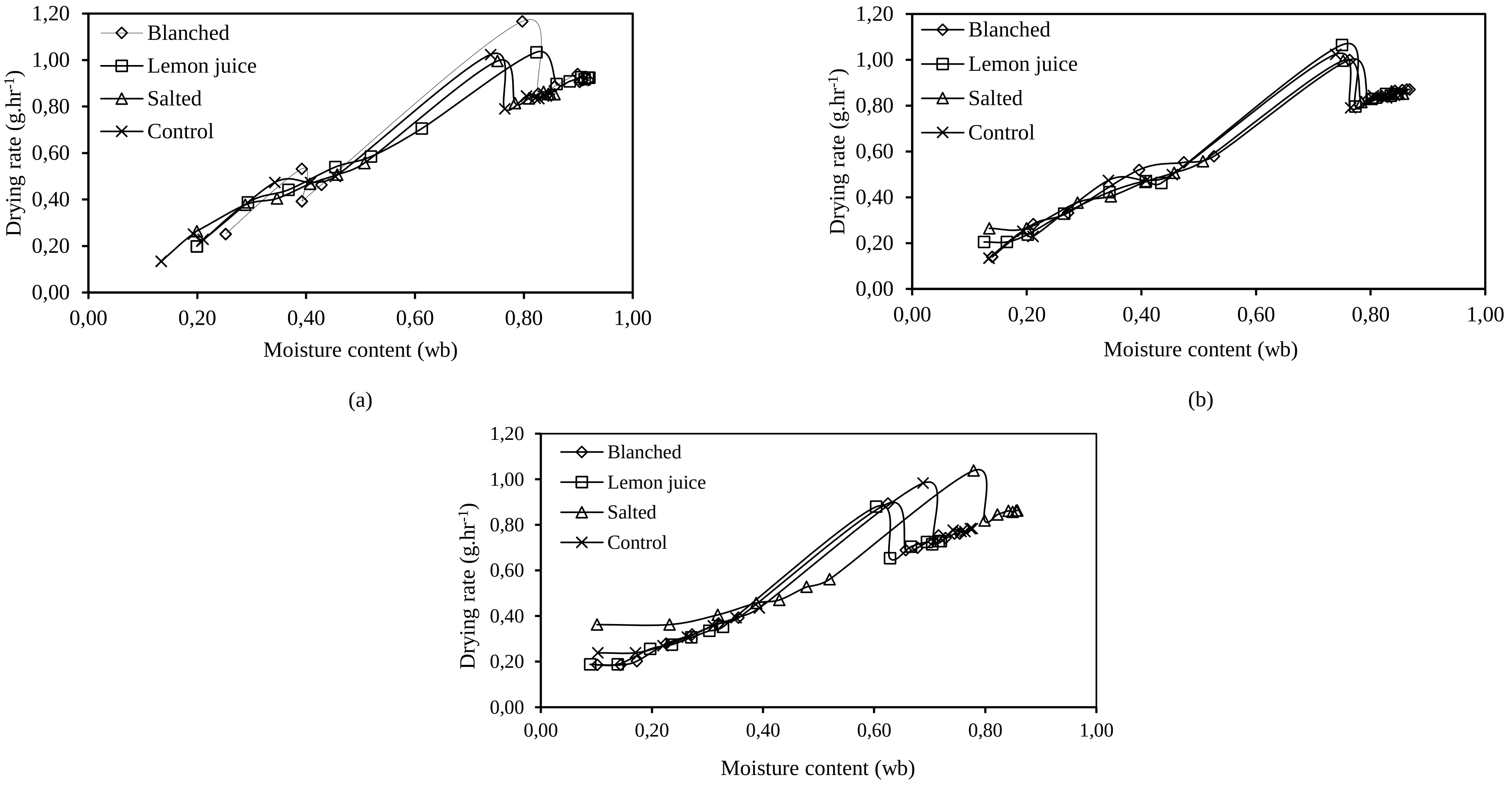


(a)

(b)

(c)

Figure 4.4 Drying rates for (a) = 3 mm, (b) = 5 mm and (c) = 7 mm thickness sweet potato slices drying in a hot-air oven dryer at 70°C



(a)

(b)

(c)

Figure 4.5 Drying rates for (a) = 3 mm, (b) = 5 mm and (c) = 7 mm thickness sweet potato slices drying in a naturally-ventilated solar-venturi dryer

4.3.2 Modelling of sweet potato slices drying curves

Tables 4.2 and 4.3 presents statistical parameters of different drying models. In all cases R^2 values were higher than 0.83 ranging between 0.8395 - 0.9946 for SD and between 0.8514 - 0.9996 for HAD, respectively, as shown in Tables 4.2 and 4.3. The RMSE values ranged from 0.0339 - 0.1723 for SD and between 0.0074 – 0.1439 for the HAD. The SSE values ranged between 0.0115 – 0.3564 and 0. 0016 – 0.6004 for SD and HAD, respectively. From Tables 4.2 and 4.3 the higher values of R^2 and the lower values of RMSE and SSE were obtained from Midilli and Kucuk model. The highest R^2 for Midilli and Kucuk model was obtained in drying samples pre-treated with lemon juice for both the SD and HAD. The lowest R^2 and highest RMSE and or SSE was obtained in the Two-term model for the HAD and Henderson and Pabis for the SD.

Table 4.2 Statistical parameters of selected thin-layer drying models under solar drying

Pre-treatment	Thickness [mm]	Model	R^2	RMSE	SSE
Blanching	3	Henderson and Pabis	0.9081	0.1211	0.1759
		Logarithmic	0.9463	0.0967	0.1028
		Two-term	0.9124	0.1295	0.1676
		Midilli and Kucuk	0.9849	0.0538	0.0289
	5	Henderson and Pabis	0.8902	0.1370	0.2252
		Logarithmic	0.9501	0.0965	0.1024
		Two-term	0.9506	0.1006	0.1012
		Midilli and Kucuk	0.9894	0.0467	0.0218
	7	Henderson and Pabis	0.8861	0.1368	0.2246
		Logarithmic	0.9441	0.1002	0.1103
		Two-term	0.9445	0.1046	0.1094
		Midilli and Kucuk	0.9804	0.0622	0.0387
Lemon Juice	3	Henderson and Pabis	0.8935	0.1368	0.2247
		Logarithmic	0.9465	0.1013	0.1123
		Two-term	0.9479	0.1048	0.1099
		Midilli and Kucuk	0.9946	0.0339	0.0115
	5	Henderson and Pabis	0.8642	0.1578	0.2988
		Logarithmic	0.9291	0.1191	0.1560
		Two-term	0.9299	0.1242	0.1542
		Midilli and Kucuk	0.9848	0.0578	0.0334
	7	Henderson and Pabis	0.8638	0.1547	0.2872
		Logarithmic	0.9296	0.1162	0.1484
		Two-term	0.9295	0.1219	0.1486
		Midilli and Kucuk	0.9819	0.0618	0.0381
Salting	3	Henderson and Pabis	0.9124	0.1215	0.1773
		Logarithmic	0.9517	0.0943	0.0979

Pre-treatment	Thickness [mm]	Model	R^2	RMSE	SSE
		Two-term	0.9536	0.0969	0.0940
		Midilli and Kucuk	0.9944	0.0338	0.0114
	5	Henderson and Pabis	0.8826	0.1409	0.2381
		Logarithmic	0.9417	0.1037	0.1184
		Two-term	0.9625	0.0873	0.0762
		Midilli and Kucuk	0.9884	0.0486	0.0236
	7	Henderson and Pabis	0.8642	0.1545	0.2863
		Logarithmic	0.9297	0.1161	0.1482
		Two-term	0.9532	0.0993	0.0986
		Midilli and Kucuk	0.9814	0.0626	0.0391
Control	3	Henderson and Pabis	0.8832	0.1460	0.2558
		Logarithmic	0.9392	0.1100	0.1331
		Two-term	0.9672	0.0847	0.0717
		Midilli and Kucuk	0.9926	0.0403	0.0163
	5	Henderson and Pabis	0.8591	0.1607	0.3097
		Logarithmic	0.9282	0.1198	0.1578
		Two-term	0.9284	0.1255	0.1575
		Midilli and Kucuk	0.9876	0.0522	0.0272
	7	Henderson and Pabis	0.8395	0.1723	0.3564
		Logarithmic	0.9144	0.1315	0.1902
		Two term	0.9368	0.1185	0.1404
		Midilli and Kucuk	0.9816	0.0639	0.0408

*R^2 = coefficient of determination, RMSE = root mean square error and SSE = sum of square errors

Table 4.3 Statistical parameters of selected thin-layer drying models under hot-air oven drying

Pre-treatment	Thickness [mm]	Model	R^2	RMSE	SSE
Blanching	3	Henderson and Pabis	0.9931	0.0303	0.0285
		Logarithmic	0.9939	0.0288	0.0249
		Two-term	0.9929	0.0316	0.0289
		Midilli and Kucuk	0.9989	0.0124	0.0044
	5	Henderson and Pabis	0.9930	0.0302	0.0283
		Logarithmic	0.9935	0.0295	0.0261
		Two-term	0.8514	0.1439	0.6004
		Midilli and Kucuk	0.9990	0.0120	0.0042
	7	Henderson and Pabis	0.9952	0.0251	0.0195
		Logarithmic	0.9958	0.0237	0.0169
		Two term	0.9167	0.1080	0.3380
		Midilli and Kucuk	0.9992	0.0108	0.0034
Lemon Juice	3	Henderson and Pabis	0.9130	0.1078	0.3605
		Logarithmic	0.9459	0.0864	0.2240
		Two-term	0.9943	0.0285	0.0235

Pre-treatment	Thickness [mm]	Model	R^2	RMSE	SSE
		Midilli and Kucuk	0.9991	0.0116	0.0039
	5	Henderson and Pabis	0.9948	0.0259	0.0209
		Logarithmic	0.9951	0.0256	0.0196
		Two-term	0.8713	0.1332	0.5143
		Midilli and Kucuk	0.9991	0.0110	0.0035
	7	Henderson and Pabis	0.9968	0.0206	0.0132
		Logarithmic	0.9971	0.0201	0.0121
		Two-term	0.9115	0.1131	0.3707
		Midilli and Kucuk	0.9996	0.0074	0.0016
Salting	3	Henderson and Pabis	0.9909	0.0353	0.0386
		Logarithmic	0.9916	0.0344	0.0356
		Two-term	0.9941	0.0293	0.0250
		Midilli and Kucuk	0.9983	0.0158	0.0073
	5	Henderson and Pabis	0.9944	0.0275	0.0235
		Logarithmic	0.9947	0.0274	0.0225
		Two-term	0.9961	0.0238	0.0164
		Midilli and Kucuk	0.9987	0.0138	0.0055
	7	Henderson and Pabis	0.9953	0.0252	0.0197
		Logarithmic	0.9956	0.0248	0.0184
		Two term	0.9963	0.0232	0.0156
		Midilli and Kucuk	0.9986	0.0141	0.0057
Control	3	Henderson and Pabis	0.9919	0.0317	0.0312
		Logarithmic	0.9929	0.0302	0.0273
		Two term	0.9983	0.0149	0.0064
		Midilli and Kucuk	0.9988	0.0127	0.0047
	5	Henderson and Pabis	0.9965	0.0208	0.0134
		Logarithmic	0.9969	0.0200	0.01196
		Two term	0.9971	0.0194	0.0110
		Midilli and Kucuk	0.9990	0.0117	0.0040
	7	Henderson and Pabis	0.9959	0.0232	0.0167
		Logarithmic	0.9964	0.0221	0.0146
		Two term	0.9980	0.0167	0.0081
		Midilli and Kucuk	0.9992	0.0107	0.0033

*R^2 = coefficient of determination, RMSE = root mean square error and SSE = sum of square error

Figures 4.5 and 4.6 shows a comparison between experimental and predicted MR using the studied models. The prediction using the model showed Midilli predicted MR values banded along the straight line, which showed the suitability of the model in describing drying characteristics of SPS.

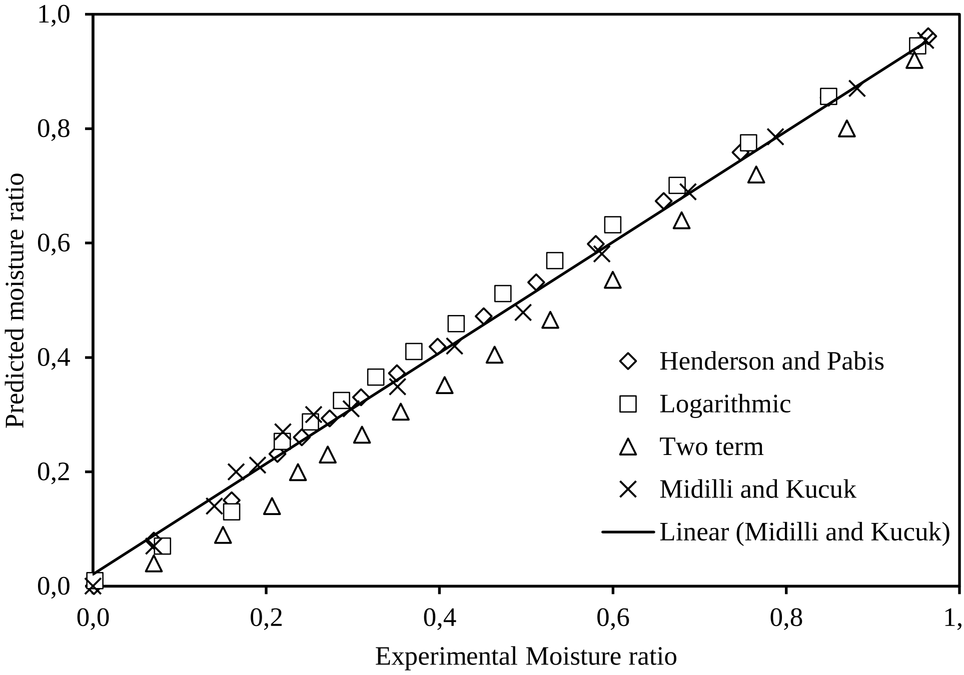


Figure 4.6 Comparison of experimental MR and predicted MR in SD

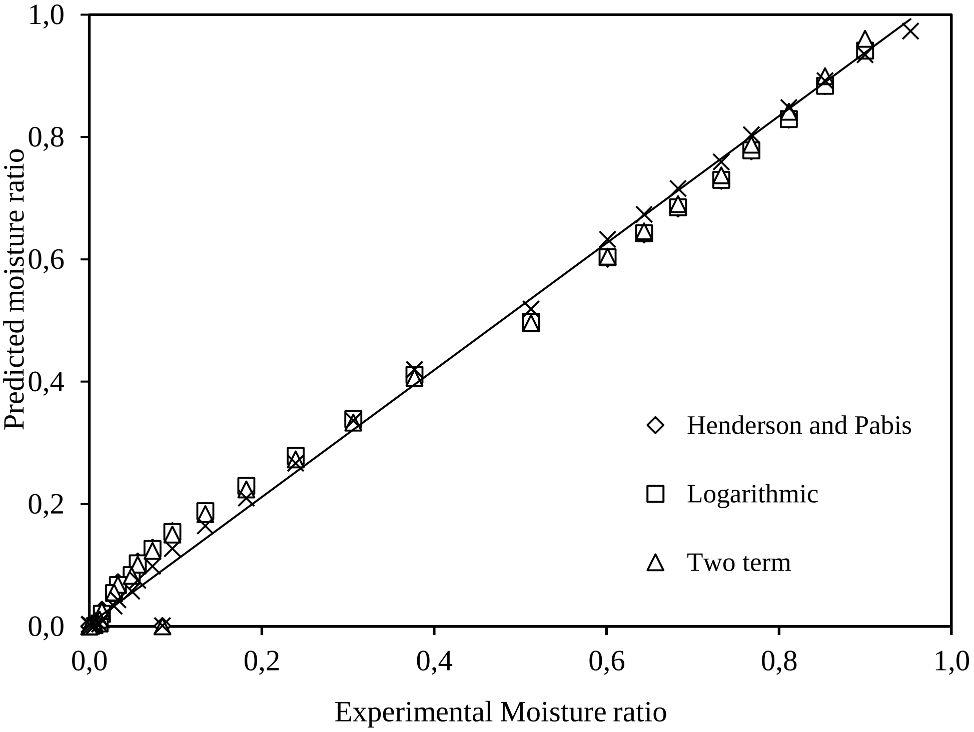


Figure 4.7 Comparison of experimental MR and predicted MR in HAD

4.3.3 Estimation of effective moisture diffusivity and activation energy

The variation of ln (MR) with drying time, for the Midilli *et al.* model indicates that the graph has a negative slope, as shown in Figures 4.5 and 4.6. The effective moisture diffusivity (D_{eff}) varied between 1.02x10^{-8} and 3.32x10^{-9} $m^2.s^{-1}$ as shown in Table 4.4. The diffusivity values obtained from the experimental data fall within the (10^{-11} – 10^{-6} $m^2.s^{-1}$) range (Tulek, 2011). The effective moisture diffusivity varied with sweet potato slice thickness. A 3 mm thickness had higher moisture diffusivity than, 5 mm and 7 mm thick slices. The influence of temperature and thickness on the effective diffusivity was obtained by plotting ln(D_{eff}) against 1/(T+273.2). From the slope of the graph, the activation energy (E_a) was found to be 16.53, 19.11 and 20.12 kJ.mol^{-1} for 3, 5 and 7 mm thick slices.

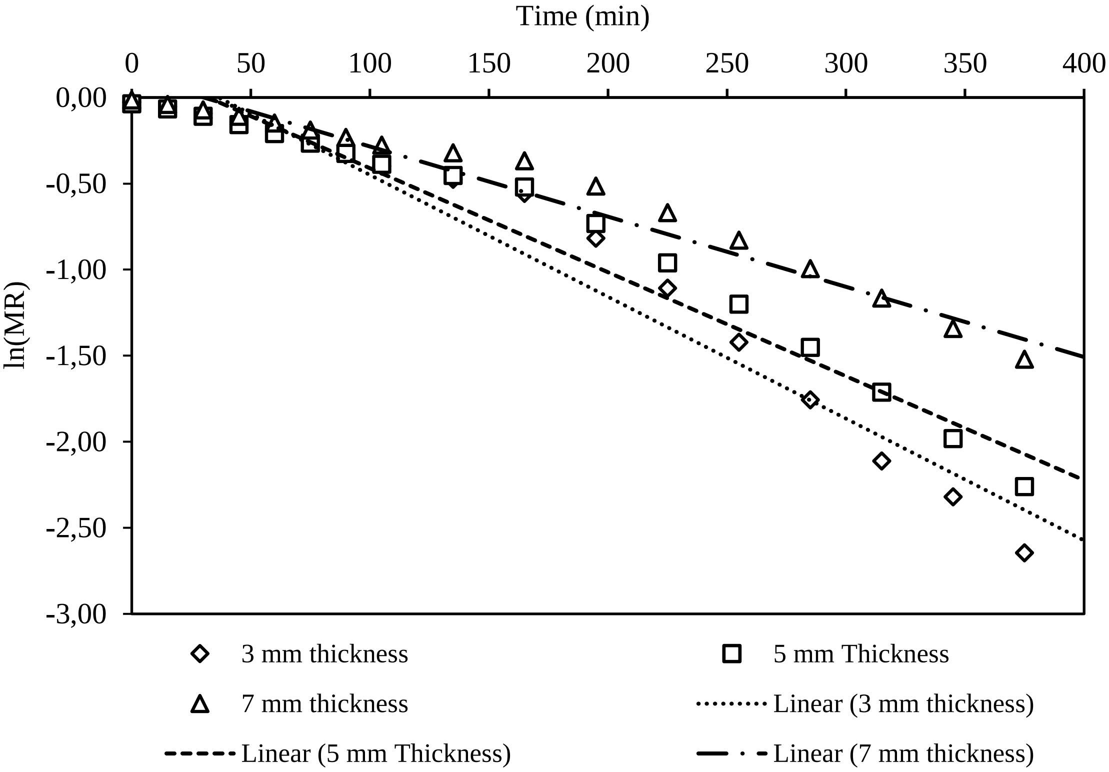


Figure 4.8 Effective moisture diffusivity curves for lemon juice pre-treated sweet potato slice at 3, 5 and 7 mm thickness dried in the HAD

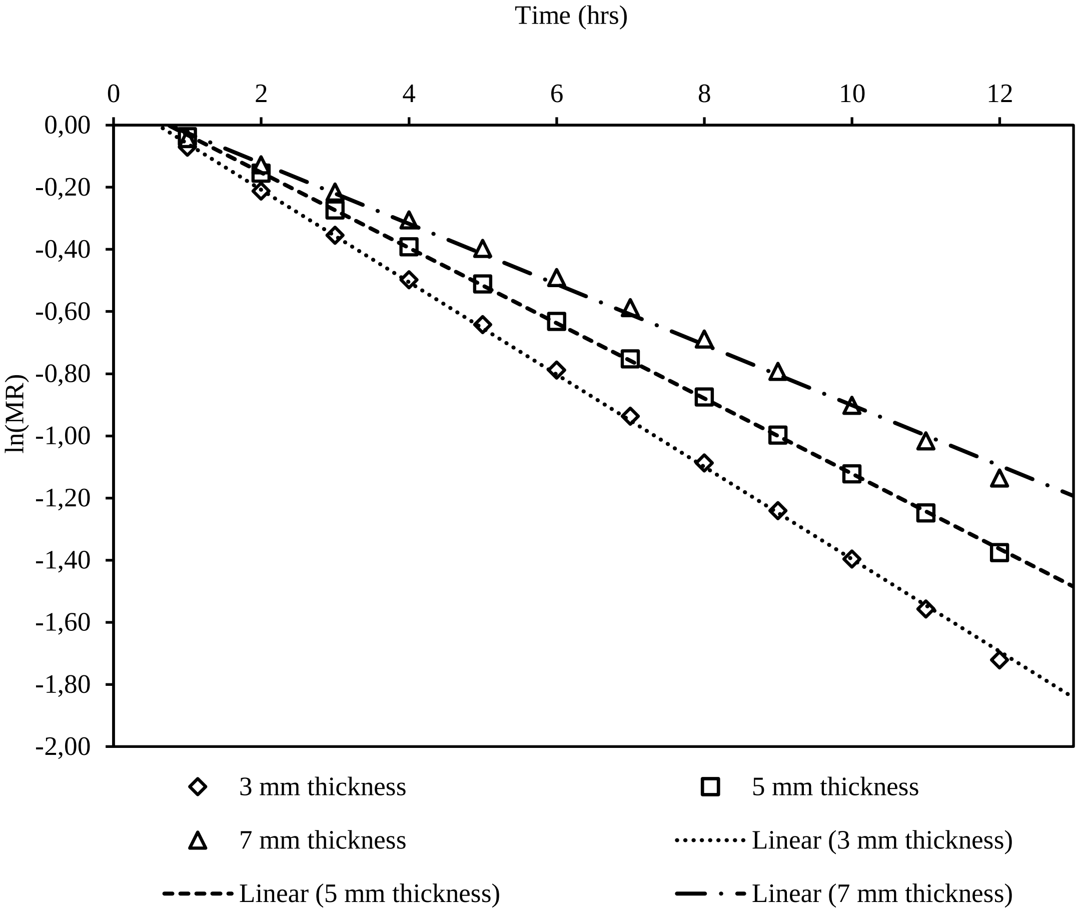


Figure 4.9 Effective moisture diffusivity curves for lemon juice pre-treated sweet potato slice at 3, 5 and 7 mm thickness dried in the SD

Table 4.4 Effective moisture diffusivities of sweet potato slices in different thickness sizes

Drying method	Thickness [mm]	D_{eff} [$m^2.s^{-1}$]
HAD	3	$2.19x10^{-8}$
	5	$1.56x10^{-8}$
	7	$1.02x10^{-8}$
SD	3	$6.31x10^{-9}$
	5	$4.16x10^{-9}$
	7	$3.32x10^{-9}$

*HAD – hot air oven dryer, SD – solar venturi dryer, D_{eff} – effective moisture diffusivity

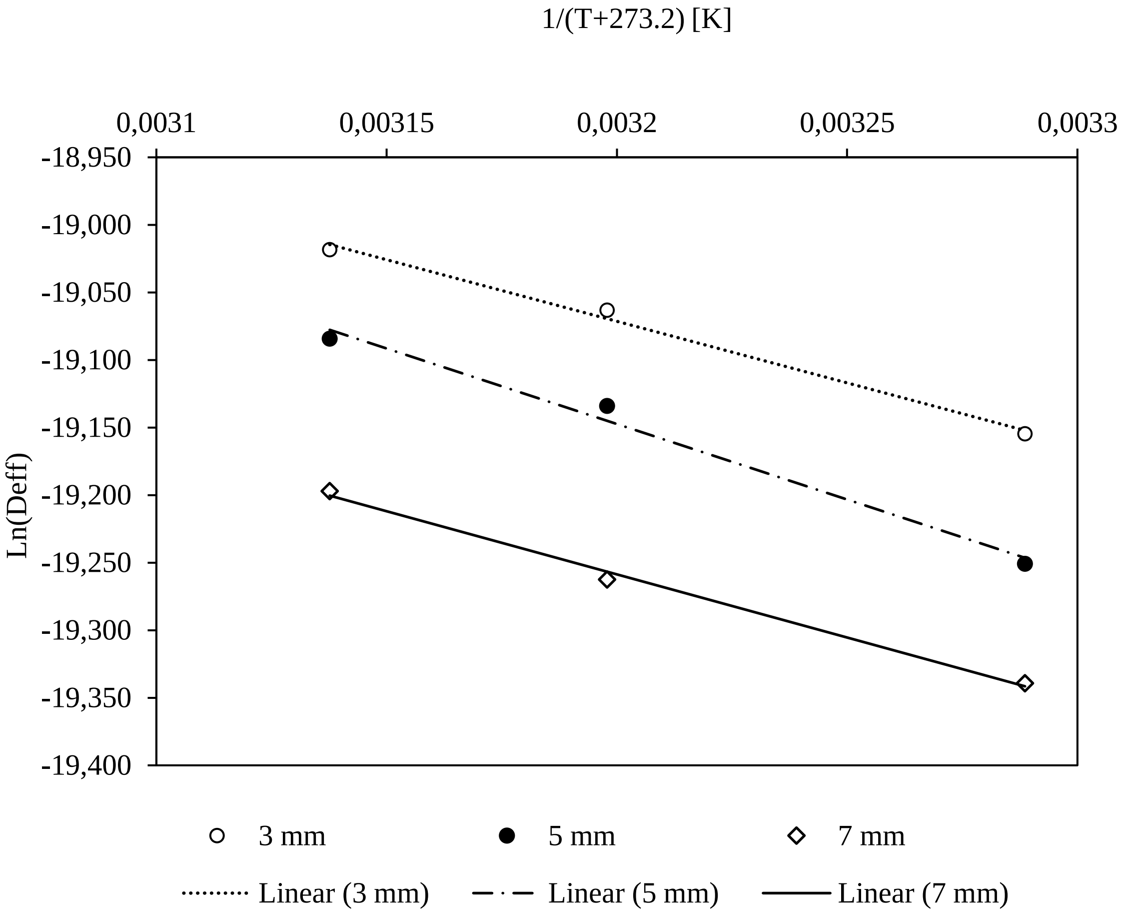


Figure 4.10 Arrhenius-Type relationship between average effective moisture diffusivity and drying temperature for sweet potato slices

4.4 Discussion

The drying time in HAD was observed to be less than the drying time in SD. This was expected as a result of constant and higher drying air temperature. This resulted in higher mass transfer and higher drying rate and consequently lower drying time. SPS pre-treated with lemon juice had shorter drying time for both HAD and a SD. Immediately after the start of drying, the rate significantly increased and the drying process occurred in the falling-rate drying period. There was almost no constant-rate drying period, and though moisture was evaporating from the surface, internal moisture was coming towards the surface at the same rate as that of moisture vaporization. Therefore, it is safe to assume that internal moisture diffusion occurs. The results showed that the drying rate was rapid at the start of the drying process and decreased with time, as reported by Doymaz 2011. The drying rate curves showed that the thickness size of SPS had a significant effect on the drying rate of the samples in both the HAD and SD. This agrees with the findings of Asiru *et al.* (2013), in the drying of cashew kernels, and Hussein *et al*. (2016) in the drying of tomato slices. The total drying time was longer for the 7 mm thickness size.

The drying rates were higher at the beginning of the drying process and gradually decreased as the drying process progressed, which confirmed the findings by Babiker *et al.* (2016). This was because of the more radiation energy is absorbed by the water at the productsurface initially, resulting in faster drying. The drying rate of SPS in SD was observed to vary with the time of the day, due to varying environmental conditions (air temperature, relative humidity and air velocity) over a day. This was also observed by Khanal and Lei, 2011; Afriyie and Bart-Plange, (2012).

The dimensionless moisture ratio decreased with the increase in the drying time. The moisture ratio of SPS in SD and HAD depicted that drying occurred in the falling rate period (Jabeen *et al.*, 2015; Naderinezhad *et al.*, 2016). The experimental moisture ratios were then fitted to the four thin-layer drying models. Of all models fitted on the experimental moisture ratios, Midili and Kucuk model gave the highest R^2 and the lowest values of RMSE and SSE. The Midilli and Kucuk model was selected as the best fit model and it was then used to predict the moisture ratio of both SD and HAD. The comparison between experimental data and the predicted moisture ratios shows that the four drying models used gave good correlation with experimental data.

Moisture transfer during drying was governed by diffusion in both HAD and SD, hence, Fick’s second law of diffusion and Midilli *et al.* model was used to predict the effective moisture diffusion rate of lemon juice pre-treated SPS at different thickness size. HAD showed a higher effective moisture diffusivity (D_{eff}) than the SD. This could be as a result of a relatively high temperature in HAD compared to the SD. The effective moisture diffusivity obtained in this study was within the range found in research studies for hot-air drying methods (Tulek 2011). Dinrifo (2012) found a moisture diffusivity range of 7.76×10^{-9} to 1.2×10^{-8} $m.s^{-1}$ in drying of SPS using hot-air drying method which is within the range for most dried food materials as reported by Tulek (2011).

The activation energy for drying was observed to increase with the increase in thickness size. This indicates that it was easier to induce water release for smaller samples. This is because a higher amount of energy is required for heat and mass transfer for products with large thickness than smaller thickness. This trend is similar to findings by Chijioke *et al.,* (2016). The values of E_a are within the general activation energy range of 15-40 $kJ.mol^{-1}$ for various food materials as reported by Dinrifo *et al.*, (2012).

4.5 Conclusions

Four models were evaluated to illustrate the drying characteristics of SPS under HAD and SD, select the drying models that best fit the drying data and to estimate the effective moisture diffusivity. HAD took a shorter drying time compared to SD, however, this was expected as the temperature of the HAD was relatively higher than SD temperature. The thickness of the SPS had influence on the drying characteristics (drying time and drying rate). The 3 mm slices dried faster in both HAD and SD, compared to 5 and 7 mm thickness slices. Consequently, the moisture diffusivity in 3 mm thick SPS was relatively higher. Although the drying of SPS in SD had a longer drying time, the moisture removal rate was relatively high and drying occurred at the falling-rate drying period, enabling moisture removal by diffusion and this result in better product quality. Therefore, the drying conditions (temperature and relative humidity) in SD are suitable for drying SPS, however, increase in drying air velocity is recommended to eliminate challenges resulting from energy-intensive methods. SD is therefore, a practical method for use in the drying of large quantities of a product and it allows for the use of renewable energy as an alternative to electricity. This study found Midilli *et al.,* model to be the best fit to experimental moisture ratio data that can be used to estimate the moisture ratio of SPS during drying. Furthermore, the study showed that SD is a practical solution for small-scale farmers. However, the study recommends increase in air flow velocity in order to increase the drying rate, hence effectiveness for the use of the SD.

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5. EFFECT OF TWO DRYING METHODS ON QUALITY OF DRIED SWEET POTATO SLICES

Abstract

Firmness, colour and changes in microstructure were investigated to assess the effect of naturally-ventilated solar-venturi drying (SD) and a hot-air oven drying (HAD) on dried sweet potato slices (SPS). Investigation was done using SPS at different thickness sizes (3, 5 and 7 mm), pre-treatments (lemon juice, salting and pre-treatment) and without pre-treatment (control). TA.XTplus Texture analyser was used to determine firmness and Colorflex was used to determine colour changes, while Scanning electron microscope (SEM) was used to determine microstructure changes before and after drying. The study observed that as thickness increases, firmness and fracturability values increase in all treatments and drying method. It was observed that thickness size has a significant influence ($P<0.05$) on the firmness and fracturability. Thickness size, drying method and pre-treatment method had a significant influence on the final dried sweet potato slices. Lemon juice treated samples dried using HAD had lower firmness compared to samples with no pre-treatment (control), salted and blanched samples. Furthermore, the results of the study showed that SPS dried using a HAD were lighter those on SD for all treatments. SPS dried in SD had a lightness index ranging between 40.27-75.67 with a coefficient of variation (CV) of 24.72% while those under HAD had a CV of 12.29% and lightness index ranging between 55.36-73.70.

The pre-treatment and drying method influenced the quality of the final dried product. Fresh SPS were observed to have regular oval surface structures. However, the starch morphology of blanched sweet potatoes was flat, indicating that the heat pre-treatment has influence on quality of dried pre-treated SPS. Lemon juice pre-treated samples dried using both HAD and SD retained oval-shaped starch granules after drying; hence, the lemon juice pre-treatment was found to be the best pre-treatment method for the dehydration of SPS. The naturally-ventilated solar-venturi dryer can be used for the dehydration of SPS with lemon juice as a pre-treatment. However, it is recommended to find other methods to further reduce the drying time and further investigate other available pre-treatment methods to improve quality of the final dried SPS.

Keywords: drying method, colour, firmness, morphology

5.1 Introduction

Amongst the numerous methods used for food preservation, drying is the most ancient and commonly used method. The main objective of drying is to increase shelf life and preserve food by reducing moisture content. Open sun drying has been used for the partial removal of water (Madhlopa and Ngwalo, 2007). However, a number of drawbacks, such as prolonged drying time, microbial contamination and dust result in a poor final dried product (Kiaya, 2014; Lingayat *et al.*, 2017). Therefore, hot-air drying becomes an alternative drying technology used for dehydration. However, it has a number of limitations, such as its high energy input requirements and cost (Meher and Nayak, 2016; Miraei *et al.*, 2017).

The drying method and equipment have an impact on the final product, hence there is a need to study the effect of the drying method on the quality of chips after drying (Luther *et al.*, 2004). Convective hot-air drying is the most common method of drying agricultural crops both for industrial and commercial purposes. Studies report that drying has an effect on the physico-chemical properties and quality of dried sweet potato slices (Dinrifo, 2012; Mujumdar, 2012). Doymaz (2011) reported that heat and mass transfer during the drying process cause browning of the product resulting in reduction in quality compared to the original food. The physico-chemical properties and nutritional quality include carbohydrates, dietary fibre, iron, calcium and vitamins.

Several studies have investigated the use of solar drying of SPS. However, there is a limited research conducted on the quality parameters of SPS dried under naturally-ventilated solar-venturi dryer (SD) in South Africa. A comparative analysis of the drying methods will enable the dissemination of knowledge on the drying methods that have been assessed and how they preserve the quality of the dried sweet potato slices. Therefore, the objectives of this study are to evaluate the effect of drying pre-treatments and drying method on the quality of the final dried sweet potato slices.

5.2 Materials and Methods

The preliminary experiment was "drying of sweet potato slices" in a study site with climatic conditions described in section 5.2.1. The drying samples were prepared as explained in section 5.2.2 before drying. This chapter evaluates the effect of the two drying methods and pre-treatments on the quality of dried sweet potato slices as explained in 5.2.3, 5.2.4 and 5.2.5.

5.2.1 Study site and climatic data

The study was carried out at the Ukulinga Research Farm, at University of KwaZulu-Natal, Pietermaritzburg, South Africa (30°24'S'' and 29°24'E at an altitude of 721 m above sea level). The average long-term minimum and maximum temperatures of the study area range from 6.0 - 16.4°C and 20.6 - 27.4°C, respectively, while the relative humidity ranges from 61.1 - 75.3%. The area receives an average solar radiation of between 15.1 and 27.8 $MJ.m^{-2}.day^{-1}$, which is sufficient for solar drying applications (Schulze and Maharaj, 2007).

The study was conducted during the month of September 2018. The average long-term minimum and maximum temperatures in September range from 10.0 - 17.1°C and 12 - 27°C respectively, while the relative humidity ranges from 61.1 – 68.1%. The average solar radiation, wind speed and average sunshine hours for the month of September range from, 15.1 - 27.8 $MJ.m^{-2}.day^{-1}$, 0.8 – 9.7 $m.s^{-1}$, and 7 hours, respectively (Schulze and Maharaj, 2007). The weather data (temperature, relative humidity, solar radiation and wind speed) recorded during the study period was obtained from the weather station at Ukulinga research farm.

5.2.2 Sample preparation and treatments

A 50 kg batch of fresh sweet potato tubers was purchased from a local supermarket (Pick n Pay, Pietermaritzburg, South Africa). Sweet potato tubers with no physical damage and no sign of fungal or microbial attack were selected. The selected tubers were peeled, using a carbon steel blade potato peeler, after which they were washed, using deionized water. The tubers were dabbed, using paper towels to remove the water on their surface. Thereafter, the sweet potato tubers were sliced into rectangular-shaped with the dimensions of, 50 by 20 mm, using a stainless steel kitchen knife (Oke and Workneh, 2014). The thickness size of the slices were 3, 5 and 7 mm. The slices were pre-treated by either dipping in a salt solution (0.1 % w/v concentration for 20 minutes), a lemon juice solution (1 % w/v concentration for 20 minutes), blanched in a water bath at 70°C for 10 minutes (Labotech water bath, Thermo Fisher Scientific, Waltham, Massachusetts, United States) and other batch was not pre-treated (control) (Olawale and Omole, 2012). The pre-treated samples were dabbed, using paper towels to remove any liquid from their surface.

5.2.3 Firmness and fracturability analysis

Firmness and fracturability was measured using TA.XTplus Texture Analyser (Vienna Court, Lammas Road, Godalming, Surrey GU7 1YL, UK) with a 0.5 kN loading capacity. This was used to determine the maximum breaking force of both the natural-ventilated solar-venturi (SD) and a hot-air oven dried (HAD) sweet potato slices (SPS), using methodology described by Pedreschi and Moyano (2005). The test was carried out using a 2 mm stainless steel probe, attached to a load cell, at a penetration rate of 1 $mm.s^{-1}$ and a penetration depth of 8 mm.

5.2.4 Determination of colour in dried sweet potato slices

The colour of dried sweet potato chips was determined, using Colorflex EZ’s 45°/0° colorimeter. The colour properties of the samples before and after drying were measured and compared to colour of fresh SPS. Colorflex was calibrated against a black and white standardization tile, before taking the actual measurements. Colour measurements were carried out, in terms of CIE L*a*b colour measurements. Lightness, L* indicates the colour coordinate of lightness (ranging between zero (black) and hundred (white). Redness, a* indicates the colour coordinate of redness (+ = red and - = green) and b* indicates the colour coordinates of yellowness (+ = yellow and - = blue). During the colour test, three measurements were taken from different positions in each sample, and the average value was determined.

5.2.5 Determination of microstructure changes

A scanning electron microscope (SEM), Zeiss Evo LS15 (Zeiss, Germany) was used to take micrographs of fresh and dried sweet potato chips. The SEM magnification was set at a 124 x high vacuum and the extra high tension (EHT) voltage was set at 20 kV. Micrographs were taken for the dried and fresh SPS using standard SEM procedure.

5.3 Results

5.3.1 Firmness and fracturability of dried sweet potato slices

The results showed that the drying method and pre-treatments had an effect on the physical properties of dried SPS. Table 5.1 shows the firmness of SPS using HAD and SD pre-treated. SPS dried using HAD had firmness values ranging between 8.8±0.8 – 38.3±3.5 N. The average firmness of SPS dried in HAD at 3, 5 and 7 mm thickness were 14.5±1.9, 21.5±2.6 and 27.4±3.3 N, respectively. Control samples with 3 mm thickness had lower firmness values compared to all treatments. However for 5 and 7 mm thickness lemon juice pre-treated samples had lower firmness values followed by salted treated samples.

SPS dried using SD had firmness values for control and pre-treated samples ranging between 5.3±0.1 - 97.8±4.6 N. The average firmness values for 3, 5 and 7 mm thickness size were 13.8±2.0, 24.8±3.3 and 48.8±6.6 N, respectively. SPS with no pre-treatment had lowest firmness value at 3 mm thickness, while for 5 and 7 mm thickness lemon juice pre-treated samples had lower firmness values followed by control and salted.

Table 5.1 Firmness of sweet potato slices dried in a hot-air dryer and a naturally-ventilated solar-venturi dryer

Drying method	Thickness [mm]	Control [N]	Salting [N]	Lemon juice [N]	Blanching [N]
HAD	3	8.8±0.8	11.6±1.0	9.5±0.9	28.0±4.8
	5	26.0±3.2	14.4±4.0	11.4±1.9	34.0±1.2
	7	28.8±4.5	26.7±3.9	15.8±1.2	38.3±3.5
SD	3	5.3±0.1	10.7±1.8	8.9±2.0	30.3±4.1
	5	23.6±1.0	24.4±5.0	11.4±3.2	39.7±4.0
	7	26.8±9.2	44.0±11.8	26.7±0.9	97.8±4.6

*HAD = hot-air oven dryer, SD = solar-venturi dryer, N = Newton, control, lemon juice, salted and blanched – pre-drying treatments for sweet potato slices.

The fracturability measured on SPS that were dried using HAD and SD is shown in Table 5.2. The results obtained ranged from 23.0±0.5- 112.8±26.1 N for both drying methods. The HAD had fracturability values ranging between 25.1±2.3 - 85.3±7.8 N. The average fracturability values for SPS dried in HAD at 3, 5 and 7 mm thickness size were 28.18±2.4, 52.2±7.5 and 55.5±9.5 N. The SD dried SPS had mean fracturability values ranging between 23.0±0.5 - 112.8±26.1 N. The average values for fracturability at 3, 5 and 7 mm thickness sizes were 27.4±1.8, 46.8±7.4 and 85.1±18.2 N for control and pre-treated samples.

Table 5.2 Fracturability of dried sweet potato slices

Drying method	Thickness [mm]	Control [N]	Salting [N]	Lemon juice [N]	Blanching [N]
HAD	3	26.9±3.7	25.8±2.0	25.1±2.3	34.9±2.6
	5	57.9±13.3	34.1±7.6	31.4±1.1	85.3±7.8
	7	60.7±7.6	55.5±7.0	39.9±3.5	65.8±19.9
SD	3	25.4±3.1	24.7±1.7	23.0±0.5	35.3±1.7
	5	42.5±2.3	57.2±9.3	31.9±6.2	55.5±11.7
	7	64.1±20.6	101.4±19.7	62.1±6.3	112.8±26.1

*HAD = hot-air oven dryer, SD = solar-venturi dryer, N= Newton, control, lemon juice, salted and blanched – pre-drying treatments for sweet potato slices, mean values (±SD).

5.3.2 Colour of dried sweet potato slices

Colour is an important quality parameter used as a measure for market value of produce. The colour evaluation tests results (L^*, a^* and b^*) of SPS dried, using SD and HAD are presented in Figures 5.1; 5.2 and 5.3. The final dried SPS were evaluated at a 5% significance level (Xu *et al.*, 2012). It was observed that the SPS dried using SD had lightness (L^*) values ranging between 40.27-75.67, with the control, salted, lemon juice and blanched samples measured to be 59.41, 65.35, 75.67 and 40.27, respectively. The Redness (a^*) values were measured to be 3.37, 2.72, 1.26 and 3.18 for control, salted, lemon juice and blanched samples, respectively. The yellowness of these samples was measured to be 17.23 (control), 17.09 (salted), 11.70 (lemon juice) and 12.67 (blanched). The average lightness, redness and yellowness was calculated to be 60.18, 2.63 and 14.67, respectively. Redness and yellowness ranged between 1.26 - 3.37 and 11.70 - 17.23, respectively. The coefficient of variation (CV) for lightness, redness and yellowness in a SD was 24.72, 36.35 and 19.78 %, respectively.

The SPS samples dried in HAD had lightness values that ranged between 55.36 and 73.70, with the control, salted, lemon juice and blanched samples measured to be 68.39, 73.70, 71.82 and 55.36, respectively as shown in Figure 5.3. The redness values ranged from 2.35 - 4.70, with control, salted, lemon juice and blanched samples measuring 2.49, 2.35, 3.12 and 4.70, respectively. The yellowness was measured to be 19.51 (control), 15.81 (salted), 17.76 (lemon juice) and 31.91 (blanched). The (CV) for lightness, redness and yellowness were measured to be 12.29, 33.94 and 34.20%, respectively. The average of all colour indicators in the HAD (lightness, redness and yellowness) were measured to be 67.32, 3.17 and 21.25, respectively.

The hue angle for dried SPS ranged from 80.0 – 82.7° for a HAD and from 75.9 – 83.9° for SD, as shown in Table 5.4. The calculated mean hue angle was 82.7, 81.5, 80.0 and 81.6° for the control, salted, lemon juice and blanched samples in a HAD, respectively. Samples dried under SD had 78.9, 81.0, 83.9 and 75.9° mean hue angle values, respectively.

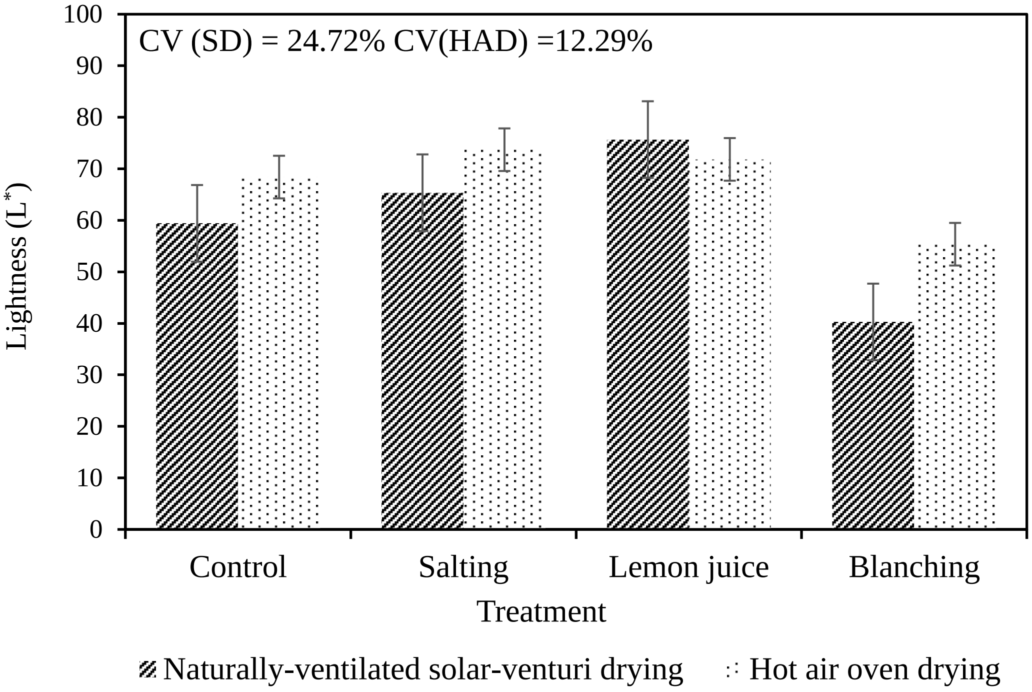

Figure 5.1 Variation of lightness in sweet potato slices dried using SD and HAD (*CV = coefficient of variation, SD = solar-venturi dryer and HAD = hot-air oven dryer)

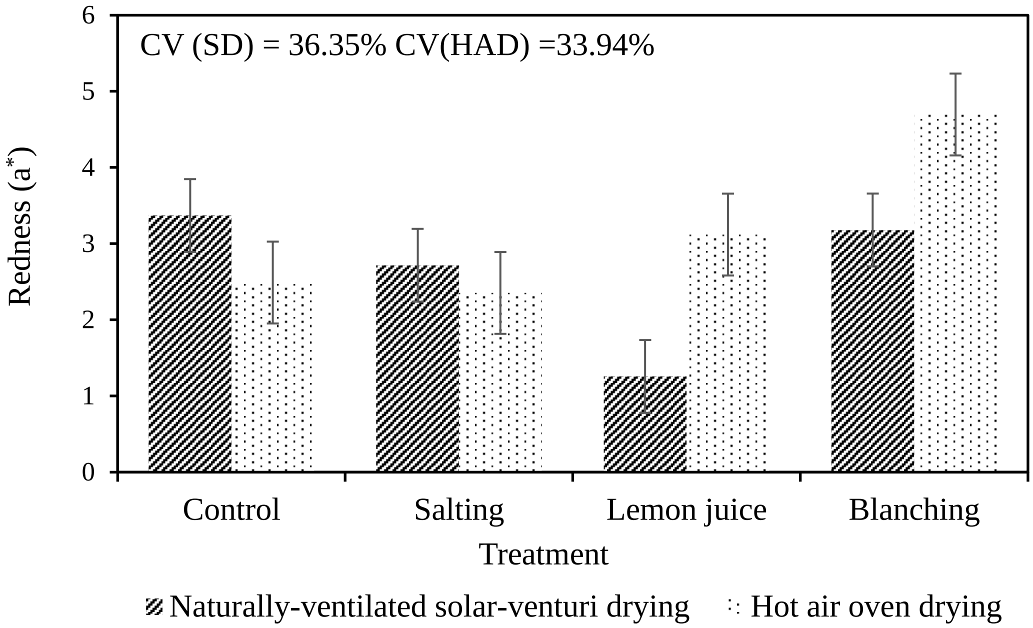

Figure 5.2 Variation of redness in sweet potato slices dried using SD and HAD (CV = coefficient of variation, SD = solar-venturi dryer and HAD = hot-air oven dryer)

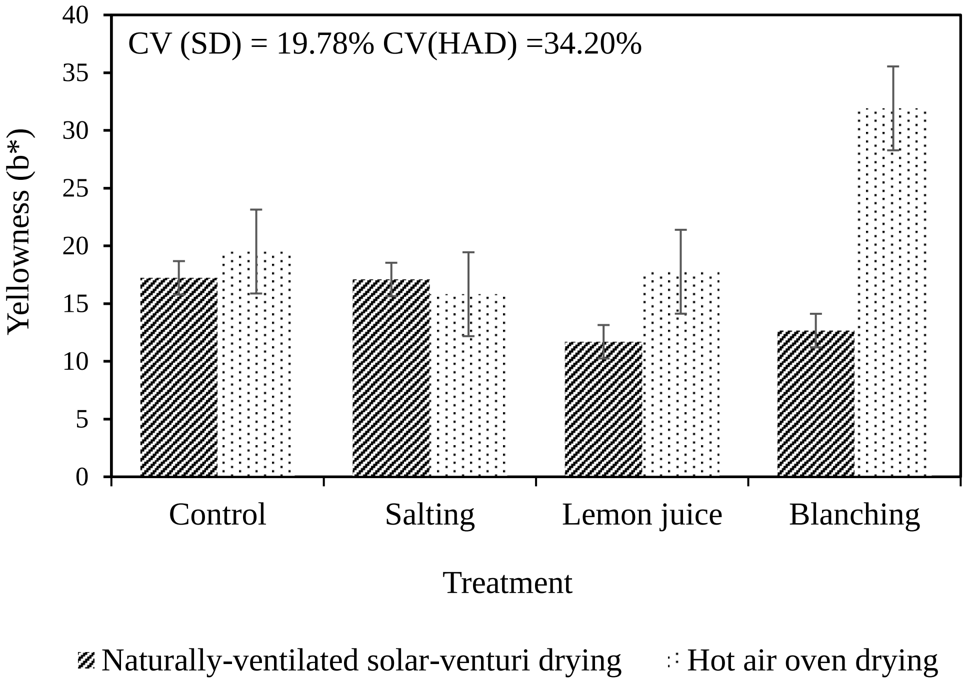

Figure 5.3 Variation of yellowness in sweet potato slices dried using SD and HAD (CV = coefficient of variation, SD = solar-venturi dryer and HAD = hot-air oven dryer)

Table 5.3 Hue angle measured on sweet potato slices dried in a solar-venturi dryer and hot air oven dryer

Treatment	HAD [º]	SD [º]
Control	82.7^a	78.9^a
Salted	81.5^a	81.0^a
Lemon juice	80.0^a	83.9^b
Blanched	81.6^a	75.9^a
CV [%]	1.4	4.20

*HAD – hot-air oven dryer, SD – solar-venturi dryer. Means with the same latter in the column do not differ from each other tested at 5% level of significance, CV – coefficient of variation.

Sensory evaluation of dried sweet potato was assessed, as shown in Figures 5.4 and 5.5. The images show that SPS dried under SD were darker than the SPS dried under HAD. In SD, SPS treated with lemon juice were found to be lighter than all other treatments. This was observed in the Lightness values shown in Figure 5.1 and the image shown as A4 in Figure 5.4. In HAD, the SPS pre-treated with a salt solution were lighter than other treatments. The final dried product of SPS pre-treated with blanching were darker in colour, which can be seen in Images A3 and B3 in Figures 5.4 and 5.5. Colour change was observed in all final dried SPS (Xu *et al.*, 2012).

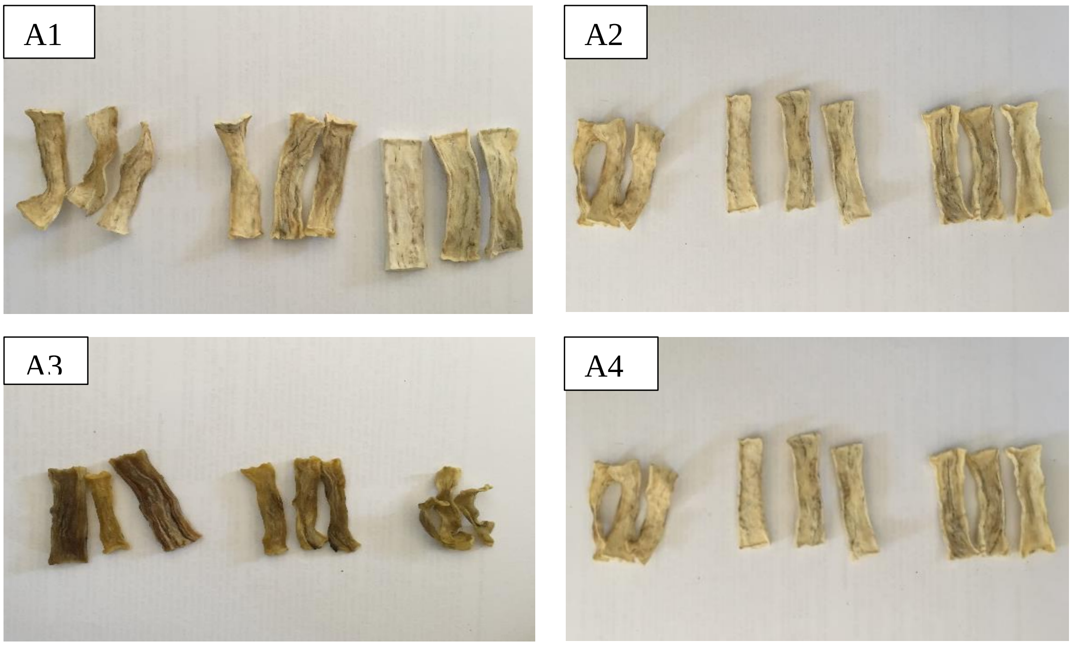

Figure 5.4 Solar dried SPS (A1 = Control, A2 = Salting, A3 = Blanching, A4 = Lemon juice)

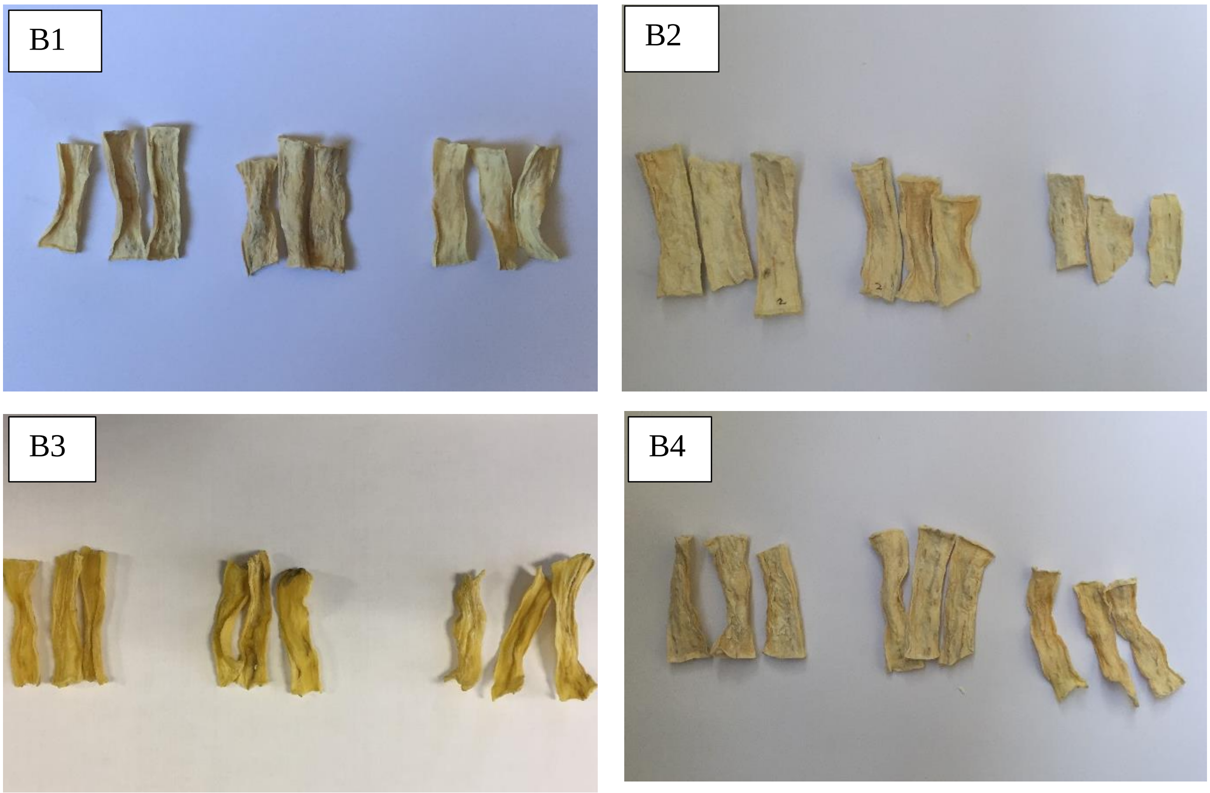

Figure 5.5 Hot-air oven dried SPS (B1 = Control, B2-Salting, B3 = Blanching, B4 = Lemon juice)

5.3.3 Changes in the microstructure

Scanning electron micrographs (SEM) was used for comparing the surface microstructure of fresh and dried SPS using micrographs of fresh and dried sweet potato slices, as shown in Figure 5.6 and 5.7. This investigation was done to study the effect of pre-treatments and drying method on final dried SPS. Starch morphological images were taken at the centre of each SPS. Most of the starch granules were oval-shaped, and in various sizes. Blanched SPS slices that were dried in both SD and HAD were observed to have flat deformed starch surface granules, this shows that a fraction of starch was disrupted during processing and it resulted in change of the granular structure. The size of starch granules varied, depending on the treatments and drying methods. Sweet potato samples dried in HAD with lemon juice, salt pre-treatment and control displayed an oval shape, while the blanched samples had a flat-shape. SPS dried in the SD drying system also resulted in oval-flat shape granules, while the blanched slices had flat-shaped granules. Fresh SPS showed a great number of oval and spherical granules.

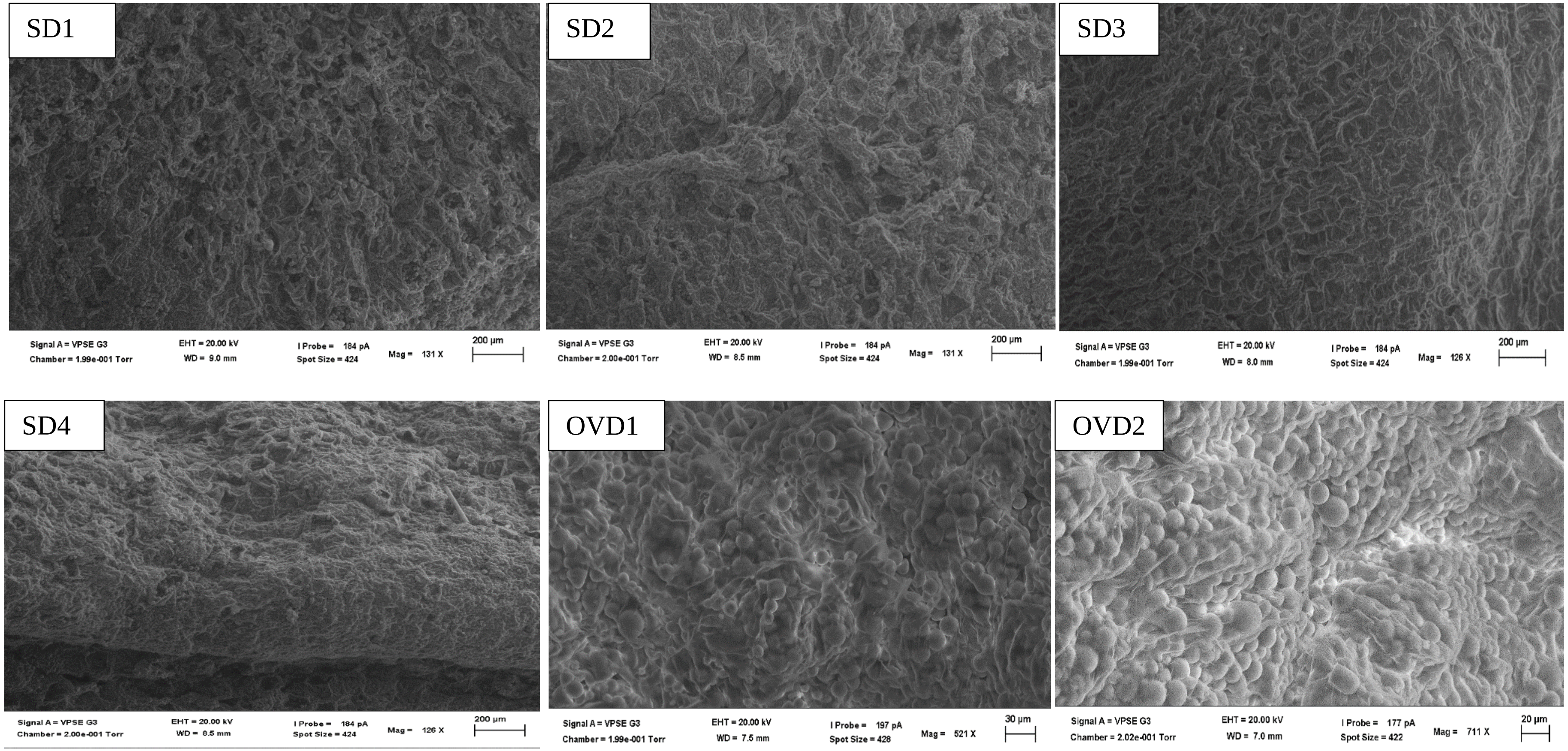

Figure 5.6 Solar dried SPS (SD1 = Control, SD2 = Salted, SD3 = Blanched, SD4 = Lemon juice) and Oven dried SPS (OVD1 = Control, OVD2 = Salted)

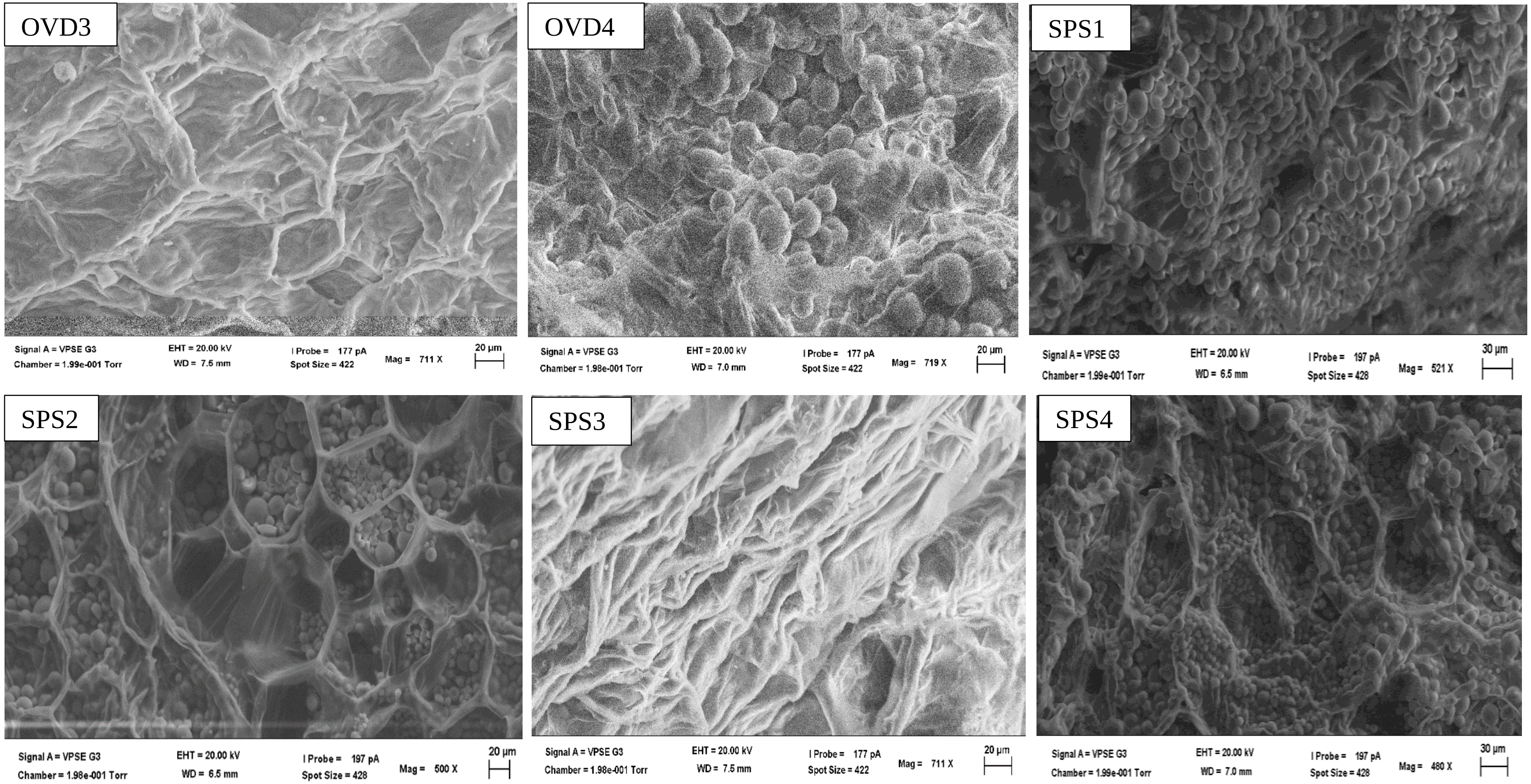

Figure 5.7 HAD dried SPS (OVD3 = Blanched, OVD4 = Lemon juice) and Fresh SPS (SPS1 = Control, SPS2 = Salting, SPS3 = Blanched, SPS4 = Lemon juice)

5.4 Discussion

Texture and fracturability were found to vary among SPS of different thickness sizes and the pre-treatment methods. The overall average shows that as thickness increases, texture and fracturability values also increase in all pre-treatments and drying method. This shows that thickness size, drying method and pre-treatment had an influence on the final dried product. Lemon juice samples dried using HAD had lower textural values compared to samples with no pre-treatment (control), salted and blanched for samples. Dried samples with small thickness sizes had lower texture values for all pre-treatment methods. This was similar to findings by Meher *et al.* (2015). There was no significant difference ($P>0.05$) between the firmness and fracturability values obtained from samples dried using HAD and SD for the same thickness size and the drying pre-treatment method. Blanched SPS had maximum fracturability in HAD and SD, this indicates less sensorial tenderness and crunchiness as reported by Caetano *et al.,* (2018).

Colour is one of the most important parameters used to determine the value of the final product and it has a major influence on the buyers' choice (Nisha *et al.*, 2011; Oyebanji *et al.*, 2013). The literature reviewed reported that the drying method and temperature had impact on the colour and structure of the final dried product. Hence, the colour and microstructure changes as a result of both drying methods (SD and HAD) and pre-treatments was studied using surface micrographs, imagery and colour change evaluation. The effect of thickness size of the slices was also investigated on fresh and dried SPS. Imagery of dried SPS blanched (pre-treated) were darker in colour among other samples. This may be because sugar and starch content were altered during hot water pre-treatment (blanching).

The treatment and drying method were observed to have an influence on the quality of the final dried product. HAD had a better final dried sweet potato chips, in terms of colour and lightness compared to SD. All SPS dried in HAD were bright in colour ($L^* >50$). This is similar to findings by Odenigbo *et al.* (2012) who observed L^* above 50. This was a result of the higher drying temperature and the shorter drying time, which inhibited change in colour of SPS. Blanched SPS had minimal lightness values for both drying methods and treatments. This indicates that blanching did not improve the colour of the dried samples. Sweet potato samples dried in SD were dried in a slightly lower temperature, hence there was a longer drying time which may have allowed change in surface characteristics of the samples thus a change in colour. It was observed that there was no significant difference ($P<0.05$) on the lightness of the SPS dried, using HAD. This resulted from a high temperature and a shorter drying time. The redness (a*) of dried SPS was not significantly different ($P<0.05$). SD-dried SPS had a higher redness, as compared to HAD, which was evident by the browning and yellowness of the final dried products that was observed on the hue angle (Odenigbo *et al.*, 2012). This would be a result of polyphenol oxidase activity which allowed enzymatic browning in low temperature drying. However, low values of redness indicates that SPS had more of a greenish colour rather than red. SPS dried in HAD and SD had a hue angle of 80.0 – 82.7^o and SD 75.9 – 83.9^o, respectively. Studies have shown that the hue angle has a great influence on the yellowness of the drying food material, which was reported by the findings of Caetano *et al.* (2017).

Fresh SPS were observed to have regular oval surface structures. However, the starch morphology of blanched sweet potatoes was flat, which means that heat pre-treatment has impact on the quality of starch in dried SPS. Iheagwara (2013) reported that hydrothermal treatment alters the starch properties of sweet potatoes, resulting in modified starch granules. Lemon juice pre-treated samples dried using both HAD and SD retained oval-shaped starch granules after drying; hence, the lemon juice treatment was found to be the best treatment method for the dehydration of SPS. Babu *et al.* (2014) also reported that starch regions are more susceptible to acid than crystalline regions, which increases enthalpy and gelatinization.

5.5 Conclusions

Drying method had no significant influence on the final dried product; however, thickness size and pre-treatment method had a significant method on textural and colour of the final dried products. HAD dried SPS were characterised lower firmness values, fracturability values, higher lightness, relatively higher redness, higher yellowness, hue angle and mostly oval shaped starch granules. SD dried SPS were characterised by a relatively low firmness, fracturability values, lightness, redness and yellowness. Lemon juice pre-treatment was observed to be best method for drying SPS for both the HAD and SD. The SD was observed to be a competent drying method which can be used for the dehydration of SPS. Naturally-ventilated solar-venturi dryer is recommended for the dehydration of SPS with lemon juice pre-treatment. However, it is recommended to find other methods to further reduce the drying time and further investigate other available pre-treatment methods to improve quality of the final dried SPS.

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6. CONCLUSIONS AND RECOMMENDATIONS

Drying of sweet potatoes before storage is the most promising method of preservation due to the amount of available solar radiation in South Africa. The literature studies showed that hot air drying is the simplest applicable drying method, in terms of cost and ability, to dry a wide range of produce. The study experiment was of two drying methods, namely, naturally-ventilated solar-venturi dryer (SD) and the hot-air oven dryer (HAD). Naturally-ventilated solar-venturi dryer and a hot air oven dryer were compared and their effect was observed on 3 mm, 5 mm and 7 mm thick sweet potato slices (SPS) that has been pre-treated with lemon juice, salted, blanched and samples that were not pre-treated. The following conclusions were made from this study:

(a) The SD raised the air temperature to ± 20°C above the ambient air temperature and was able to reduce the relative humidity under fully-loaded and unloaded drying to less than 20%, which is the maximum tolerable relative humidity for drying. There is a strong relationship between ambient and the dryer temperature. The thermal efficiency of the solar-venturi dryer was observed to be highly-depend on the amount of solar radiation available, which ranged between 8 – 72.81% for a loaded and empty dryer. The total solar radiation captured under Pietermaritzburg conditions ranged between 387.95 - 894.28 $W.m^{-2}$.

(b) Thin-layer models were used to evaluate drying characteristics and to model the heat and mass transfer of SPS. The Henderson and Pabis, Logarithmic, Two-term and Midilli are the models used to describe the drying kinetics. The moisture ratio relationships were used to select the best model describing drying in both the solar-venturi dryer and the HAD. Statistical parameters were used to select the best model to describe the drying process. Midilli was found to be the best equation to describe drying kinetics in both drying methods.

(c) The effect of the pre-treatment and thickness size of sweet potato slices were studied by evaluating the final dried sweet potato slices. Lemon juice as a pre-treatment was observed to be the best pre-treatment method for both SD and HAD. SPS cut at 5 mm thickness size was observed to be the best thickness size for drying conditions.

Natural-ventilated solar-venturi dryer was found to be a feasible solution for small-scale farmers in Pietermaritzburg of KwaZulu-Natal, however, further research is recommended to increase the volumetric air flow rate of the solar-venturi dryer by increasing the chimney height and varying the concentration of the lemon juice, for the optimal performance and quality of the final dried slices. The study also recommends modelling of chimney size (height and diameter) and solar collector area that will be applicable to various locations for the optimum performance of a SD.