LIFE CYCLE ASSESSMENT AND THE PRODUCTIVITY STUDY OF THE SUGAR INDUSTRY IN SUDAN

by

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PREFACE

The candidate completed the research contained in this thesis in the Discipline of Bioresources Engineering, School of Engineering of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa.

The contents of this study have not been submitted in any form to another university. Except where the work of others is acknowledged in the text, the reported results are based on the candidate's investigations.

____

Signed: Professor TS Workneh

Date: December 2020

DECLARATION 1: PLAGIARISM

I, Tageldeen Saeed Tageldeen Ibrahim, declare that:

(i) this thesis, except where otherwise indicated, is my original work;

(ii) this thesis has not been submitted for any degree or examination at any other university;

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

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

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

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DECLARATION 2: PUBLICATIONS

The list of publications in this thesis is as follows:

Chapter 2

Ibrahim, TS and Workneh, TS. 2019. An evaluation of the current status of the production performance of the sugar industry in Sudan: an overview. *Sugar Industry* 144(11): 655-659.

This paper is based on a literature review that I carried out to give baseline information about the Sudanese sugar industry. The paper focused on the current status of the sugar industry, especially the productivity of the factories that were studied. I reviewed, summarised and synthesised the literature and wrote the article under the supervision of Prof. Tilahun Workneh. As a co-author, he provided me with guidance, revision and proofreading, prior to its submission for publication.

Chapter 3

Ibrahim, TS and Workneh, TS. 2020. Identification of technical factors that influence the sugar productivity of factories in Sudan. *African Journal of Science, Technology, Innovation and Development.* doi: 10.1080/20421338.2020.1824324.

This paper is based on a documentary review of the data that I collected from the databases of Sudanese sugar factories. I extracted the data (i.e. qualitative information that was relevant for the potential causes of the problems that were studied) from annual reports and records. I conducted personal communications with the engineers, managers and administrators of the relevant departments. I developed and used the cause and effect analysis technique to extract the most significant factors influencing sugar productivity in the factories that were studied. In this paper, I generated and discussed the results and came up with recommendations to solve the problem of declining production. My co-author, Prof. Tilahun Workneh, provided enormous guidance and reviewed the paper prior to submission and publication.

Chapter 4

Ibrahim, TS and Workneh, TS. 2020. The environmental impact of sugar industry waste in Sudan. *Journal of the Air and Waste Management Association.* **[Submitted - under review]**

The research in this paper is based on a cross-sectional survey that employed self-administered questionnaires. I developed and evaluated the questionnaire and collected data from 377 respondents living in the vicinity of the six selected sugar factories in Sudan. I employed the multinomial regression analysis to establish a unique relationship between the identified factors that influenced the surrounding environment. I generated and discussed the results in this paper. My co-author, Prof. Tilahun Workneh, provided guidance and revision, and proofread the article prior to submission and publication in a peer-reviewed journal.

Chapter 5

Ibrahim, TS and Workneh, TS. 2020. Data for understanding the health risks of Sudanese sugar industrial waste: wastewater and suspending particulates. *Data in Brief.* **[Submitted - under review]**

In this paper, I highlighted the impact of exposure to industrial sugar waste on human health and the environment. I identified the diseases (i.e. on the eye and inflammation) associated with the wastewater, gases and bagasse ash that endanger the people residing in the vicinity of the sugar factories. My co-author, Prof. Tilahun Workneh, provided guidance and reviewed the final paper, prior to submission and publication.

Chapter 6

Ibrahim, TS and Workneh, TS. 2020. Life-cycle assessment of sugar production in Sudan: green-house gas emissions and energy usage. *Journal of the Air and Waste Management Association.* **[Submitted - under review]**

The research in this paper is based on the application of the methodology of a life-cycle assessment of the Sudanese sugar factories. I identified and designed the stages of sugar production, ran the SimPro software, analysed the data, created the results and wrote the paper. My co-author, Prof. Tilahun Workneh, provided guidance and reviewed the paper prior to its submission for publication.

The following papers were presented at national and international conferences:

1. Ibrahim, TS and Workneh, TS. Evaluation of the production performance and environmental impact of the sugar industry in Sudan. South African Institute of Agricultural Engineers (SAIAE) Symposium and Biennial CPD Event. Durban North, South Africa. 17th – 20th September 2018.

2. Ibrahim, TS and Workneh, TS. Identification of the technical factors influencing sugar productivity in Sudan. The 2nd All-Africa Postharvest Congress and Exhibition at the African Union Commission, Addis Ababa, Ethiopia. 17th – 20th September, 2019.

[redacted]

Signed: TS Ibrahim

Date: December 2020

ABSTRACT

For decades, sugar has been produced in Sudan in six factories, namely, Kenana, Assalaya, Guneid, Halfa, Sinnar and White Nile mills. The industry is facing challenges that influence its productivity and the health of its environment. This study aimed at assessing the life-cycle and technical factors that influence the sugar productivity of the factories. The effect of sugar industry waste on the health of communities was also evaluated. Finally, their energy use and greenhouse gas emissions, and their impact on the environment, were also assessed. The study involved a documentary review and data collection from the databases of the six selected sugar mills. Qualitative content analysis techniques, namely, a linear regression analysis and the intensity relation matrix technique, were used to identify the factors that influence sugar productivity. The study also employed a cross-sectional survey approach, comprising a total of 377 sample respondents who live in the vicinity of the selected six sugar mills. By using SPSS software as a tool, the descriptive statistics, non-parametric statistics, and logistic regression analyses were performed to quantify the impact of waste on community health. The data on the energy use and the emissions generated during the assessments were analysed by using SimaPro software Version 9.0.0.49, as well as the characterisation methods of ReCiPe 2016 and the Intergovernmental Panel for Climate Change (IPCC) 2007. The results showed that sugar production has dropped by 32%, namely from 775,000 tonne to 526,000 tonne, over the past ten years. The sugar production in the Kenana factory, which produces 50% of the country's sugar, has declined by about 24%, from 391×10^3 tonne to 299×10^3 tonne. Sugar production has also decreased at the Guneid, Halfa, Sinnar and Assalaya factories by 24%, 50.2%, 36.1%, and 42.7%, respectively. The results revealed that the sugarcane yield was the main contributor to the decrease in sugar productivity. The sugar productivity had a significant ($P < 0.01$) effect on the sugarcane yield. The most dominant factors that influenced the sugarcane yield were the lack of agricultural inputs, improper land preparation and soil salinity, the disruption of fallow practices, the shortage of irrigation water, and a non-optimal sugarcane harvesting age. Depreciation and wear of machinery have resulted in a 22% reduction in the sugar extraction rate and milling efficiency, which remains at 78%. The results also showed that the wastewater has significantly ($P < 0.05$) influenced community health, crop growth, and animal production in the vicinity of these factories. It develops an off-odour and creates a favourable environment for the breeding of mosquitoes, which has a significant ($P < 0.05$)

influence on the incidence of malaria for the residents living near the sugar factories. The industrial sugar pollutants were identified as the cause of human eye and respiratory infections in the region. Moreover, the results revealed that sugarcane production was the most significant energy consumer in the life-cycle of sugar production, namely, 2166 Mega Joule (MJ) per tonne (t) sugar, with a share of 39%. The rest of the energy consumption of 26.6%, 20.7% and 13.7% occurs during sugar processing, sugarcane cultivation and sugarcane harvesting and transportation, respectively. The contributors to the global warming potential, based on a 100-year time scale, were 51%, 27%, 12%, and 10% for sugar processing, sugarcane production, sugarcane cultivation, and sugarcane harvesting with transportation, respectively. The main contributors to ozone depletion were sugarcane production (44%) and sugar processing (22%). The results showed that sugar processing has contributed to eutrophication, acidification, particulate matter, and human toxicity by 1.1×10^{-7} species.yr, 1.3×10^{-6} species.yr, 8.4×10^{-4} DALY, 4.2×10^{-3} DALY, respectively. For the first time, this study has provided valuable base-line data and information that can be of benefit to the Sudanese sugar industry. In summary, the sugar industry in Sudan requires a well-structured plan, in order to increase the productivity of sugarcane and sugar. Substantial reforms are needed to improve the energy use and to decrease the emissions, in order to minimise the environmental impact. The waste management strategy of the sugar industry should also be enhanced to protect the communities from being subjected to health deterioration due to the impact of waste disposal in the environment.

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First of all, I thank the Almighty, Allah, for his strength and persistence that has seen me through this research study.

My appreciation goes to Prof. TS Workneh, for his immense support and for providing me with vital input throughout the study. Besides his professional support, he has been so friendly, open and approachable. Prof. Workneh, above all, guided and encouraged me to develop each of the chapters into research article format and to send one after the other to internationally-recognized journals for possible publication. I am very grateful to him for his efforts, for the time he spent on facilitating my research visits and organising financial support.

I want to thank the University of KwaZulu-Natal (UKZN) for providing me the opportunity to enroll in the Ph.D. program and for sponsoring my studies. I am also grateful to the University of Khartoum and the Ministry of Higher Education (Sudan). Their financial support has contributed to the smooth completion of this research project.

To my mother, Haleema, and my father Saeed: thank you for your moral support and unconditional love.

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1. INTRODUCTION

This chapter gives some background on the sugar industry, particularly in Sudan, and the challenges facing this sector i.e. its productivity, the waste disposal management that is currently practiced and its energy consumption. It includes the problem statement, the research questions, as well as the objectives of the research and the significance of the study.

1.1 Background to the Study

For a long time, sugar has been one of essential components in the human diet (Contreras *et al*., 2009; Ramiro *et al.*, 2019). It is important because it contributes to meeting the energy requirements of individuals. More than one hundred countries produce sugar, and approximately 70% of the sugar is produced from the sugarcane stalks (Contreras *et al*., 2009). An evaluation of the environmental and economic aspects is of paramount importance for optimizing the usage of resources in sugarcane production and sugar processing and for reducing the environmental impact (Contreras *et al*., 2009). In Sudan, the sugar industry plays an important role because it contributes significantly to the national income, to local consumer satisfaction, and to the export (Abdalla, 2006; Adam *et al*., 2015). Sudanese sugar has a distinguished place among the African states, as Sudan is the third-largest producer of sugar in Africa (Hassan, 2008; Nations Encyclopedia, 2019). Its estimated production is about 800 000 tonne, which is equivalent to 7.5% of the African continent (Hassan, 2008). The industry is well-established, and it has a reasonable performance level with regard to production efficiency and technological advancement, and it is considered to be one of the main strategic sectors in the country (Bushara, 2016). The Guneid factory was the first sugar producer in the country, while the other sugar factories came into operation later, between 1965 and 2004. The six sugar factories are classified into two groups: the Kenana and White Nile are private limited companies, while the Guneid, Halfa, Sinnar and Assalaya factories are publicly owned (Elzebair *et al*., 2015). The total cultivated area is about 173 000 ha, which represents 5% of the arable land in the country (Adam *et al*., 2015). The area of harvested sugarcane was between 69 600 and 74 672 ha over the 2013 to 2017 period (Knoema, 2017). About 8 million tonne of sugarcane is produced and harvested mechanically per annum (Federal Ministry of Agriculture [FMA], 2010).

However, due to major problems, the industry has deteriorated. The most significant setback is its declining sugar productivity, due to unknown factors. The amount of sugar produced in Sudan is fluctuating, as shown in Figure 3. The Kenana mill produces about 56% of the sugar in the country and its production has declined by an average of 2.5% annually over the 2001 to 2016 period (Abdalla, 2006; Elzebair *et al*., 2015; Kenana Sugar Company [KSC], 2016).

Similarly, productivity has been declining in the Guneid, Halfa, Sinnar and Assalaya factories (Bushara, 2016), despite the fact that Sudan has the right growing conditions and that the planted area has been expanded (Ibrahim, 2017). The decline has led to a decrease in sugar exports (Knoema, 2016). It has been concluded that the reasons for this problem are the poor design of the factories and the improper utilization of the production inputs (Hassan, 2008; Ibrahim, 2017). Ibrahim (2011) found that reforming the structure of the production process had a positive effect on the performance level of the Kenana factory. However, it was concluded that the study limited to the investigation of only this one factory (i.e. Kenana). Also, the technical factors influencing the production process has not been considered, which makes the analysis general and fallacious. However, based on the above literature reviewed, there are many questions raised and need to be drastically answered. The questions are as follows: what factors affecting the efficiency of sugarcane production? What are the constraints for the sugar processing in the factory? Thus far, there was no study with a precise method has been implemented to investigate the technical factors of the sugar-processing in Sudan, especially those of the older factories. In addition to that, finding sustainable solutions to the raised problems must be considered. Therefore, a research work is required to identify the technical factors that influence sugar productivity in Sudanese factories.

In addition, the sugar industry discharges its waste into open drains, without being treated (El Hassan, 1998; Sanket, 2015), which could have polluted the freshwater and the surrounding environment. This problem needs to be solved sustainably, in order to mitigate its environmental impact. In this respect, Ali *et al*. (2006) conducted research to assess the pollution load of waste from the Assalaya Sugar Factory into the Nile River. The study found that the wastewater contaminates river water. Alim (2012) stated that the Kenana Factory is in the process of constructing waste recycling plant, and Oboody (2016) conducted a study to produce biogas from the sugar industry waste in the Kenana Factory, using the anaerobic digestion technology. Some sugar factories do not have adequate databases to attend to the issue of waste treatment. This trend could influence the environment, as well as the surrounding communities. The reason for this is that previous studies have limited their research to only certain factories (i.e. at Kenana and Assalaya). The impact of the sugar industry waste on community health is not clear. The sugar production process also consumes resources such as fossil energy (Nakhla, 2014). The utilization of fossil fuel releases harmful gases that cause global warming. Combusted bagasse releases ash, which affects human health (Cordiero *et al*., 2004; Mohamed and Samah, 2011; le Blond *et al*., 2017). Nevertheless, the manufacture of pollutants from sugar production could be minimized and controlled (Abdeen, 2002; Sahu, 2018). To date, no study has been conducted in Sudan to assess the impact of the sugar industry effluents, and no attempt has been made to identify the best practices for management. An assessment of greenhouse gas emissions and energy consumption in the life-cycle of the sugar industry has not been previously conducted in Sudan.

A life-cycle assessment is a technique or tool that is used for managing environmental performance, for auditing and for impact assessments (Nakhla, 2014). The International Organization for Standardization (ISO) defines a life-cycle assessment as a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life-cycle". An LCA is a well-established and well-constructed method that can be applied for industry research (Nakhla, 2014). It considers the life-cycle stages of the product (i.e. sugar production) starting with the extraction, the processing of the raw materials, manufacturing, the use, re-use, recycling, final disposal, transportation and distribution of the product (Contreras *et al*., 2009). A life-cycle assessment of sugar production is a method that is based on scientific procedures that are used to evaluate the environmental effects and energy consumption of all phases of the sugar production process, from its raw materials to its final disposal (Williams, 2009; Livison *et al*., 2010). The advantage of carrying out an LCA is to get a full insight into the environmental impact of the product and to identify the proper solutions and improvements (Curran, 2016). The demerits of the LCA is time consuming, expensive and requires extensive detailed data to conduct and come up with reasonable interpretation and conclusion (Gregory *et al.,* 2009). An LCA is essential in the aspects of environmental management and for maintaining sustainable goals (Curran, 2016).

Many studies have been conducted on a global scale in different countries around the world (i.e. Brazil, South Africa, Egypt and Mauritius) where Life-Cycle Assessments (LCAs) have become a well-known tool for carrying out environmental assessments on the sugar production system. Therefore, a study is required that will identify the factors influencing productivity and the effects of sugar waste disposal on the surrounding environment and on community health. This present research has generated extensive empirical data that addresses the factors influencing the productivity of the sugar industry in Sudan. It analyses the current sugar-processing operation and it determines the impact of sugar industry waste on the health of communities living in the vicinity of the factories. Hence, this study identifies opportunities for improving the environment of the surrounding areas, and it assesses the energy use and Greenhouse Gas (GHG) emissions of sugar production by applying the life-cycle assessment methodology. It identifies the possibilities for improvement and it develops a model to steer decision-makers towards achieving sustainable production and services for the sugar industry in Sudan.

1.2 Problem Statement

The sugar industry in Sudan suffers from a deteriorating sugar quantity, the sugar quality and its environmental performance. There has been a notable decline in sugar productivity over many years, since 2007, and unknown factors have been threatening the sustainability of the industry. The country has introduced various intervention measures to improve its productivity, for example, the rehabilitation of the boilers, power plants and the irrigation pumps of the publicly-owned factories.

However, the annual productivity has continued to decrease, and an examination of the sugar-processing supply chain of the Sudanese sugar industry has been limited, especially for the older factories. Indeed, many types of research have been conducted on the reduced productivity of sugar in Sudan. These studies have evaluated the total productivity of sugarcane farms in Sudan over the 1999 and 2007 period (Bushara, 2016), they have examined the determinants of growth in sugar production over the 1980 to 2004 period (Abdallah, 2006), and they have assessed the development of the sugar industry in Africa (Hassan, 2008). However, none of these studies have addressed the technical factors that influence sugar productivity in the country. Except for the research conducted by Abdalla (2006), hardly any other studies have given attention to the determinants of productivity in the Sudanese sugar industry. Bushara (2016) used data dating back twelve years, but provided no precise method for analyzing the growth of productivity in the Sudanese sugar schemes. Other researchers, for example Hassan (2008), have indicated that the sugar industry in Sudan is historically as one of the significant producers in Africa.

Therefore, the aim of this study is to bridge the research gap, in order to understand the factors that have caused the decline in productivity in Sudan over the past ten years.

In addition to the above, sugar industry waste is being discharged into open drains, resulting in environmental degradation, such as air pollution, as well as other health problems, which influence the communities residing in the vicinity of the factories. There is a lack of scientific data on waste management and its environmental impact; thus, it has been challenging to quantify the effects of the waste and the exact problems that lead to human health risks. Considerable research has been conducted on the impact of debris on the environment in Sudan. For example, Katir *et al*. (2017) studied the environmental influence of waste disposal from the Assalaya sugar factory on the residents of the city of Rabak, Hassan *et al*. (2017) conducted a case study on the source of pollution at the Guneid sugar factory, Yasir *et al*. (2017) analysed the wastewater of the Assalaya factory, Oboody *et al*. (2016) evaluated the feasibility of producing biogas from mixed biomass (i.e. vinasse, wastewater and filter cake) in the Kenana mill, and Alim (2012) assessed the liquid and solid waste from the Guneid factory. However, these researchers did not give sufficient attention to the effects of the waste on the communities living in the vicinity of the sugar factories, their methods were not clear and their research was limited to only one sugar factory. There is a lack of data on the impact of sugar industry waste on the environment and the health of the community. Except for a study done by Khatir (2017), hardly any other studies have been conducted on the effects of sugar industry waste on the environmental and on the health of the Sudanese communities. Therefore, this study highlights the impact of sugar industry waste on the health of the communities living in the vicinity of sugar factories, and its object is also to draw attention to the environmental effects of the waste on crop and animal production.

Sugar processing consumes energy and emits harmful gases. As the sugar industry is part of the industrial sector in the country, it is often affected by shortages in the energy supply. In order to address this problem, the publicly-owned mills in Sudan have been working on improving their ability to produce energy and power by using the by-products of the sugar industry.

The shift to using renewable resources of energy, such as bagasse, has been adopted for the past twenty-five years. This process has helped to solve the heavy dependence on fossil fuel energy (Abdeen, 2002). However, the development of power sources in most of the Sudanese sugar industry has remained limited. Except for the study done by Rabah *et al*. (2016), limited research has been conducted on evaluating the use of energy in Sudanese sugar factories. The study aimed to design an energy flow diagram of Sudan; however, it did not identify an energy supply for the sugar industry.

Moreover, the greenhouse gas emissions associated with the different stages of sugar production have not been calculated for the sugar industry in Sudan. Hence, it will be challenging to evaluate the environmental performance and to identify proper solutions for this industry. It is crucial to understand the energy usage and its environmental impact on the performance of aspects of the sugar industry. Therefore, the aim of this study is to fill the identified research gap.

The interest in this study is based on personal experience of the author, who lives in the vicinity of the Kenana Sugar Factory and has observed the continuous, almost daily, decline in sugar productivity over several years.

His attention was drawn to this particular problem after consulting the relevant literature, and the purpose of this research work was to resolve the productivity problem by uncovering the associated technical factors. The author also noticed some environmental issues relating to the waste products of the sugar manufacturing industry, as well as the community health problems that are caused by the debris for those living in the vicinity of the Sudanese sugar factories. It also conducted an examination of which stage of the sugar production life-cycle has the most impact on the environment in Sudan.

1.3 Research Questions

The research questions are as follows:

a) What technical factors (i.e. engineering factors) influence the productivity of the sugar industry in Sudan?
b) What influences the efficiency of factories in the processing of sugarcane to crystal sugar?
c) What influences the performance of the mills and the production supply chain?
d) What are the impacts of sugar industrial waste on the communities living close to the factories?

e) What health problems are associated with these waste products? (to indicate the extent of the impact sugar industry waste on the surrounding environment including the health of people).
f) To what extent are greenhouse gases emitted into the air? and
g) How much energy is used for sugar production in Sudan?

1.4 Objectives

The main objective of this study was to evaluate the performances of the sugar-processing supply chain, to assess the life-cycle of sugar production, and to identify the impact of sugar industry waste on the communities surrounding the selected sugar factories in Sudan.

The specific objectives of this study were:

a) to evaluate the factors influencing the productivity of the Sudanese sugar industry;
b) to analyze the efficiency of the sugar-processing steps in the factory;
c) to assess the energy use and GHG emissions of the selected and most crucial life-cycle stages of sugar manufacturing in the Sudanese factories;
d) to identify the impacts of wastewater disposal, particle pollutants and toxic gases on the communities residing around the sugar industries; and
e) to develop an integrated framework for sustainably improving the processing of sugar and adequately handling the associated waste products of the selected factories.

1.5 Significance of the Study

The importance of sugar is realized by its contribution to meeting the energy requirements of individuals and providing job opportunities. Many countries have developed strategies for ensuring the high productivity of this commodity, in order to satisfy local consumption and for the export. However, it is crucial to consider the environmental aspects (i.e. the health risks and the greenhouse gas emissions and associated problems) of this industry. Identifying the issues of the sugar industry in Sudan is a decisive step towards finding sustainable solutions. This study has clearly stated the factors influencing the decline of sugar production in the country over the past several years. It has also revealed the health risk to humans and the environmental burden caused by sugar manufacturing waste and its associated problems. The outcome of this research project is expected to provide highly useful information that can be used by the sugar industry in Sudan and that will benefit all the steps in the production and processing of sugarcane. It will help decision-makers to design and adopt appropriate strategies that will improve the productivity of the sugar industry in the country, and it will assist the authorities in taking the necessary remedial action against its environmental impacts. Furthermore, the results of this study will fill the existing gaps on the topic in the literature and they will serve as a further reference for future research.

1.6 Thesis Organisation

The thesis includes seven chapters, with each chapter containing a Materials and Methods section, as well as the Results, Discussion and Conclusion sections. Chapter One provides the introduction to thesis, including the background to the study, the problem statement, the research questions, the objectives, and the significance of the study. Chapter Two is based on a paper published in the *Journal of the Sugar Industry* in 2019 and encompasses a review of the current status of production performance in the Sudanese sugar industry. Chapter Three contains the details of the technical factors that influence sugar productivity in the country. The contents of this chapter are based on a paper published in the *African Journal of Science*, *Technology*, *Innovation and Development* in 2020. Chapters Four and Five represent the culmination of the impact of the sugar industrial waste on the environment and health of people residing the vicinity of sugar factories. The contents of these two chapters are based on two papers that were submitted for publication during the course of 2020, namely, *Data in Brief* and *Journal of the Air and Waste Management Association*. The sixth chapter covers the results and discussion sections and is based on a paper submitted for publication in the *Journal of the Air and Waste Management Association* in 2020. This chapter shows the measurement of greenhouse gas emissions and the energy consumption of sugar production in Sudan by using the life-cycle assessment method. Chapter Seven presents a synthesis of all the information in Chapters One to Six, and it includes the Conclusions and Recommendations.

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2. AN EVALUATION OF THE CURRENT STATUS OF THE PRODUCTION PERFORMANCE OF THE SUGAR INDUSTRY IN SUDAN: AN OVERVIEW

This chapter is based on the following paper:

Ibrahim, TS and Workneh, TS. 2019. An evaluation of the current status of the production performance of the sugar industry in Sudan: An overview. *Sugar Industry* 144(11): 655-659.

Abstract

The Sudanese sugar industry has been suffering from a decline in sugar productivity. The production of the six sugar mills dropped by 32%, from 775 000 tonne in 2008 to 526 000 tonne in 2017. At the Kenana sugar mill, which produces 50% of the country's sugar, production has declined by 25.8% over the same period. Production also decreased by 24%, 50.2%, 36.1%, and 42.7%, respectively, at the Guneid, Halfa, Sinnar and Assalaya factories. The lower sugar production has led to the annual import of about 599 500 tonne of sugar. The reasons for the decline in sugar production are discussed below. In addition, the wastewater discharge from sugar manufacturing could cause health risks to the communities living in the vicinity of the factories. There is a lack of data on wastewater management in the Sudanese sugar industry. Thus, it is recommended that the impacts of sugar industry waste on communities in Sudan should be investigated.

Keywords: productivity, sugar industry, wastewater, constraints, by-products, Sudan

2.1 Introduction

Sugar is produced in more than 120 countries and approximately 65% to 70% of all sugar is produced from sugarcane (Contreras *et al*., 2009; Sahu, 2018). Sudan is the thirtieth-largest sugar producer worldwide and the third-largest in Africa, with an estimated production of between 762 000 tonne and 800 000 tonne (Hassan, 2008; World Population Review [WPR], 2019). It produces 7.5% of the total sugar produced in the African region (Hassan, 2008), and the industry is considered to be one of the main strategic sectors in Sudan (Bushara, 2016). In Sudan, sugarcane is grown in the central clay plain between 16° and 10° N latitude and 32°

and 37° E longitude because of the availability of water sources and soil in this area (Intisar, 2003; AbuZeid, 2015). Figure 2.1 shows the location of the sugar factories in the country. The total size of arable land in the northern and southern parts of Sudan is estimated to be 84 million ha. About 15% of the arable land is cultivated and 5% of the farms, which is equal to 173 300 ha of land, are used for sugarcane production (Adam *et al*., 2015). The harvested sugarcane area was between 69 600 and 74 672 ha over the 2013 to 2017 period (Knoema, 2017). There are six sugar factories in total, namely, the Kenana, White Nile, Guneid, Halfa, Sinnar and Assalaya factories. These are divided into two groups, namely, the Kenana and White Nile mills, which are registered as private limited companies, while the others are publicly owned (Elzebair *et al*., 2015). Table 2.1 shows the production capacity of the respective sugar industries. With the exception of the White Nile factory, the largest sugar producer is the Kenana factory, which produces about 53% of the sugar in the country. Sudan is constructing a new sugar factory under the umbrella of a project called the White Nile Sugar Project (Tyler, 2004). Production began at the Guneid sugar factory in 1962, and the rest of sugar factories came into operation between 1965 and 2004 (Table 2.1). Sudan produces about 8 million tonne of sugarcane per year (Federal Ministry of Agriculture [FMA], 2010), while it also produces 1.8 million tonne of bagasse and 11 000 tonne of ash per year (Cordiero *et al*., 2004).

Table 2.1 Sudanese sugar factories capacities (Federal Ministry of Agriculture [FMA], 2010; White Nile Sugar Project [WNSP], 2012; Adam *et al*., 2015; Kbashi, 2017)

Factory	Startup date	Production capacity (tonne.year^{-1})	Total area (ha)	Crushing capacity (tonne.day^{-1})	Highest actual production (tonne.year^{-1})
Guneid	1962	60 000	16 600	4 000	94 171
Halfa	1964	75 000	16 600	5 000	110 400
Sinnar	1976	110 000	15 800	6 500	87 100
Assalaya	1980	110 000	18 300	6 500	97 500
Kenana	1981	330 000	40 000	17 000	391 200
White Nile	2012	450 000	66 600	30 000	74 162
	Total	1 135 000	173 900	69 000	854 533

The overall trend of sugar production in Sudan has been fluctuating over the past decade. Production at the Kenana factory, which produces between 53% and 58% of the sugar in Sudan, has declined by an average of 2.5% annually, from 2001 to 2015 (Abdalla, 2006; Elzebair *et al.*, 2015; Kenana Sugar Company [KSC], 2016). Similarly, the Guneid, Halfa, Sinnar and Assalaya factories began suffering from a decline in production, from 1999 to 2007 (Bushara, 2016). Despite the fact that there are good growing conditions, there have been good yields and the planted areas have expanded, the problem still remains (Ibrahim, 2017). This has led to a 7.8% annual decrease in the amount of sugar exported between 2001 and 2009 (African Development Bank Group [ADBG], 2011). The reasons for this decline are the poor factory design and the improper utilization of production inputs (Hassan, 2008; Ibrahim, 2017). However, these are quite general reasons and have not been studied in detail. What if the mass balance during the manufacturing process is insufficient? Are the systems for converting the raw materials of sugarcane to sugar crystals working efficiently? In order to enhance the production performance of sugar factories and to find sustainable solutions, research is required to identify the factors that influence sugar productivity. Ibrahim (2011) reported that reforming the infrastructure of the production process has had a positive effect on the performance of the Kenana factory. However, the analyses made in that study were found to be general and fallacious. No clear methods that have been developed and implemented to test the technical efficiency of the sugar processing supply chain for Sudanese factories, especially for the old factories.

In addition, wastewater that results from sugar processing is discharged into open drains without any treatment (El Hassan, 1998). This pollutes the fresh water and the environment around the sugar factories. This problem needs to be solved sustainably, in order to mitigate the impact of the waste in the surrounding environment and on the communities living near the sugar factories. From this perspective, Ali *et al.* (2006) assessed the pollution load of waste from the Assalaya factory on the Nile River and found that the water was highly contaminated. Further studies are therefore necessary, in order to find solutions. Alim (2012) indicated that the Kenana factory is in the process of constructing waste recycling plant. Oboody (2016) reported that biogas has been successfully produced from the sugarcane waste of the Kenana factory, using anaerobic digestion technology. This indicates that the production of bioenergy from the waste is promising for the Kenana factory, and that it will mitigate the negative impact of the waste, at the same time. Some of the sugar factories do not have an adequate database that they can use to attend to the issue of treating wastewater and mitigating its effects on the environment and on the surrounding communities. This is because the abovementioned research studies were limited because they were only conducted on selected factories. The questions that still need to be addressed are: What are the factors influencing the productivity of sugar factories in Sudan? and What are the impacts of sugar factory waste on the surrounding communities? Therefore, it is necessary to establish a research work that aims to identify the factors influencing productivity and the impacts of wastewater disposal on the communities residing in the vicinity of the sugar factories. This study aims at review the current production performance, the factors influencing the growth and the waste disposal systems that are practised in the Sudanese sugar industry.

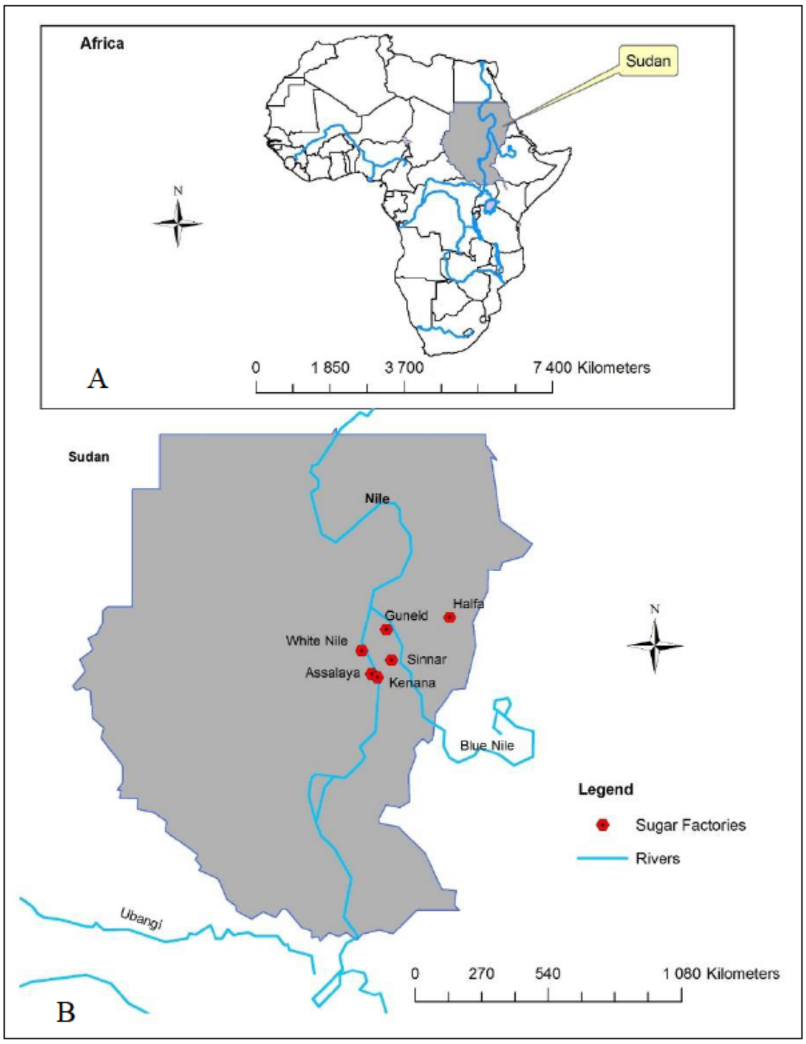

Figure 2.1 Location of sugar factories in Sudan (GIS, 2016)

2.2 Sugarcane Agriculture

The main sugarcane varieties that are grown for the Sudanese sugar industry are Co 997 and Co 6806. Other varieties, such as R 579, TUC 75-3, KnB 01-156, KnB 01-619 and KnB03-1184, are also grown. The Kenana factory produces two or more different sugarcane varieties on one plot. Research on some varieties, such as FR 9841, FR 9821, B 871294 and CP 881762, is still in its early stages and they are not yet ready to be released for commercial production. The propagation of variety BR 81116 has begun recently on the four Sudanese sugar estates (Ahmed, 2017; Kenana Sugar Company Manual, 2013; Obeid, 2013; Oboody, 2018; Sudanese Sugar Company, 2015). Figure 2.2 shows the sugarcane varieties and their plot sizes, as a percentage of the total planted area in 2015. The early stages varieties (i.e. FR 9841, FR 9821, KnB03-1184 and B 871294) appear as zero percentages in Figure 2.2, as they are still under development and not yet commercially produced.

Sugarcane is harvested mechanically in Sudan. It is chopped into 12-14 inch billets by a combine harvester and hauled by wagons, or trailers that run alongside the harvester, which transport them to the mills. At the publically-owned mills, the sugarcane is transported by trailers, while wagons are used at the other mills (Adam, 2015). One of the problems that the Sudanese sugar factories often face is how to transport the sugarcane from the farms to the mills within a reasonable time-frame (Abdalla, 2006).

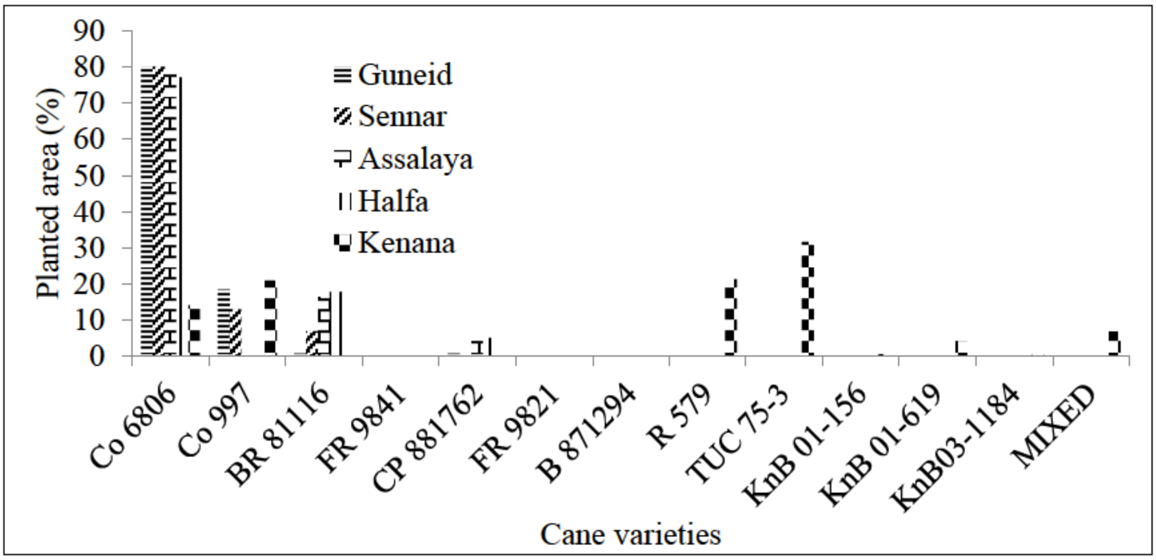

Figure 2.2 Sugarcane varieties in Sudan in 2015 (Kenana Sugar Company Manual, 2013; Obeid, 2013; Sudanese Sugar Company [SSC], 2016; Ahmed, 2017)

Sugarcane that is delivered to the Kenana, Assalaya, Guneid, Sinnar and White Nile factories is irrigated by using water from the Nile River, or else it is delivered directly, by means of gravity; for example, from the Atbara River to the Halfa factory. Water is diverted into the field canals that run parallel to the long furrows, which are 1.5 to three kilometers long at Kenana, and short furrows of about 75 to 300 meters long in the other areas (Ahmed, 2017). Based on the sugarcane variety and the planting dates, the total requirements of water range from 22.61×10^3 to 28.73×10^3 $m^3.ha^{-1}$ per season, in the Kenana area (Kenana Sugar Company Manual, 2013).

It is reported that the factories at Guneid, Sinnar, Assalaya and Halfa have been relying on only two sugarcane varieties (CO 6806 and CO 997) for the past three decades, which may have influenced the sugar productivity per unit in these areas (Ahmed, 2017; Contreras *et al.*, 2009). Figure 2.3 shows the declining sugar productivity per hectare in each factory. The fibre percentage in the sugarcane, the harvesting age, as well as the flowering and irrigation, could also possibly contribute to the decline (Obeid, 2013). However, the majority of the selected factories in Sudan are inadequately managed (Suliman, 2017).

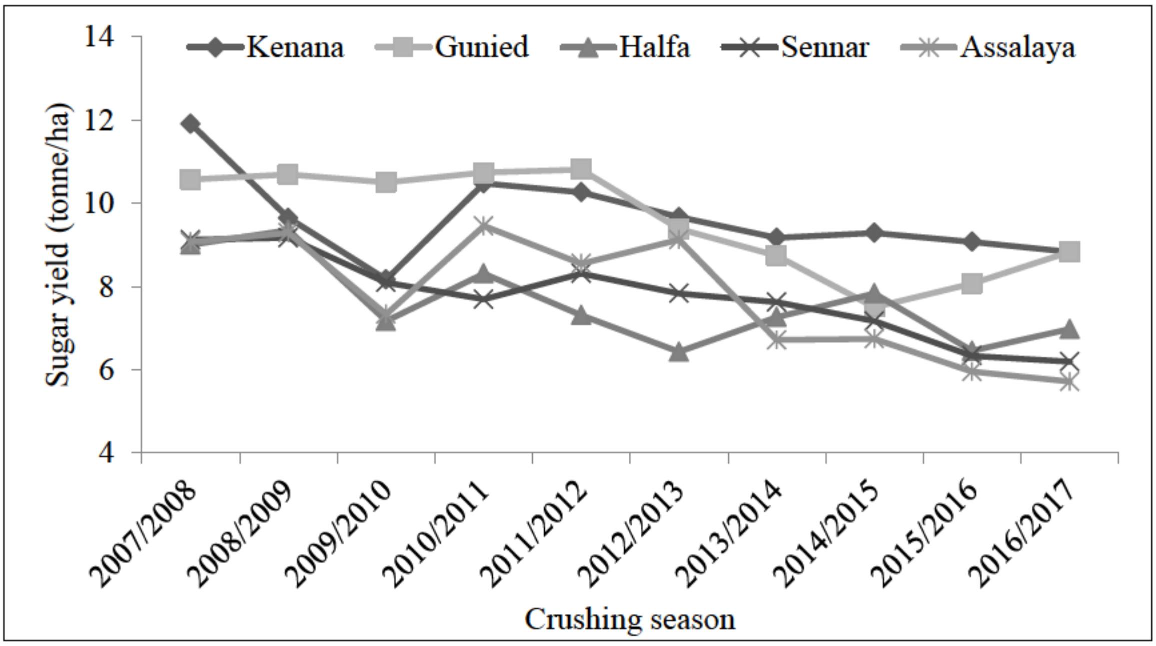

Figure 2.3 Average sugar yield per ha for the selected sugar factories (KSC, 2016; SSF, 2016; HSF, 2016; GSF, 2016; ASF, 2016)

The sugarcane yield per unit area has decreased in the whole Sudanese sugar industry over the past ten years, as shown in Figure 2.4. The causes of this decline are as follows:

(a) The lack of irrigation water and the improper maintenance of irrigation canals and ditches, before and during the irrigation season, hinder the growth of the sugarcane (Obeid, 2013; Suliman, 2017). For example, the availability of water for irrigation in the Halfa area is limited. At the moment, the factory has access to only 950 m^3 of water per day for irrigation purposes, which represents about 50% of the daily requirement (2000 m^3). This quantity of water is not enough to satisfy the daily water requirements of the farm, which therefore limits the expansion of the sugarcane production area (Arbab, 2009) and leads to the inadequate application of irrigation water, thus causing droughts in the field (Suliman, 2017).

(b) The low availability of agricultural inputs, such as fertilizers and pesticides, as well as machinery for irrigation, in the Guneid, Sinnar and Assalaya production areas (Abdalla, 2006).

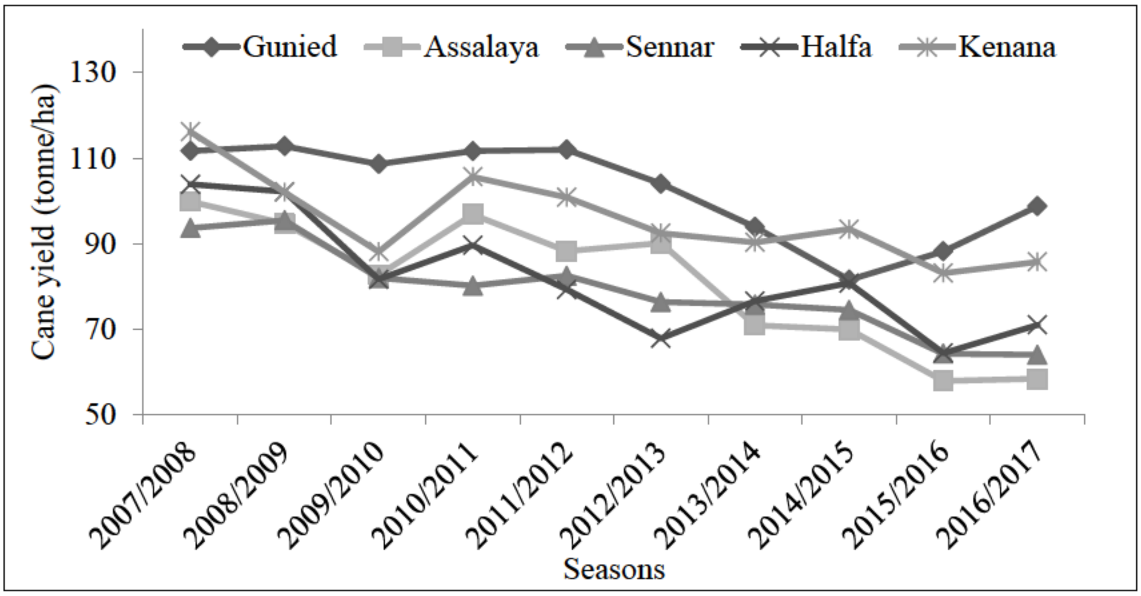

Figure 2.4 Sugarcane yields of the selected sugar factories in Sudan (KSC, 2016; SSF, 2016; HSF, 2016; GSF, 2016; ASF, 2016)

2.3 Sudanese Sugar Production

Sugar production in Sudan has not exceeded the average of 516 000 tonne.year^{-1} between 1980 and 2004, although the production potential is 855 000 tonne.year^{1} (Abdalla, 2006). The production declined between 2008 and 2016, as shown in Figure 2.5. The annual sugar production of the country over the past ten years was between 775 000 to 526 000 tonne, and the factors causing the decline in productivity need to be identified. Mohamed and Lubna (2016) conducted a study to measure the change in productivity by analyzing the factory data, from 2000 to 2007, and they concluded that the total changes in productivity remained negative and also declined over this period of time.

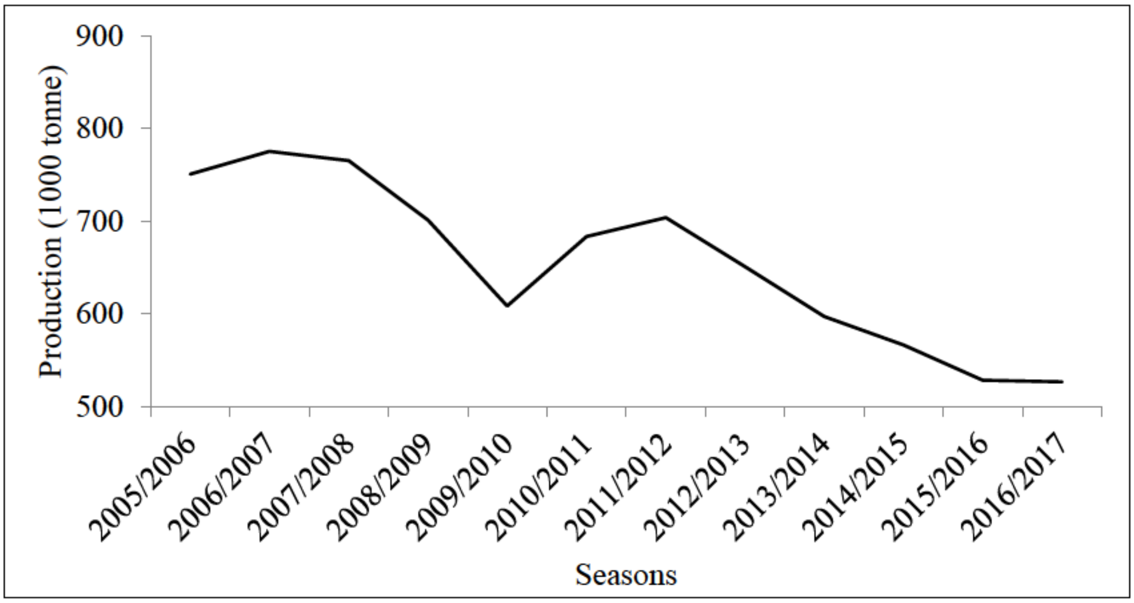

Figure 2.5 Sugar production in Sudan (KSC, 2016; SSF, 2016; HSF, 2016; GSF, 2016; ASF, 2016)

In 2000, a rehabilitation program was undertaken that targeted the renewal of boilers, power plants and irrigation pumps for all publicly-owned factories, in order to improve productivity. However, the program became non-functional, as the annual productivity continued to decrease after 2007 (Alam-Eldin, 2008). Therefore, in order to solve the problem of productivity and to create opportunities for the improved performance in the Sudanese sugar factories, empirical data collection and analyses are required.

The domestic consumption is currently estimated to be around 1.2 and 1.3 mn tonne per year**.** This means that a shortfall of about 600 000 tonne of sugar is required to bridge the gap of the annual local consumption (Obeid, 2013). As shown in Figure 2.6, the declining sugar production has caused sugar exports to drop to below 100 000 tonne per year since 2001 (African Development Bank Group [ADBG], 2011; Obeid, 2013).

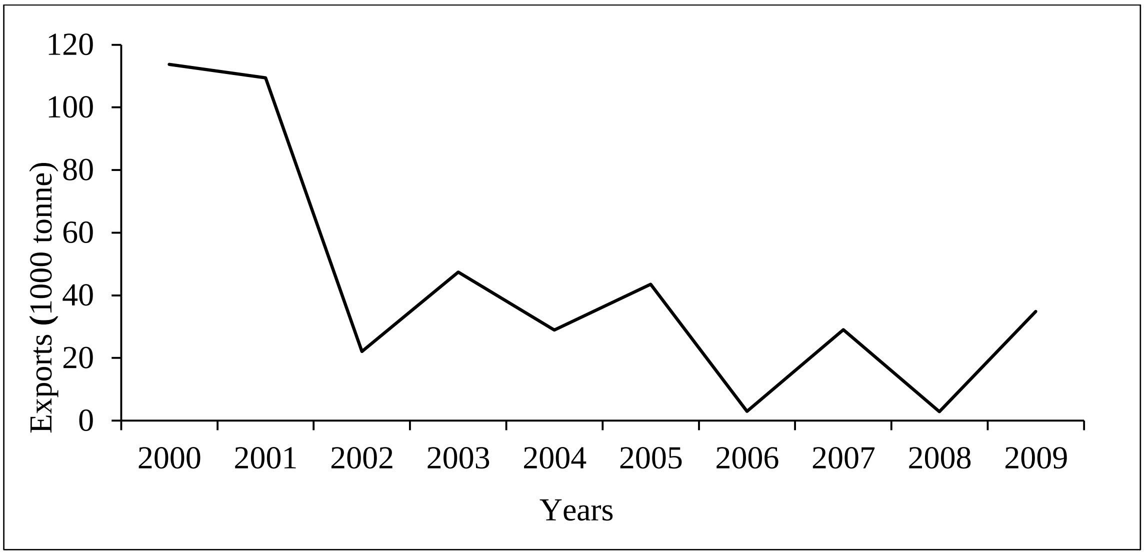

Figure 2.6 Sudanese sugar exports to international markets (ADBG, 2011)

As can be seen from the data represented in Figure 2.7, the sugar extraction efficiencies of the government-owned sugar factories varied between 76.6% and 78.6%, between 2007 and 2017. Practically, this shows that the factories were subjected to a low efficiency, compared to the optimal extraction efficiencies, which varies between 90% and 98% (Cotlear, 2004; Jia *et al*., 2013). This low percent is attributed to the wear-and-tear of the equipment in the factories (Suliman, 2017). The sugar extraction rate therefore declined, due to the low efficiency in processing. The reason for the decline in the sugar extraction rate may be due to the increased impurities in the extracted juice, as a large quantity of mud is mixed with the raw materials that are received at the factory. Ultimately, this reduces the total sucrose content (Suliman, 2017; Yunis, 2017).

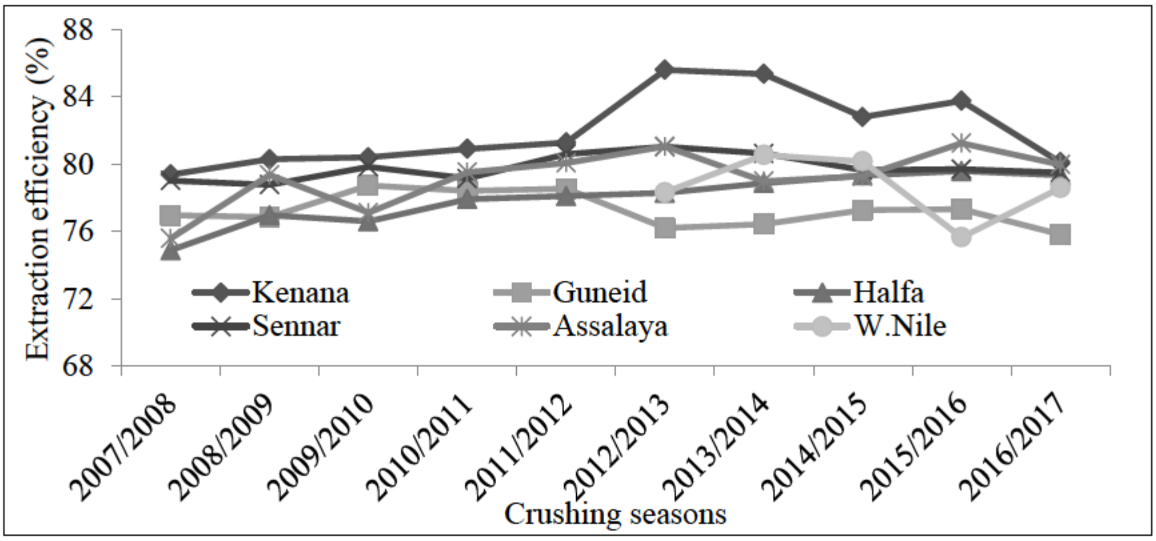

Figure 2.7 Extraction efficiencies (KSC, 2016; SSF, 2016; HSF, 2016; GSF, 2016; ASF, 2016; WNSP, 2012)

Figure 2.8 shows the length of the crushing season i.e. the number of crushing days for each factory. The Sudanese sugarcane stalk harvesting season could last for eight months, starting in November and ending in June (Arbab, 2009). This is because the harvesting machinery has depreciated and the implements need to be replaced. The frequent stoppages, due to harvesting breakdowns, contributed significantly to the extension of the crushing season. The government-owned factories also faced the challenge of not having enough trucks for sugarcane transportation, as well as the poor condition of the routes to and from the mills (Suliman, 2017).

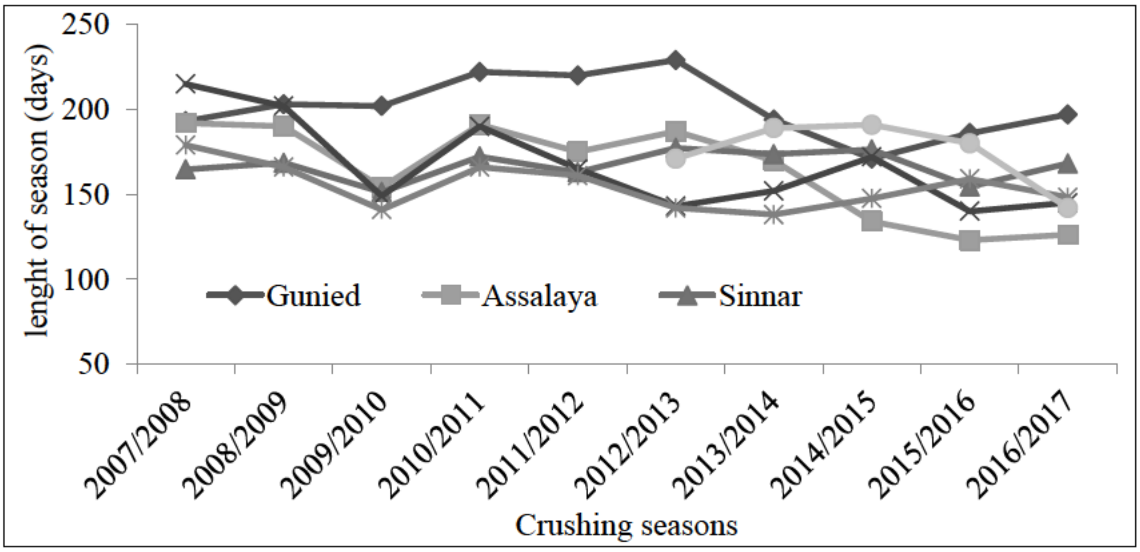

Figure 2.8 Length of the crushing season for the selected sugar mills (KSC, 2016; SSF, 2016; HSF, 2016; GSF, 2016; ASF, 2016; WNSP, 2012)

Figure 2.9 shows the amount of power that is produced and consumed by each sugar factory. The electricity is generated by burning the bagasse in the factory boiler houses during the sugarcane crushing season. The government-owned factories use back-pressure turbines with a low efficiency, which convert 10 tonne of steam to one MW per hour. The White Nile mill uses high efficiency turbines, which consume only 6.5 tonne of steam to produce one MWh of power (Yassen, 2017). In the off-season, furnaces and diesel, instead of bagasse, are used to produce the power that is needed for the factories. This power meets the requirements of the mills and their residential campuses (Ahmed, 2017). About 50% of the power that is produced in the White Nile factory is exported to the national grid (AbuZeid, 2015).

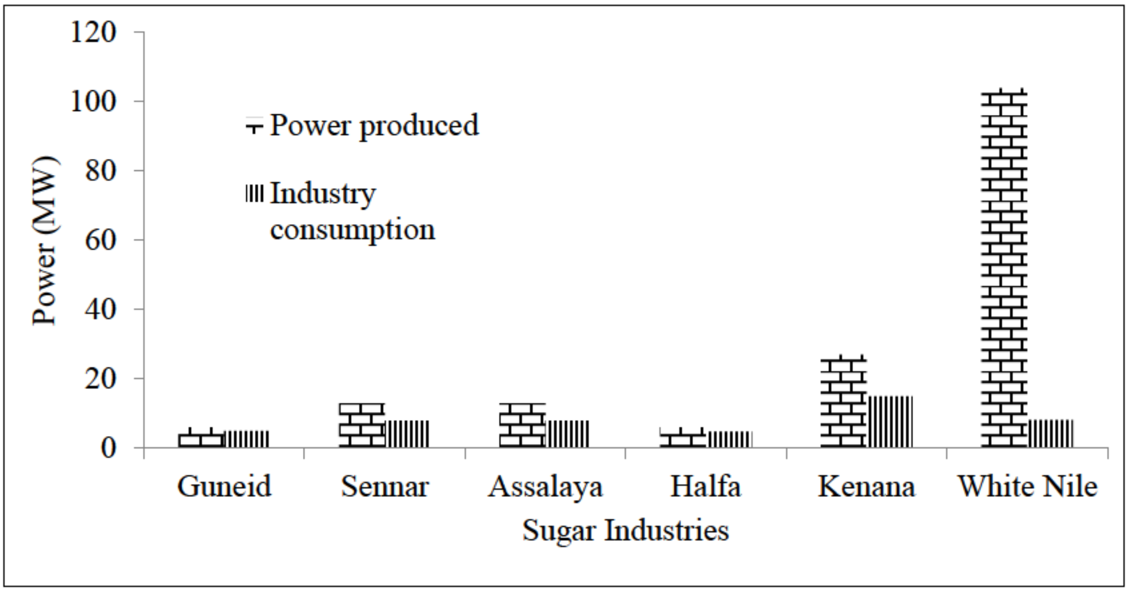

Figure 2.9 Power sales in the sugar industry in Sudan (KSC, 2016; SSF, 2016; HSF, 2016; GSF, 2016; ASF, 2016; WNSP, 2012)

2.4 Sugar Manufacturing and its By-products

Sugarcane is received in the factory and prepared to extract the juice. Figure 2.10 shows the processing flow chart for sugar production. After the cane is weighted, it washed by sprayed clean water (Kouzi, 2008). Continuously, it crushed by revolving knives driven by high-voltage electricity. The crushing capacity of all sugar factories in Sudan is about 69 000 tonne cane per day (FMA, 2010 and WNSF, 2012). The crushed cane is then milled to separate the juice. The mill carrier transports the crushed cane by using the imbibition system to condensate the used water and exit the bagasse. In some countries (i.e., South Africa), a diffusion process is used for juice extraction, giving a higher extraction rate with lower

energy consumption (Alim, 2012). The clarification phase is done by heating the juice to 30°C and liming using milk of lime with phosphoric acid. Then, the juice temperature is raised up to 105°C. At this stage, the filter cake is precipitated and separated from the juice into two clarifiers at 98°C and 100°C. the clear juice is separated from the mud in a rotary vacuum filter. The clarified liquid is heated to 115°C and moved to the evaporator (Kouzi, 2008). Quadruple-effect evaporators used to concentrate the juice from 16 to 60 %. This process produces the syrup with about 65 % solids and 35 % water (Arbab, 2011). The sugar is then conveyed to the vacuum pans for the crystallization stage (Kouzi, 2008; Arbab, 2011).
The crystallization starts when the syrup reaches the saturation stage during the evaporation. The process begins with seeding, then the sugar' size increases by discharging the massecuite into the cooling crystallizer. Massecuite is transferred to high-speed batch centrifugal machines to separate heavy molasses from crystals A sugar. The crystals are washed with water and centrifuged again as light molasses. The heavy molasses is reboiled to yield B massecuite, which in turn yields B crystals. The B massecuite is transferred to the crystallizer and then to the B centrifuge to produce B sugar and B molasses which its purity is lower than A molasses. This B sugar is mixed with water to make the magma. It is reboiled with A light molasses to form a low-grade massecuite, which goes to cooling crystallizers and then centrifuged to form C sugar. The sugar is dried in rotary driers cooled and transferred to bagging bins and Storage (Kouzi, 2008). In some factories, further refining before bagging for shipment could carry out (Alim, 2012). However, the current milling efficiency needs to be evaluated. Thus, identifying the factors that lead to the decline of sugar production and opportunities for proper solutions for the sugar industry in the country can be made.

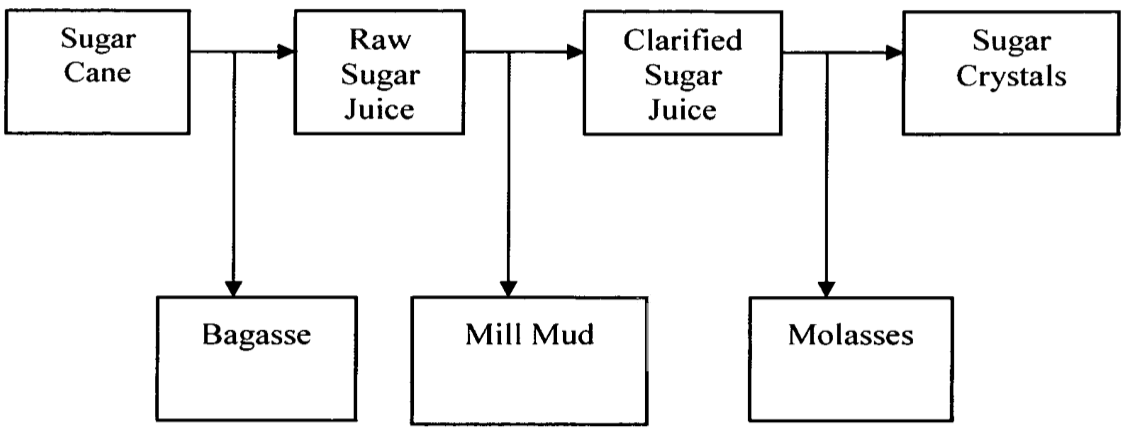

Figure 2. 10 Processing flowcharts of sugarcane and by-products (David *et al*., 2009)

The most important by-products from the sugar manufacturing process are bagasse, molasses and filter mud, which are used in many diverse fields (Intisar, 2003).

2.4.1 Molasses

The estimated quantity of molasses that was produced in the sugar mills in Sudan in 2006, 2013 and 2017was around 267 000 tonne, 252565 tonne and 205974 tonne, respectively (Hajer, 2007 ASF, 2016; FAOSTAT, 2015; GSF, 2016; HSF, 2016; Kbashi, 2017; KSC, 2016; SSF, 2016). Figure 2.11 shows the quantity of molasses that was produced between 2004 and 2017. One of the possible alternatives for maximizing the usage of molasses is to transform it into ethanol, although the loss of sucrose from sugarcane influences the factory profits (Gasmalla *et al*., 2012). This indicates that the potential for the production of biofuels in Sudan is promising, which fits into the overall development plan of bioenergy (Abdel Raheem and Lang, 2015). In addition, some of the factories in Sudan export the molasses to the international market, while other factories, such as Kenana, utilize the mollasses locally as a supplement for animal feed and for ethanol production (Hajer, 2007).

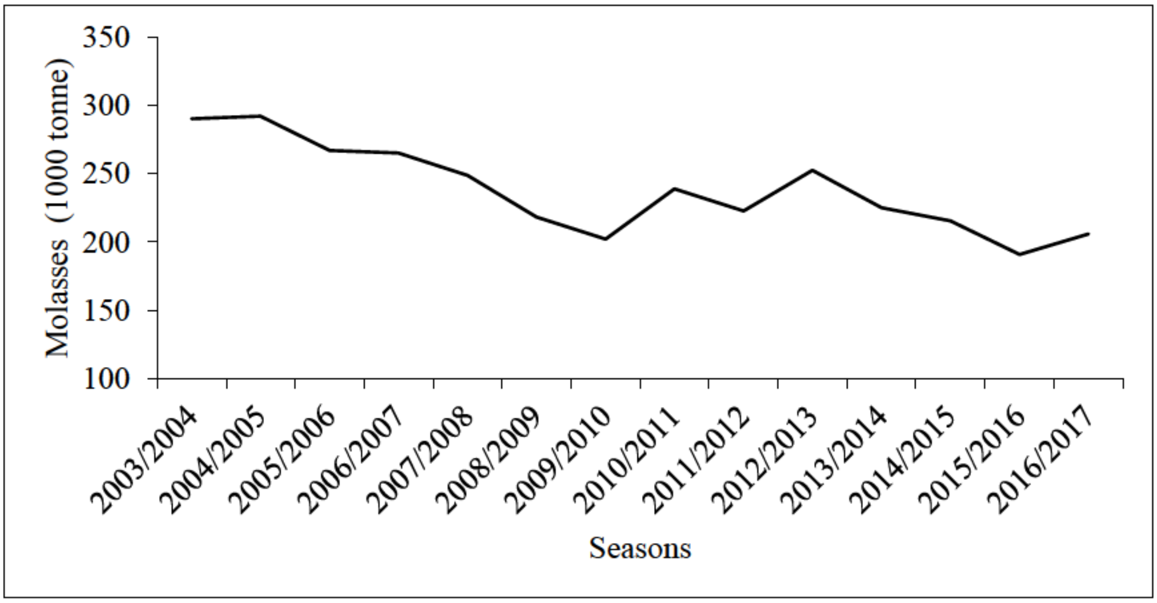

Figure 2.11 Molasses production in Sudan (ASF, 2016; FAOSTAT, 2015; GSF, 2016; HSF, 2016; Kbashi, 2017; KSC, 2016; SSF, 2016)

2.4.2 Bagasse

According to Abdeen (2002), bagasse provides a significant amount of renewable energy for power generation. Most sugar factories produce about 30 $kWh.tonne^{-1}$ cane of electricity. Accordingly, about 400 - 800 kWh $.tonne^{-1}$ cane of electricity could be produced if the factories in Sudan were supplied by combined gasified biomass cycle systems. Figure 2.12 shows the quantity of bagasse for the six Sudanese sugar factories over the past ten years, from 2008 to 2017, including the White Nile project data for the last five years, from 2013 to 2017. However, bagasse residue ash has a negative effect on the environment. Therefore, it is necessary to assess the environmental impact of burnt bagasse on the communities living near the factories.

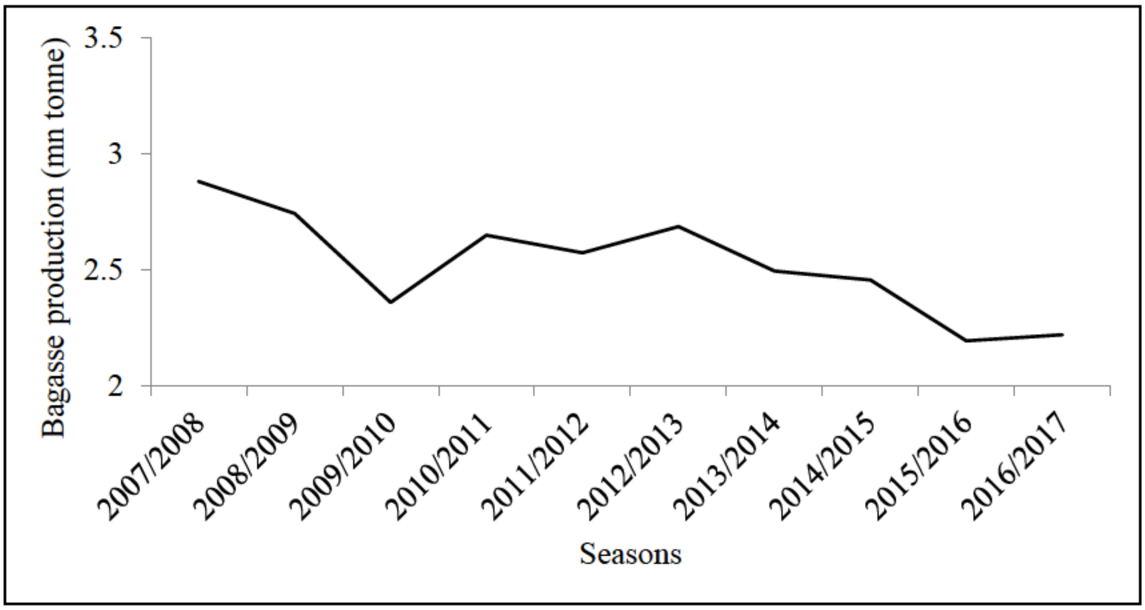

Figure 2.12 Bagasse available in Sudan (United Nations Statistics Division [UNSD], 2016; SSC, 2016; KSC, 2016; WNSP, 2012)

2.4.3 Filter mud

Filter mud is a precipitate in the clarification stage of the sugar manufacturing process. It settles as sludge in the clarifier. About 3 - 4% of the weight of the crushed sugarcane is made up of filter mud. Filter mud (cake) in Sudan is generally used for fertilizing the sugar farms (Oboody, 2016).

2.5 Sugar Factories in Sudan

Sudan has six sugar industries that are located in four different states of the same region, called the Sugar Belt. Two factories, i.e. Kenana and White Nile, are privately-owned companies, while the rest are government-owned. Figure 2.13 shows locations of the sugar factories in different states in Sudan.

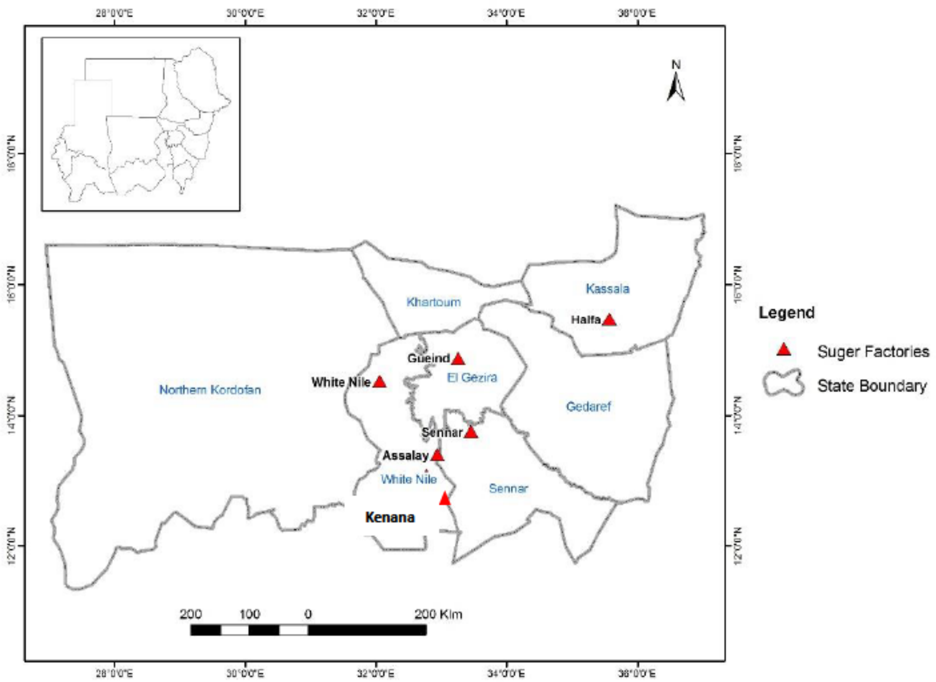

Figure 2.13 Sugar factories in Sudan (Fatima, 2017)

2.5.1 The Guneid sugar factory

The Guneid sugar factory is located beyond the plantations on the banks of the Blue Nile River. The total area under cultivation is 16 600 ha (Table 2.1). The factory is designed to produce a capacity of 60 000 tonne of sugar per year; however, the annual production began to decrease in 2013 (Elzebair *et al.,* 2015). Table 2.2 shows the annual harvested area per hectare and the sugar production per tonne. The Guneid mill is reportedly suffering difficulties, such as low yields and high agricultural operations costs, due to the tenant system. The poor management of the farms has been attributed to the unsatisfactory water distribution caused by the uneven terrain, the lower water-pumping capacity, sugarcane diseases and poor weed control. The sugar-processing system of the mill has a lower sucrose recovery rate, which also negatively influences productivity (Abdalla, 2006).

In addition, the wastewater resulting from sugar manufacturing is discharged into the Blue Nile River without receiving any treatment. It contains a high percentage of pollutants, particularly at the point of disposal into the waterbody. The factory produces unburnt fiber, carbon particulates, pollutant particles and suspended solids that settle down in the surrounding area, especially in the vicinity of the Wad Essayed village (Alim, 2012). These circumstances could cause an environmental problem for the community residing near the factory, and therefore, the production and ecological performance of this factory needs to be investigated. Hence, it is essential that opportunities be identified for enhancing production performance, and that solution be found to minimise the effect of waste on the community residing around the sugar industry.

2.5.2 The Halfa sugar factory

The Halfa factory is located in the centre of the sugar-farming area. Its average sugarcane transportation distance is 11 km, which is less than the distance from the Guneid factory. This location simplifies the sugarcane transportation logistics and reduces the break-downs at the mill. The production costs in Halfa are low because of the high sugarcane yield, which are reflected in its consistent profit growth (Farah, 2005). However, production declined between 1999 and 2015, especially after 2012 (Farah, 2005; HSF, 2016). Tables 2.1 and 2.2 illustrate the actual highest sugar production and the annual production of the harvested area over the past ten years. The plantation (15 540 ha) is irrigated by means of gravity from the Khashm El Giraba Dam (Ahmed, 2017). The mill crushes 5 500 tonne of sugarcane and processes 600 tonne of sugar per day (Ahmed, 2017). Most of the fields need proper land-leveling to facilitate the application of the water. Obtaining sufficient water for irrigation remains a challenge in this sugar-processing area. The main reason for the water shortage is a disagreement between the factory and the agricultural foundation (Arbab, 2009). The fields also have a meagre yield (Arbab, 2009), and therefore, studies should be conducted to identify the factors that influence the declining sugar production and the handling of raw materials.

2.5.3 The Sinnar sugar factory

The sugarcane-crushing capacity of the Sinnar sugar factory is 6 500 tonne per day, and it aims to produce 110 000 tonne of sugar per year (Table 2.1). The total area that is used for sugarcane production is approximately 16 000 ha. The 1994 rehabilitation program was carried out to renew some factory equipment, which led to a continuous average increase of 5% in its annual production figure until 2007 (Alam-Eldin, 2008).

However, since then, the mill's performance has been declining by an annual average of 6%. Table 2.2 shows the sugar production and the area that has been harvested annually for the past ten years. The sugar extraction of this mill is lower than that at the Guneid and Halfa mills (Abdalla, 2006). The factory has suffered from a lack of equipment and labor, which may have led to the inadequate preparation of the sugarcane fields (Arbab, 2009), and it has also suffered from defective boilers and steam control, as well as a defective lubricating mechanism.

Furthermore, a lack of stability in its foundations, due to soil subsidence, has thrown the machines out of alignment. These factors have led to delays in the factory operations, which have negatively influenced sugar production. Research work is therefore required to examine the current sugar-processing chains and to evaluate its extraction efficiency.

2.5.4 The Assalaya sugar factory

The Assalaya sugar factory is located on the eastern banks of the White Nile River, and it has suffered severe technical failures in recent years. The factory boiler, the power, and the milling houses have been defective, which has led to difficulties in the processing of sugar. Consequently, the milling capacity was reduced by 41.5% between 2008 and 2016, which means that 3 800 tonne of sugarcane is produced per day instead of 6 500 tonne (Abdalla, 2006). Table 2.1 shows the mill's designated crushing capacity, and Table 2.2 specifies the actual sugar productivity and harvested area per annum.

The continuous failure of the irrigation pumps, the salinity of the farm soil, and the uneven level of the land also play an essential role. The unavailability of proper agricultural machinery on this farm is the primary reason for its reduced production level (Arbab, 2009;

Suliman, 2017). Therefore, research is required to examine the sugar-processing supply chain, and to identify ways in which productivity can be improved.

2.5.5 The Kenana sugar factory

This factory is located in the White Nile state and began producing sugar in 1981. Its capacity is designed to produce 330 000 tonne of sugar per year, while its crushing capacity is 17 000 tonne of cane per day (Table 2.1). The sugarcane area is around 40 000 ha, which produces about 4 mn tonne of cane (Ahmed, 2017). Table 2.2 shows the harvested area of the mill and its sugar production per year. The yield of sugar per hectare has reached 11.9 tonne (Abdalla, 2006). The crushing season lasts between 150 and 160 days, from November to mid-April. The factory produces sugar from both green and burnt cane, which is packed into 50 kg bags. Other plants work together with the sugar factory to produce ethanol, animal feed and charcoal (Ahmed, 2017).

However, production has been declining since 2004, and the factors causing this problem need to be investigated. The untreated wastewater that is produced in the factory also influences the health of the communities living near the factory (Oboody, 2016). The environmental impact needs to be evaluated, and opportunities for sustainable solutions must be identified.

2.5.6 The White Nile sugar factory

The White Nile Sugar Factory (WNSP) was launched in 2012 and is the largest of the Sudanese factories. The Kenana sugar company owns 30% of this factory, while the remaining stake is shared between Egyptian investors and the Sudanese government. The total area covers about 66 000 ha in the White Nile state (Table 2.1), and the crushing capacity of the mill is 30 000 tonne per day. Its sugar-production capacity is 450 000 tonne per year. However, the sugarcane fields are located on salty land, and hence reasonable sugarcane yields are not expected (Ahmed, 2017). Some proposed expansion projects are associated with the by-products of this factory, namely, ethanol production and animal feed plants. The projects also produce other cash crops for export (WNSP, 2012).

Table 2.2 Sugarcane production areas and the quantity of sugar production in Sudanese factories (KSC, 2016; SSF, 2016; HSF, 2016; GSF, 2016; ASF, 2016)

Years	Guneid		Assalaya		Sinnar		Halfa		Kenana	
	Area (ha)	Sugar (tonne)	Area (ha)	Sugar (tonne)	Area (ha)	Sugar (tonne)	Area (ha)	Sugar (tonne)	Area (ha)	Sugar (tonne)
2007/2008	7958.3	87200	9928.8	85500	9307.9	90800	8941.7	110400	32599.2	391200
2008/2009	8125.0	84800	10416.7	87100	9377.5	97500	8929.2	108200	33235.8	323300
2009/2010	8325.0	87600	10220.8	76500	9386.3	75500	7916.7	92600	33537.5	276100
2010/2011	8470.8	88200	9827.1	70800	9141.7	93600	8916.7	74700	33688.3	355700
2011/2012	8481.7	91800	10390.8	76700	9156.3	89500	8958.3	95800	33835.4	349800
2012/2013	8490.4	92400	9741.3	76000	9628.3	89500	8666.7	66030	33534.6	326600
2013/2014	8311.3	76700	9660.4	73000	9507.5	65000	8104.2	74400	33267.1	307600
2014/2015	8312.5	66000	8541.7	61200	8883.3	58000	8572.5	56200	34584.2	324800
2015/2016	8085.4	62800	8792.1	54600	8541.7	52000	8458.3	59300	35041.7	299500
2016/2017	7979.2	65800	8900.3	54600	8977.5	52000	8176.3	54900	35084.6	299000

2.6 Factors that Influence the Growth of the Sugar Industry in Sudan

There are various factors that have influenced the development of Sudanese sugar factories. The constraints include, but are not limited to, agriculture-related problems, issues relevant to sugar processing, as well as economic and energy constraints.

2.6.1 Input constraints

Nutrients are considered to be one of the most significant factors that affect both the sugarcane productivity and juice quality. They mainly regulate the sugar crop's growth and its management. The nutrient requirements for growing sugarcane generally include nitrogen, phosphorus and potassium. Insufficient fertilization during the cultivation phase leads to unbalanced sugarcane nutrition and affects the soil fertility, resulting in low productivity (Singh *et al.*, 2019). The productivity of some factories, such as Guneid, Sinnar and Assalaya, has been affected by such problems. Besides the insufficient utilization of agricultural inputs, the problems include the inefficient irrigation pumps and inadequate sugarcane transportation to the mills (Abdalla, 2006). In order to solve these problems, research work must be conducted to investigate the factors that cause the delays in the utilization of agricultural inputs, and the factors that hinder sugarcane handling must be identified.

2.6.2 Manufacturing constraints

There are many constraints hindering the manufacture of sugar in Sudanese factories, including the fast deterioration of technology, the increased production costs, inefficient resource allocation, the mediocre factory design and management, ineffective input utilization, and the shortage of capital and labour. Bushara (2016) reported that the Guneid, Halfa, Sinnar and Assalaya sugar factories suffered from a fluctuation in their productivity between 1999 and 2007. The increasing deterioration of technology has caused the declining performance in publicly-owned sugar factories, as production has dropped by 26%. The increasing production costs and inefficient resource allocation are constraining the sugar-processing process. Despite having the right sugarcane-growing conditions, the performance of some factories is low, due to poor management and their poor design (Hassan, 2008). Abdalla (2006) conducted a study to identify the determinants of sugar production growth and analysed the factories' data from 1980 to 2004. The results showed that the growth of sugar output fluctuated tremendously during that period. The significant contributors to the growth of sugar production were having sufficient capital and a good labor force. However, according to the information discussed above, sugar factories in Sudan have suffered from declining productivity. Therefore, it is necessary to obtain empirical data and identify the factors that influence productivity, in order to improve the production performance of these factories.

2.6.3 Economic constraints

Sudan is considered to be one of the highest sugarcane-producing countries in the Arab and African regions. The overwhelming contribution of the sugar industry to the national economy is losing ground to the oil industry, which creates economic problems. This can be avoided by creating strategic objectives and long-term planning to maintain viable agriculture (Ismail, 2008). However, the financial aspect is one of the crucial factors that influence the availability of the necessary inputs. The lack of funding could constrain the sector and lead to poor infrastructure and poor services (Abdalla, 2006). The inflation rate in the national economy, price fluctuations and the increasing sugarcane production costs are also some of the constraining factors (Bushara, 2016).

2.6.4 Energy constraints

Sudan has suffered from a severe escalation in the demand for oil over the past decade. The cost of oil has consumed more than 50% of the income earned. Biomass is used to supply about 87% of Sudan's energy needs, while oil supplies approximately 12%, and 1% is generated from hydro and thermal power. The total annual energy consumption is about 11.7×10^{6} tonne of oil. As the dominant power consumer, the industrial sector has been suffering power shortages, which critically influence the industry. In 1995, the consumption of the agricultural sector was 5.7% of the total energy consumed: 13.8% came from petroleum products, 3.4% from biomass, and 8% from the electricity grid. A shift to renewable energy sources, i.e. bagasse, will help to solve the environmental issues, as well as the problem of being heavily-dependent on fossil fuel energy (Abdeen, 2002).

2.7 Sugarcane Harvesting and Transportation

The sugarcane-harvesting process is considered to be a critical operation in sugar production. The process begins with the drying of the fields one month before burning the sugarcane. The step is followed by the repair of the irrigation water banks and roads, in order to ease the movement of the harvesters and sugarcane transportation trucks. The process includes different equipment, such as tractors with trailers, grab-loaders, trucks and harvesters (Adam *et al*., 2015). Most of the sugarcane harvesting in Sudan is mechanical. The stalks are chopped into 30-35 cm billets by the combine harvester, which hauled into wagons or trailers that run alongside the harvester, before being transported to the mill. Sugarcane is transported by trailers in publicly-owned factories, while carts are used in the private industry (Adam *et al*., 2015).

2.8 Sugar Industry Wastewater Disposal

Sugar factories dispose of untreated wastewater through open drains and in open catchments. This wastewater creates swamps that might influence the quality of the water, the soil and the surrounding environment (El Hassan, 1998; Qureshi *et al.*, 2015). The Kenana factory discharges about 40 000 m^3 of polluted wastewater per day. All the sugar factories in Sudan release about 150 000 $m^3.day^{-1}$ of the sewage, which is useful for crop irrigation (Aisha, 2007; Kumar, 2014). However, the untreated wastewater could influence the environment and the communities residing in the vicinity. This research therefore investigates the impact of sugar manufacturing waste on the population living in the vicinity of the selected factories.

2.9 Sudanese Sugar Marketing

The sugar industry has contributed effectively to the income growth of the country (Farah, 2005). The domestic consumption is currently estimated to be around 1.2 and 1.3 mn tonne per year. A shortfall of about 600 000 tonne of sugar is required to bridge the gap of the annual local consumption (Obeid, 2013). About 40 000 tonne is exported to the prevailing market countries in eastern and southern Africa and the European community. However, as shown in Figure 2.14, a decline in sugar production has led to a drop of 78% of the export quantity between 2000 and 2009, and it has increased to more than 50% since then. The African Development Bank Group [ADBG] (2011) has stated that this decline has significantly influenced Sudan's competitiveness on the international sugar market.

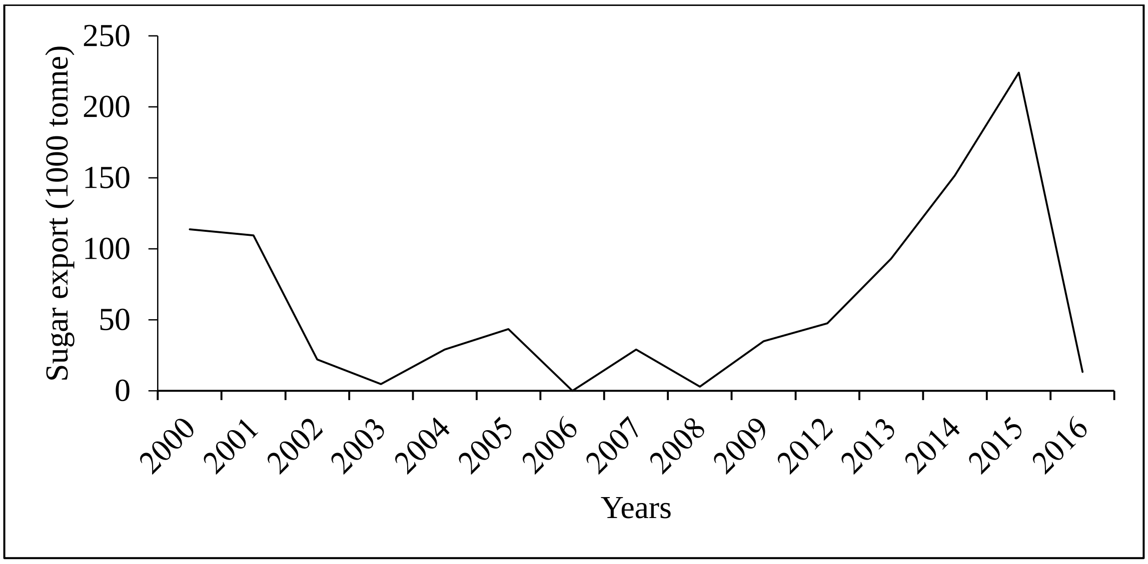

Figure 2.14 Sudan sugar exports to world markets (ABDG, 2011; Knoema, 2017)

2.10 Socio-economic Importance of Sudanese Sugar Industry

The sugar industry plays an essential role in the development of Sudan's economy by contributing more than 25% of the Gross Domestic Product (GDP), which is equal to 4.8 billion dollars (Farah, 2005; Adam *et al.*, 2015). The socio-economic significance of the sugar sub-sector comes through the provision of employment and job opportunities for a considerable number of the labour force, and training them to improve their skills and capacities. The Sudanese sugar factories employ more than 14 500 permanent workers and more than 19 000 seasonal workers. The sugar sub-sector also provides health, education and social services to its citizens (Farah, 2005; Takalani, 2013). The economic situation of these villages has changed due to the interventions of these factories (Hind, 2015). The interventions have influenced the livelihood of households in the rural areas, as many people had previously been displaced and were resettled in groups, after losing their land (Farah, 2005). Therefore, the environmental impact of the industry on the communities residing near these factories needs to be investigated.

2.11 Sugar Production and Environmental Issues

The environment is one of the main elements of individual and community health. Environmental pollution has been considered globally since the 1960s. Many factors could pollute the environment in which people reside. Pollutants are discharged in different forms, such as sewage, waste and by-products from the process of sugar manufacturing (Hassan *et al.*, 2017). Due to the increase in urbanization and industrialization in Sudan, pollution is also rapidly increasing (Alim, 2012), and Hassan *et al.* (2017) reported that the sugar industry in the country is polluting the areas in the vicinity of the factories. However, the measures of pollution control, in terms of institutes and legislative frameworks, are limited. The environmental governance of the industry was virtually non-existent until the year 2000. Therefore, significant challenges need to be considered, in terms of impact assessments, to improve the operation of the older, government-managed sugar factories (Alim, 2012). For instance, most sugar factories release untreated wastewater into the river, which contains pollutants and which might poison the waterbody. A reasonable amount of waste results from sugar processing (i.e. vinasse, wastewater and filter mud), which may harm humans and the ecosystem (Oboody *et al.*, 2016). To achieve sustainable solutions for this problem, the Kenana factory is in the process of constructing wastewater treatment plant (Alim, 2012).

However, the problem of this waste needs to be solved sustainably and collaboratively for all the sugar factories in Sudan. The environmental aspect was therefore examined for the selected sugar factories by identifying the impact of the effluent on the communities in the areas surrounding the mills.

The combustion of bagasse produces ash, which is also harmful to human health (Mohamed *et al*., 2011; le Blond *et al.,* 2017). According to the Sudanese sugar companies, bagasse represents 26% of sugarcane stalk, and about 1.82 million tonne of bagasse is produced annually, with about 0.62% of the burnt bagasse becoming residual ash (Cordiero *et al*., 2004). Theoretically, about 11 284 tonne of residual bagasse ash is produced annually by the sugar factories in Sudan. Therefore, the impact of this pollutant needs to be determined and the problem needs to be appropriately solved.

However, the sugar authorities are concerned about the difficulty of solving this waste problem and the high cost of treatment (Oboody, 2016). There is a lack of sufficient scientific data on various waste treatments and their impact, which makes it difficult to identify the adverse effects of these waste products on the communities (Abid, 2008). Therefore, research work must be conducted to find sustainable solutions for the effective treatment of sugar industry waste.

Sugar factories also release large amounts of various gases (carbon and others) and ash, which influence humans, animals and plants. The harvesting process causes strong dust storms, which affect the labour and the householders in the vicinity. The intensive use of chemicals (fertilizers, pesticides, fungicides and herbicides) in sugar production is inevitable, and this negatively influences the soil and the sugar produced. The intensive use of machinery results in a spillover of mineral oils, which pollute the land and water. The various operations in the factories and the heavy machinery required during the production process are also a source of noise (Abid, 2008; Takalani, 2013). Therefore, the environmental damage of the sugar industry in Sudan must be evaluated. A study to assess the greenhouse gas emissions resulting from sugar processing should be carried out.

2.12 Sugarcane Production and Global Warming

Fossil fuel utilization has been blamed for releasing greenhouse gases, which could cause global warming by the trapping of heat in the atmosphere (Abdeen, 2002; Zahedi *et al*., 2018). Industrialized countries have the highest emission levels and, therefore, a greater responsibility for global warming. The development of sugarcane production in the past few years is one of the issues that have exacerbated pollution and energy use (Zahedi *et al*., 2018). Developing countries must act to mitigate future emissions (Abdeen, 2002), and a top priority should be to make more efforts to implement innovative programs to reduce emissions from the agricultural sector (Eduardo, 2010). On the other hand, expanding biofuel production from by-products of the sugar industry, such as molasses, has benefitted the climate by reducing greenhouse gas emissions. The expansion of biofuel production is an essential solution for minimizing climate change (Scott *et al.*, 2011). Zhao and Rui (2015) reported that the expansion of sugarcane into the existing crop and pasture lands cools down the surrounding areas. Sugarcane may be able to protect the environment better than other field crops. However, no study has yet been conducted in Sudan to determine the greenhouse gas emissions of the sugar industry.

2.13 Life-Cycle Assessment of the Sugarcane Industry

Life-Cycle Assessments (LCAs) for sugarcane production have been carried out in many countries worldwide (i.e. South Africa, Mauritius, Brazil, Thailand, Australia and Mexico). Palacios *et al*. (2019) reported that a life-cycle assessment was used in Mexico to analyze the environmental impacts associated with sugarcane production. The study revealed that the various stages of sugarcane production, as well as power generation, sugarcane transportation and sugar processing, are harmful to the environment. Mashoko *et al*. (2013) conducted a study to identify the environmental benefits of power produced from bagasse for the South African sugar industry, by developing a model that produces 150 kWh per tonne of bagasse. The study concluded that bagasse has significant environmental benefits, as it releases less GHG emissions, compared to coal, when it is burnt. Sugarcane cultivation, transportation and water use contributed significantly to the CO_2 discharge. Minimizing the utilization of chemicals inputs and optimizing the irrigation water will reduce the impacts of the cultivation phase. Silva *et al.* (2012) conducted an LCA study to determine the main environmental impacts of the energy generation, transmission and distribution of bagasse in Brazil. The study concluded that the burning of sugarcane before harvesting must stop, in order to reduce emissions. It also recommended the use of sugarcane straw as a soil conditioner, to improve its nutrient enrichment potential, instead of burning it.

Moreover, an LCA study was carried out in Mauritius to assess the impact of bagasse combustion on electricity generation, compared to other sources. The study reported that emissions of CO_2 are equal to just 15% of all fossil fuel emissions on the island. The environmental damage of the agricultural inputs stage is five times greater than the stage of electricity generation. The study also stressed that it can be used as an effective means to control fly ash emissions from boilers, in order to optimize the use of chemicals and effective irrigation methods to reduce the environmental impacts. The utilization of bagasse to produce electricity has the benefit of reducing GHG emissions, compared to fossil fuel-derived electricity. On the other hand, freshwater consumption and eutrophication are two of the drawbacks of bagasse-derived electricity (Ramjeowon, 2008).

2.13.1 Life-cycle assessment of the Sudanese sugar industry

The sugar industry produces waste streams and emissions, while sugarcane transportation and milling consume energy (Palacios *et al*., 2019). Each waste management effort is of vital significance for the environment (Nakhla, 2014). In Sudan, the environmental performance connected with the different stages of sugar production has never been assessed. Therefore, research work is required on how to attain the ecological sustainability of the sugar industry in the country. The life-cycle assessment method must be applied in the Sudanese sugar factories to assess their energy use, their GHG emissions and their impact on the environment. The stages of sugar production should include sugarcane production, sugarcane harvesting and transportation, as well as sugarcane processing.

2.13.2 Life-cycle assessment phases

The procedure consists of four phases, namely**:** (1) the goal and definition, which defines the outline that all other LCA phases must comply with. It comprises the purpose of the study, the data specificity, the collection method, the functional unit, impact assessment and assumptions; (2) a life-cycle inventory, which completes the process of a diagram, data collection and an evaluation of the data; (3) the life-cycle impact assessment, which includes the potential impact of the process and the selection of impact categories, as well as the grouping and weighting of the impacts; and (4) the life-cycle interpretation, which provides for the identification of the significant effects, the evaluation of its findings and the final recommendations (Williams, 2009; Nakhla, 2014; Astuti *et al*., 2018).

2.13.3 Life-cycle impact assessment methodology

Different methods have been developed by many specialist organizations in various countries in the world. Table 2.3 includes, but is not limited to, the methodology of a life-cycle assessment. Each method has its distinguishing characterization models, factors and weighting factors, so that the results differ from others. The selection of one of these methods depends on the LCA study (Nakhla, 2014).

Table 2.3 Life-cycle impact assessment methodology

Method	Factors considered to be measured	Reference
Eco-indicator 99	The damage to (1) human health comprises carcinogenesis indicators, respiratory effects, radiation, ozone depletion, and climate change. (2) ecosystem quality expressed in (%) includes signs of toxicity, acidification, eutrophication and land use, and (3) fossil resources shown in mega-joules that involve the depletion of minerals and fossil fuels.	Azapagic and Perdan, 2011; Nakhla, 2014; Rigon, *et al.*, 2019
IMPACT 2002+	It considers the previous three damage categories plus climate change, as the fourth category.	Pre-Consultants, 2010; Rigon, *et al.*, 2019
CML 2 Method	The potential effect of abiotic resource depletion, global warming, photochemical oxidant formation, eutrophication, ozone depletion, acidification, human toxicity and eco-toxicity.	Azapagic and Perdan, 2011; Curran, 2012; Rigon, *et al.*, 2019
ReCiPe	This method integrates the CML2 and eco-indicator 99, so that it takes advantage of both by implementing both strategies.	Pre-Consultants, 2010; Rigon *et al.*, 2019
Ecological Footprint	It considers direct and indirect land occupation, energy use and CO2 emissions. It does not normalize the impact, so each impact has a	Pre-Consultants, 2010

	weighting factor.	
Greenhouse Gas Protocol	It calculates carbon dioxide equivalents (CO_2e) of all the non-CO_2 gases (CH4, N2O, SF6, HFCs, CFCs) used and reports on the most recent 100-year Global Warming Potential (GWP)	Pre-Consultants, 2010
IPCC 2007	It considers the factors of climate change, based on the Intergovernmental Panel on Climate Change (IPCC) for a time-frame of 20, 100 and 500 years. No normalization of the weighting factors is considered in this method.	Nakhla, 2014; Rigon *et al.*, 2019

2.14 Industrial Waste Handling Framework

The waste management strategies are significantly different between countries, as they remain a prominent issue for achieving particular objectives. A useful designed framework can steer managers to address the waste issue in a cost-effective and timely manner. It can spur on the enhancement of existing plans or aid in the design of new ones (Davidson, 2011; Singh, 2017). Various approaches have been developed to tackle the waste problem, such as Integrated Waste Management (IWM), which combines a range of techniques, technologies and management programs to achieve specific objectives and goals. A systems analysis provides useful information for defining, evaluating and adapting waste management systems (Pires *et al.*, 2010). Two main analysis methods are used for waste management, namely: (1) systems engineering models, such as predicting models, simulation models, optimization models and integrated modeling systems; and (2) system assessment techniques, such as management information systems, decision support systems, expert systems, scenario development, a material flow analysis, a life-cycle assessment, a risk assessment, an environmental impact assessment, a strategic environmental assessment and a socio-economic assessment (Pires *et al.*, 2010). Many concepts could help to structure the waste management plan, as shown in Table 2.4. Table 2.5 shows the key details (i.e. the objectives, indicators and strategies) of the prospective industrial waste-handling framework.

Table 2.4 Key concepts for structuring a waste management plan

Concept	Focus	Reference
Zero Waste	Recreating production and distribution systems to minimise waste from the outset.	Young *et al.*, 2010; Davidson, 2011
Cradle-to Cradle (C to C) / Cradle-to-Grave	Designing industrial systems in a way that materials flow in closed-loop cycles, which minimize, recycle and re-use the waste.	McDonough *et al.*, 2003; Davidson, 2011
Eco-Efficiency	Integrating the environmental and economic aspects of certain development processes.	Hellweg *et al.*, 2005; Davidson, 2011
Industrial Ecology	Restructuring, integrating and adapting technology to processes to be more sustainable, which is similar to C to C.	Davidson, 2011; Bhatnagar *et al.*, 2016

Table 2.5 Outline of the industrial waste-handling framework for the selected sugar factories

Goals / Objectives	Indicators / Targets	Strategy
• Maximize re-use and recycling of waste resulting from sugarcane manufacturing. • Support decision-makers in achieving sustainable sugarcane production in Sudan. • Achieve zero waste for the sugar industry in Sudan.	• Use additional facilities to reduce the impact of production. • Substitute reusable items for disposable items in waste handling.	• Target specific materials, such as surplus bagasse and wastewater, for re-use and recycling. • Increase the effectiveness of existing and on-process recycling programs. • Develop facilities and systems to re-use the waste as raw materials, to produce friendly environmental products, such as paper from bagasse, biogas from wastewater and ceramics from bagasse ash.

2.15 Fishbone diagram

Fishbone diagram is a systematic methodology to analysis the effects and the causes of the system problems. Normally, this technique represents probabilities of effects and their multiple correlated causes. The diagram (fish skeleton) is horizontally distributing the multiple causes and their sub-causes (Ilie and Ciocoiu, 2010; Hekmatpanah, 2011). This simplifies determining the root causes of the main problem as well as finding better solutions. Then, improvement on the quality or the productivity of a certain products can be made (Hekmatpanah, 2011).

2.16 Dot-Plot-Diagram

A dot-plot is defined as a statistical chart that consists of data as points and plotted in a simple scale. The dot-plot diagram is considered as one of the simplest ways of statistic and useful for small data sets. The diagram is effective in highlighting clusters and the outliers in data distribution (Moore, 2021).

2.17 Discussion

Despite the importance of the sugar industry in Sudan and its contribution to the national economy, its productivity is minimal (Abdalla, 2006; Hassan, 2008; Ibrahim, 2017). The annual sugar production has fluctuated between 526 000 tonne and 775 000 tonne for the past ten years. In the meantime, the country needs about 1.25 mn tonne of sugar to satisfy local consumption (Omer, 2017). This gap should have been bridged since 2012 by the White Nile Sugar Project, with its estimated capacity of 450000 tonne. $year^{-1}$. However, the demand for local sugar consumption is increasing as the population increases, and the country is now becoming an importer, rather than an exporter, of this commodity. Thus, this problem needs to be investigated and sustainably resolved.

Previous studies conducted have revealed that the reasons behind the declining productivity are the poor design of the factories (Hassan, 2008) and the improper utilization of production inputs (Ibrahim, 2017). However, what if the mass balances of the factory systems are insufficient? This may be because of a low sugar extraction efficiency of some factories. It is the system that converts sugarcane into crystal sugar that is suffering from mechanical weaknesses. Although the determining factors are not apparent at this point, it will be valuable to identify the causes of the decline in sugar productivity over the past ten years, particularly for the most significant sugar producer (Kenana). Although the areas planted with sugarcane have expanded significantly, no precise method has been used to identify the factors influencing the declining productivity. Previous studies have not examined the current systems of the sugar-processing supply chain, especially those of the older factories. A lack of research on this particular issue has led to questions about the manufacture and extraction of sugar and about the factors influencing the efficiency of sugar processing.

The disposal of untreated wastewater resulting from sugar production has also had a harmful impact on the environment and the communities living near these factories. Most factories have been releasing this massive waste into the Nile River and into open fields (El Hassan, 1998). Some researchers have stated that the treatment of this waste is costly (Mohamed and Lubna, 2016). However, the problem of wastewater disposal needs to be solved sustainably. To this end, one of the sugar factories is building wastewater treatment plant (Alim, 2012). Most of the sugar factories in Sudan do not have an adequate scientific background about this environmental issue. The deteriorating technological equipment is evidence of this and the lack of wastewater treatment measures for the vast majority of these industries makes the identification of the environmental impacts of this waste difficult (Abid, 2008; Bushara, 2016). Previous studies have not devised precise methods for assessing the effects of such garbage on the communities living near the sugar factories.

In addition, vast amounts of fossil fuel energy are used in all stages of sugar manufacturing (Palacius *et al.,* 2019). Sugarcane is mechanically harvested, so the process emits large quantities of greenhouse gases into the air, while the sugar manufacturing method releases gases and residual bagasse ash into the atmosphere (Cordiero *et al.*, 2004; Mohamed and Samah, 2011; le Blond *et al*., 2017). These pollutants influence human health, especially those who are living in the vicinity of the factories. Exposure to these pollutants is inevitable while the sugar manufacturing process is in operation. The impact of sugar processing pollutants on the health of the communities surrounding the Sudanese sugar factories has never been examined.

However, emissions resulting from the different stages of the sugar production life-cycle could be minimized and controlled. Abdeen (2002) reported that reducing the greenhouse gas emissions is urgent; however, an effort must first be made to determine the type of effluents, and secondly, to assess their impacts, and thirdly, to identify opportunities for enhancing their environmental performance. None of the previous procedures have been implemented or studied in Sudan. The assessment of energy use and the emissions associated with the country's sugar production need to be considered.

The sugar industry in Sudan needs sustainable development. In this respect, measures are required to increase productivity and to reduce the environmental impacts, which will be beneficial for both the communities and the mills. This approach will provide an opportunity to reconcile the environmental and production needs with the long-term development of the sugar industry in the country.

2.18 Conclusion

The sugar industry in Sudan is experiencing a noticeable reduction in its sugarcane production and sugar yields. Sugar production has been decreasing by 3.5% annually over the past ten years, and the expansion of the cane production areas has been negligible. The proper identification and provision of appropriate alleviation measures are needed. The current literature review has indicated that the continuous decline in sugar productivity is due to unknown factors. The problem has subjected the factories to losses of at least one-third of their total production. The quantity of sugar exports to international markets has declined by more than three-quarters. The country has become an importer, rather than an exporter, of this commodity, in order to fill the local consumption gap. In addition, the sugar manufacturing waste is released into the River Nile, which could affect human health and the environment. However, it is possible to develop power production plants from the large quantity of by-products from the industries, which would benefit the country. Attention has therefore been focused on the environmental performance of the sugar industry, namely, its energy consumption and the resulting emissions.

The next chapter represents the evaluation and identification of the factors that influence the productivity of the sugar industries. By using the system analysis technique, the chapter identifies all the potential causes and it extracts the factors that are most responsible for the problem of declining productivity. Thus, it recommends performing a well-structured plan to retrieve the productivity, by solving the causes of the problem.

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3. IDENTIFICATION OF TECHNICAL FACTORS THAT INFLUENCE THE SUGAR PRODUCTIVITY OF FACTORIES IN SUDAN

This chapter is based on the following paper:

Ibrahim, TS and Workneh, TS. 2020. Identification the technical factors influencing the sugar productivity in Sudan. *African Journal of Science, Technology, Innovation and Development*. doi: 10.1080/20421338.2020.1824324.

Abstract

This study was conducted to identify the factors that influence the productivity of the sugar industry in Sudan. The study involved collecting data from selected sugar mill databases, namely, the Kenana, Guneid, Halfa, Sinnar, Assalaya and White Nile sugar mills. The data were analyzed by using the regression analysis technique, and the intensity relation matrix analysis technique was used to determine the most important factors that influence the decline in productivity. The results showed that the main factor that decreased sugar productivity was the sugarcane yield, and the low cane yield was attributed to the lack of agricultural input and improper land preparation. The soil salinity and the cultivation of only one sugarcane variety (i.e. CO 6806) over the past thirty years have influenced the yield. The disturbance of the fallow practice has also contributed to the decline. The continuous water shortages in the field, and sugarcane that is harvested at a non-optimum age, have influenced the sucrose percentage in sugarcane, which has reduced the sugar extraction rate. Impurities in the extracted juice have increased, due to the vast quantities of mud that come with the harvested sugarcane, which may have also influenced the sucrose extraction. The depreciation of worn-out equipment and the failure to carry out proper maintenance has contributed to a decreased average efficiency of between 75% and 80% for the five sugar mills. The sugar industry in Sudan requires a well-structured plan to optimize the application of agricultural inputs and to increase sugarcane productivity. Therefore, this study provides a framework for the decision-makers in the industry, who aim to retrieve the productivity of both sugarcane and sugar by adopting new technologies in the country.

Keywords: sugarcane yield, factory performance, sugarcane quality, factors, sugar productivity

3.1 Introduction

Sudan is endowed with many resources, such as fertile soil, abundant water and an environment that has a high agricultural potential. The country is the second-largest country in Africa, with a total area of 1.88 million km^2, and its arable land is about 84 million hectares, with only one-fifth of it being cultivated, thus far (Obeid, 2013). The country is potentially one of the leading food-producing countries in the world, and the one sector that could help to achieve this goal is the sugar industry (AbuZeid, 2015), as sugarcane is a suitable remunerative crop that can be grown successfully in large areas of the country. The sugar industry in Sudan dates back more than fifty years and it has made remarkable progress. Sudan became involved in this industry in the early 60s, and it has increasingly become an integral and essential economic pillar of the country. Four governmental sugar schemes were established, starting with the Guneid mill. This is the only sugar estate that embraces the tenant system, where the farmers own the land and the sugar company owns the mill. A few years later, the Halfa sugar mill was established, with an annual production capacity of 75 000 tonne of sugar. Then, two bigger sugar mills (Sinnar and Assalaya) were established, with an estimated annual production capacity of 110 000 tonne of sugar each. In the early 80s, a private investment company, the Kenana Sugar Company, built and designed a mill to produce an annual sugar capacity of 300 000 tonne (Obeid, 2013). Today, the estimated annual sugar consumption in Sudan is 1.25 million tonne; however, the overall annual production is still around 750 000 tonne of white sugar. This gap was supposed to be bridged after the White Nile sugar factory began operating, which could potentially produce 450 000 tonne of sugar annually (Obeid, 2013). However, there has been a noticeable recession in the production of sugar in whole sugar industry over the past ten years, despite a significant investment in new buildings, particularly in the White Nile Project. Production at the Kenana mill, which is the biggest sugar producer (56%) in Sudan, has declined by 25% over the past ten years (Abdalla, 2006; Elzebair *et al*., 2015; KSC, 2016), while the other mills have suffered a similar recession during the same period (Obied, 2013; Bushara, 2016). Sugar productivity has continued to decline, despite the good growing conditions and the expansion of the planted areas (Ibrahim, 2017). According to Hassan (2008) and Ibrahim

(2017), the poor design of the factories and the improper utilization of production inputs are the main reasons behind the problem.

Many factors influence the processes within a mill, with the quality of the sugarcane being the most significant factor, as quality sugar cannot be produced without high-quality sugarcane (Boote, 2010). The quality of the sugarcane is influenced by various factors i.e. the delay between harvesting and crushing (Bocanegra-Herrera and Vidal, 2016), the harvesting method (Adam *et al.*, 2015) and the sugarcane variety (AbuZeid, 2015). Ibrahim (2011) concluded that reforming the structure of the production process has increased the performance level of the Kenana mill. However, the study was limited to one factory, and a general and fallacious analysis was made. Thus far, no study has been conducted to examine the efficiency of the sugar-processing supply chain and to identify the specific factors that influence the productivity of sugar mills in Sudan.

As mentioned above, there have been a range of studies described the challenges facing the sugar production in the Sudanese factories. However, it has been noticed that such researches are patchy. The extent, to which these studies are promising in designing an integral framework to sustainably retrieve the productivity of sugar factories in Sudan, is poorly understood. In particular, all the engineering factors that could potentially contribute to the decline sugar productivity were not clearly stated. The purpose of this paper was not only to identify the influential factors (i.e. engineering factors) to the problem of decline productivity for individual sugar factories and for the whole industry in the country. Rather, its aim was to understand the identified factors and their influential sub-factors and build an effective framework to sustain sugar productivity in the country.

Regression models are widely used to analyse data relating to quality control and prediction. This study aims to extend the application of the regression method, in order to identify the factors that influence sugar productivity. A fishbone diagram is another useful tool for risk identification. (Ilie and Ciocoiu, 2010; Hekmatpanah, 2011). It is defined as a systematic technique to analyze the effects and the causes of the system problems. The technique is systematically represents a range of probabilities for the potential effects and their multiple correlated causes. The diagram, in a shape of fish skeleton, is horizontally distributing the multiple causes and their sub-causes (Ilie and Ciocoiu, 2010; Hekmatpanah, 2011). The advantages of fish bone diagram can be stated encouraging group participation and utilizing the knowledge of the process, identifying the exact data needed for further study. This structured approach helps determining the root causes of the main problem and identifying better ways for solutions. Hence, improvement on the quality or the productivity of a certain products can be made (Hekmatpanah, 2011). However, the simplicity of fishbone diagram could be one of the weaknesses of this approach by unclear representing the nature of the problems and causes in a complex situation. It requires a massive space to construct the diagram, which complicates exploring the detailed causes and effects relationships.

This study has applied a cause and effect analysis to extract the most critical factors that have caused the decline. The factors and measures that were used for monitoring were considered, in an effort to increase sugar productivity. This study has selected the cause and effect approach due to its suitability for system analysis (i.e. process of sugar production). A statistical thinking approach is an effective tool that could solve problems, such as the decline productivity. The method is to view the whole process in one frame, as a system built by procedures. Identifying and screening the influencing factors is essential for determining the main issues that will lead to success (Hoerl and Snee, 2012; Kustiyo and Arkeman, 2019). This paper identified the potential factors that influence sugar productivity, extracted those that are most important, and set the best practices for resolving the issues.

3.2 Research Methods

The methodology includes determining the location of the sugar factories to be studied, as well as the techniques that will be used to collect, analyse and summarise the data.

3.2.1 Study area

Sudan is endowed with vast resources, such as fertile soil, abundant water sources and an environment that is conducive to a high sugarcane yield (AbuZeid, 2015). Sudanese sugarcane is grown in the central clay plain between 10° and 16° N latitude and 32° and 37° E longitude, where these resources are available (Intisar, 2003; Ibrahim and Workneh, 2019). For the reasons mentioned above, the study selected this particular region of the country because it includes six sugar mills, namely, the Guneid, Halfa, Sinnar, Assalaya, Kenana and White Nile mills. The Assalaya, Kenana and White Nile mills are in the White Nile state, while the Guneid mill is in the Gazeira state, the Sinnar mill is in the Sinnar state, and the

Halfa mill is in the Kassala state. Guneid is located between 13°17'20"N latitude and 32°46'52"E longitude, Halfa is located roughly between 15°28'20" N latitude and 35°34'32" E longitude, Sinnar lies between 13°49'38"N latitude and 33°27'35"E longitude, Assalaya is located between 13°15'43" N latitude and 32°44'74" E longitude, Kenana lies between 13°8'16" N latitude and 32°59'53" E longitude, and White-Nile is located between 14°4'30" N latitude and 32°28'21" E longitude.

3.2.2 Technical factors and method of identification

Several technical parameters were calculated, such as the sugarcane yield, sugarcane quality and the performance efficiency of the industry, which are the core of sugar processing and which influence productivity. Table 3.1 and Figure 3.1 show the final parameters that were considered for the evaluation of sugar processing performance over the past ten years. The sugarcane yield (Cy) varied according to the variety, the land and the climate and thus, it differed from one factory to another (AbuZeid, 2015). The sugarcane yield was calculated by dividing the average weight of the harvested cane per tonne per hectare. The process was recorded on a daily basis and saved on a report sheet during the harvesting season. Hence, the average tonnage of the whole season was calculated at the end of the year and kept in the harvesting section of the factory records. Sugarcane quality (Cq) encompasses determining the percentages of sucrose, fiber, water and soluble impurities in the harvested sugarcane. The estimations were calculated in the relevant laboratories and the records were kept in the factory databases. The Factory Performance (FP) was calculated by using Equations 3.1, 3.2 and 3.3, as follows:

$$FP\ (\%) = 100\left[\frac{Tx}{Tc}\left(\frac{100}{ERC\%\ Cane}\right)\right] \tag{3.1}$$

Where: Tx = crystal actually produced (tonne), Tc = sugarcane crushed (tonne)

ERC = estimated recoverable crystal of sugar, which was calculated by using the equation.

$$ERC(\%)\ Cane = a.S - b.N - \ c.F \tag{3.2}$$

Where: S = the sucrose (%) sugarcane; N = the non-sucrose (%) sugarcane (calculated as brix (%) sugarcane minus sucrose (%) sugarcane); F = the fiber percentage sugarcane; a, b and c = constant parameters of sucrose losses in the factory. The constant “a” is the fraction of the sucrose losses in the filter cake. The constant “b” represents the loss of sucrose in the final molasses. The constant “c” represents the loss of sucrose in the bagasse (Peacock and Schorn, 2002).

$$\text{Milling performance (\%)} = \frac{Mill\ Extraction\ x\ 100}{100-0.20\ F} \qquad (3.3)$$

Where: 0.20 = extraction ratio and F = actual fiber of the sugarcane (Fourmond, 2016).

Table 3.1 Sugarcane processing parameters over the 2007 to 2016 period

Parameter	Value
Total sugarcane productivity	tonne. ha^{-1}
Total sugarcane stalk	tonne. $year^{-1}$
Sugarcane crushed	tonne.day^{-1}
Milling efficiency	%
Sucrose % cane, Bagasse % cane, Sucrose % bagasse	%
Total sugar produced	tonne.day^{-1}
Factory performance	%
Total sugar	tonne. $year^{-1}$
Molasses produced	kg.$tonne^{-1}$ sugar
Bagasse burnt / total produced	%
Chemicals	kg.$tonne^{-1}$ sugar
Wastes	kg.$tonne^{-1}$ sugar

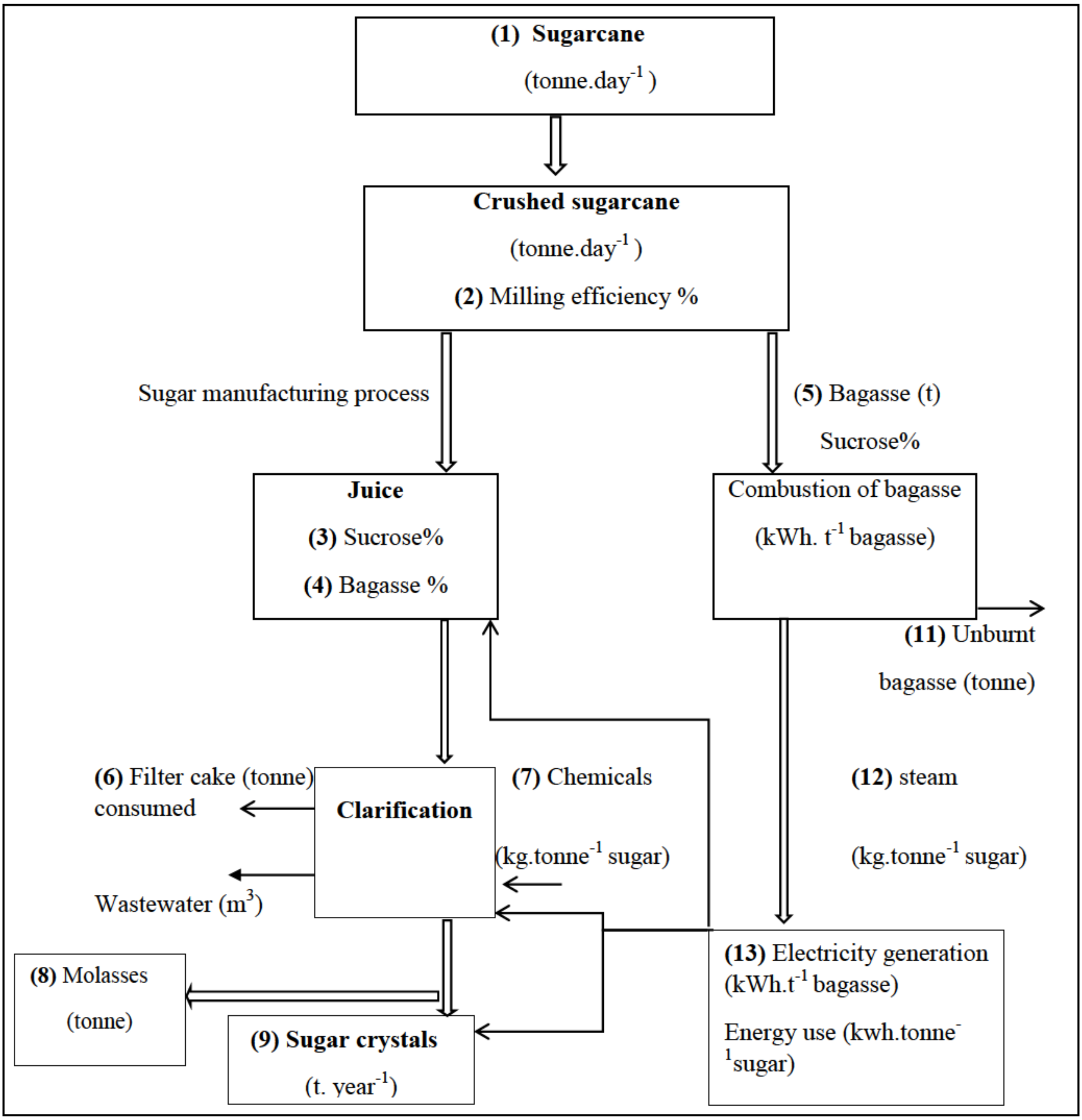

Figure 3.1 Sugar processing parameters

3.2.3 Data collection

This study involved a documentary review method of the data that were collected from the mill data bases. An introductory letter was written to the selected directors of the sugar factories, seeking permission and staff assistance in data collection. Empirical data of the selected sugar factories, i.e. the Sudanese Sugar Company (SSC) and the Kenana Sugar Company (KSC) for the past ten years, from 2007 to 2016, were collected from annual reports, office records and related companies. Data were also collected from personal contact with the engineers, managers and administrators of the relevant departments. The author conducted face-to-face interviews with a total of 29 informants, namely, 13 engineers, 12 managers and four administrators from different departments of the selected sugar factories. Related data sources, such as dissertations, books and magazines, were also considered. Some information was used as background material, some to support the arguments and some to cross-validate the statistical results.

3.2.4 Data analysis

This section shows the methods of analysis that have been used to identify factors influencing sugar productivity. The approach of performance analysis was used to interpret the information that was concluded from the communication texts. A linear regression analysis was involved to outline the influential factors to the problem of decline productivity and the relationship between these factors. The cause and effect diagram was utilized to enumerate all the important factors that potentially contributed to the main problem. The intensity relation matrix was the next analysis technique that used to estimate the effect intensities between the identified factors. Finally, the dot-plot-diagram was used to identify the most important factors that need to be investigated and drastically solved. The analysis methods used in this paper were as follows:

3.2.4.1 Qualitative content analysis

The textual analysis technique (Frey *et al.*, 1999; Fürsich, 2018) was used to describe the content of the information obtained from the key informants. A textual analysis is one method that can be used to describe and interpret the characteristics of communication texts (Frey *et al.*, 1999; Williamson *et al.*, 2018,). Pseudonyms were used in reporting the names of the key informants, to protect their identity. The communication texts of the key informants were identified according to the degree of their relationship to the particular problem that was studied. The possible understandings were then concluded from the established range of legitimate understandings. Finally, the chosen interpretations were set, refined and reported in the study.

3.2.4.2 Linear regression analysis

A linear regression analysis was used to analyse the collected data from the selected sugar factories in the Sudan over the past 10 years. A regression analysis is a widely used method in the sugar industry sector. Xiao *et al*. (2017) examined five quality indexes in China, such as the brix, purity, polarization, sucrose content and reducing sugar, by using a linear regression analysis. The study concluded that there is a strong correlation between some of the quality indexes and that the regression models are significant, which indicates that the prediction results were ideal. A multiple regression analysis was used to identify the factors influencing the sugar price in China. The study concluded that market factors (i.e. the sugarcane price) and the strict regulations were the main factors influencing the sugar price (Xie and Chen, 2014). The analysis of this study was carried out by using Microsoft Excel 2010 for the parameters i.e. the sugar productivity (Sp), sugarcane yield (Cy), sugarcane quality (Cq) and the factory performance (Fp). A linear regression equation (Weisberg, 2013) was conducted by using Microsoft Excel. A simple linear regression analysis was conducted between each parameter (i.e. Sp and Cy, Sp and Cq, and SP and Fp). In addition, a multiple linear regression was performed for all the parameters: sugar productivity (Sp) included the sugarcane yield (Cy), the sugarcane quality (Cq) and the factory efficiency (Fp).

3.2.4.3 Cause and effect analysis

A cause and effect analysis (Suripto *et al.,* 2018) was used to identify the most important factors influencing the main problem. A fishbone diagram is one of the important tools that can be used to identify the main causes behind a problem in a complex system (Hekmatpanah, 2011). A fishbone diagram was built by stating all the potential causes that could possibly have contributed to the decline in sugar productivity in the country. Figure 3.2 shows the sub-divisions in the pattern, where the cause-effect order is clearly recognizable, and it takes into consideration a further assessment of the causes. A relationship was found between some of the factors; for example, machinery failure due to poor knowledge and skills, improper sugarcane harvesting because of an inadequate mechanical harvesting system, uprooting the first ratoon for irregular land terrain, no sugarcane to the mill due to poor sugarcane transportation and a lower efficiency of machinery because of depreciation. These required further investigation, so that the interconnections could be described.

3.2.4.4 Intensity relation matrix

An intensity relations matrix analysis was conducted by using the linked-thinking technique for solving complex problems. This approach was used to estimate the effect intensities between the identified factors. The process was conducted to extract the important factors and to use them in further investigations for solving the problems. The intensity relation matrix showed a sort of linkage analysis, and it induced the method of the linked-thinking for solving complex problems. The effect intensities between the factors in the previous Figure 3.2 were estimated by using this technique. Hence, the important factors were found and further investigations were undertaken. Similar factors were also combined to avoid repetition. The square array was constructed so that the factor names that are in the first column are also in the same sequence in the first row.

Then the cause-effect was assessed from the factor in the column to the factor in the top row. The matrix structure, which was arranged cell-by-cell, ensured that all the pairs of factors were evaluated. The effect was estimated into five degrees; (0) = no effect, (1) = low effect, (2) = middle effect, (3) = high effect and (4) = very high effect. A matrix diagram was created from the preceding cause-effect diagram of the decline in sugar productivity in the Sudanese factories. Systems Analysis (2012) reported that it is necessary to use the five-level value for the top effects of the main factors. The degree of the effects is usually estimated by experts.

In this study, the five categories were valued according to the author’s experience, based on the background of documentary review and personal contact with the experts. Figure 3.3 shows the matrix that was created from the preceding cause-effect diagram of the declining productivity in the Sudanese sugar industry. The assessment took place along the matrix, as the effect between factors was marked with numbers. The fields that were estimated by no effect (0) were marked with the gray color. The input of zero (grey color) has the advantage of playing the role of a marker that identifies which cells were worked on, and where to continue from, the next time, in case there has been an interruption in the assessment process.

3.2.4.5 Dot-plot diagram

The third step was to correspond the factors in a dot-plot diagram. The rows were summed up horizontally and named as the ‘active sums’. The columns were also summed up vertically and named the ‘passive sums’. Each factor is applied to the passive and active sum in a dot-plot-diagram. The x-axis is started at zero and ends at the maximum passive sum. The y-axis is started at zero and ends at the maximum active sum. The diagram was then split into equal quarters, creating four fields, namely ‘active’, ‘reactive’, ‘critical’ and ‘sluggish’ (Figure 3.4), which were important for the further evaluations. The factors that were considered for further investigation were those in the active and critical fields. Interactions were expected between the factors in the active field and between those in the critical field. The factors in the ‘sluggish’ and ‘reactive’ fields were renounced, because they were considered to be uncontrolled factors.

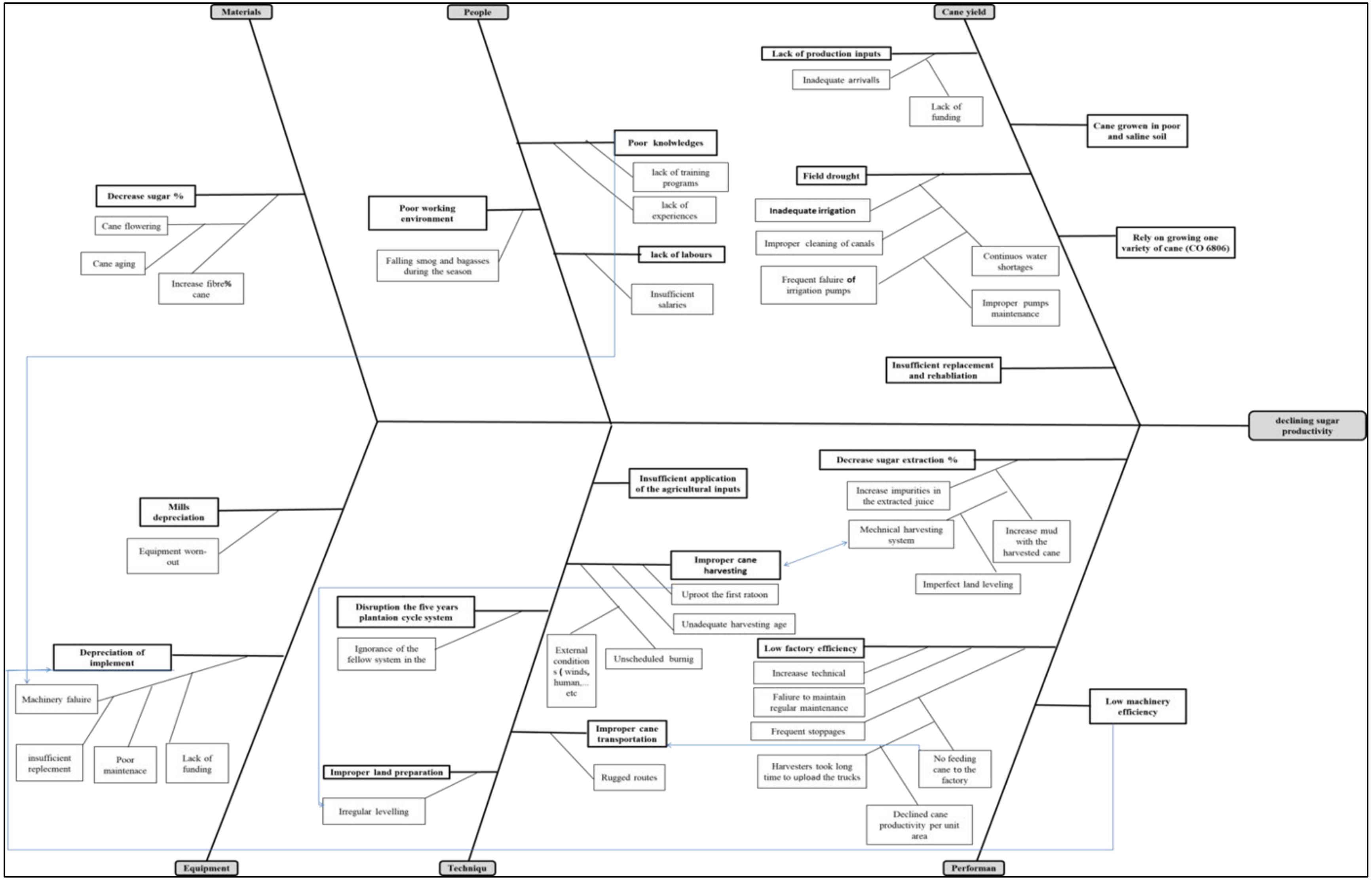

Figure 3.2 Causes and effects of the decline in sugar productivity

		Cane yield	The lack of production inputs	Inadequate arrivalls	The lack of funding	Poor and saline Soil	Field droughts	Inadequate irrigation	Continuous irriga ion water shortages	Improper cleaning of canals	The frequent fa lure of irrigation pumps	Improper pump maintenace	An insufficient replacement and rehabilitation program	Rely on growing one variety of cane (CO 6806)	Performance	The low efficiency of machinery	Low factory efficiency	Increase echnical problems	Failure to maintain regular maintenance	Frequent factory stoppages	No feeding cane o the factory	Harvesters took long time to upload he trucks	Declined cane productivity per unit area	A decrease in the sugar extraction rate	Increase impurities in the extracted juice	The ncreased proportion of mud with the harvested cane	Mechnical harves ing system	Imperfect land leveling	Technequies	Improper land preparation	Irregular leveling	Improper cane transportation	The rugged routes	Improper cane harvesting	Uproot the first ratoon	Inadequate harves ing	Unscheduled burnig	External conditions (winds, human,...etc	Disruption of 5-year plantaion cycle system	The ignorance of he fallow system	The insufficient application of the agricultural inputs	People	Poor knowledges and skills	The lack of training programs	The lack of experiences	The lack of labour	Insufficient salaries	A poor working environment	Fal ing smoke and bagasse	Materials	Decrease sugar % cane	Increased fibre% cane	Cane flowering	Cane aging	Equipment	The depreciation of implements	Machinery failures	Insufficient replacements	poor maintenance	The lack of funding	The depreciation of thr m lls	Worn-out equipment	
	Effect from to ->	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	
1	Cane yield																																																														0
2	The lack of production inputs	4																																																													4
3	Inadequate arrivalls		3																																																												3
4	The lack of funding		2																																																												2
5	Poor and saline Soil	2																																																													2
6	Field droughts	3																																																													3
7	Inadequate irrigation						2																																																								2
8	Continuous irriga ion water shortages						4																																																								4
9	Improper cleaning of canals						2																																																								2
10	The frequent failure of irriga ion pumps						3																																																								3
11	Improper pump maintenance						2																																																								2
12	An insufficient replacement and rehabilitation pro	3										2																																																			5
13	Rely on growing one variety of cane (CO 6806)	2																																																													2
14	Performance																																																														0
15	The low efficiency of machinery														3																																																3
16	Low factory efficiency														3																																																3
17	Increase technical problems																2																																														2
18	Fa lure to maintain regular maintenance																2																																														2
19	Frequent factory stoppages																3																																														3
20	No feeding cane to the factory																3																																														3
21	Harves ers took long time to upload the trucks																2																																														2
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25	The ncreased proportion of mud with the harvested cane																							3																																							3
26	Mechnical harvesting system																							2																																							2
27	Imperfect land leveling																							2																																							2
28	Technequies																																																														0
29	Improper land preparation																												3																																		3
30	Irregular leveling																													3					1																												4
31	Improper cane transportation																				1								3																																		4
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40	The insufficient application of the agricultural inputs																												4																																		4
41	People																																																														0
42	Poor knowledges and skills																																									3																					3
43	The lack of training programs																																										4																				4
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46	Insu ficient salaries																																													4																	4
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49	Materials																																																														0
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52	Cane flowering																																																		2												2
53	Cane aging																																																		2												2
54	Equipment																																																														0
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57	Insu ficient replacements																																																							2							2
58	Poor maintenance																																																							3							3
59	The lack of funding																																																							3							3
60	The depreciation of the mills																																																						3								3
61	Worn-out equipment																																																												3		3
		14	5	0	0	0	13	0	0	0	0	2	0	0	9	1	14	0	0	0	1	0	0	9	0	0	1	0	15	3	0	3	0	8	1	0	0	0	3	0	0	9	8	0	0	4	0	2	0	2	7	0	0	0	6	10	0	0	0	0	3	0	

Figure 3.3 The intensity relation matrix

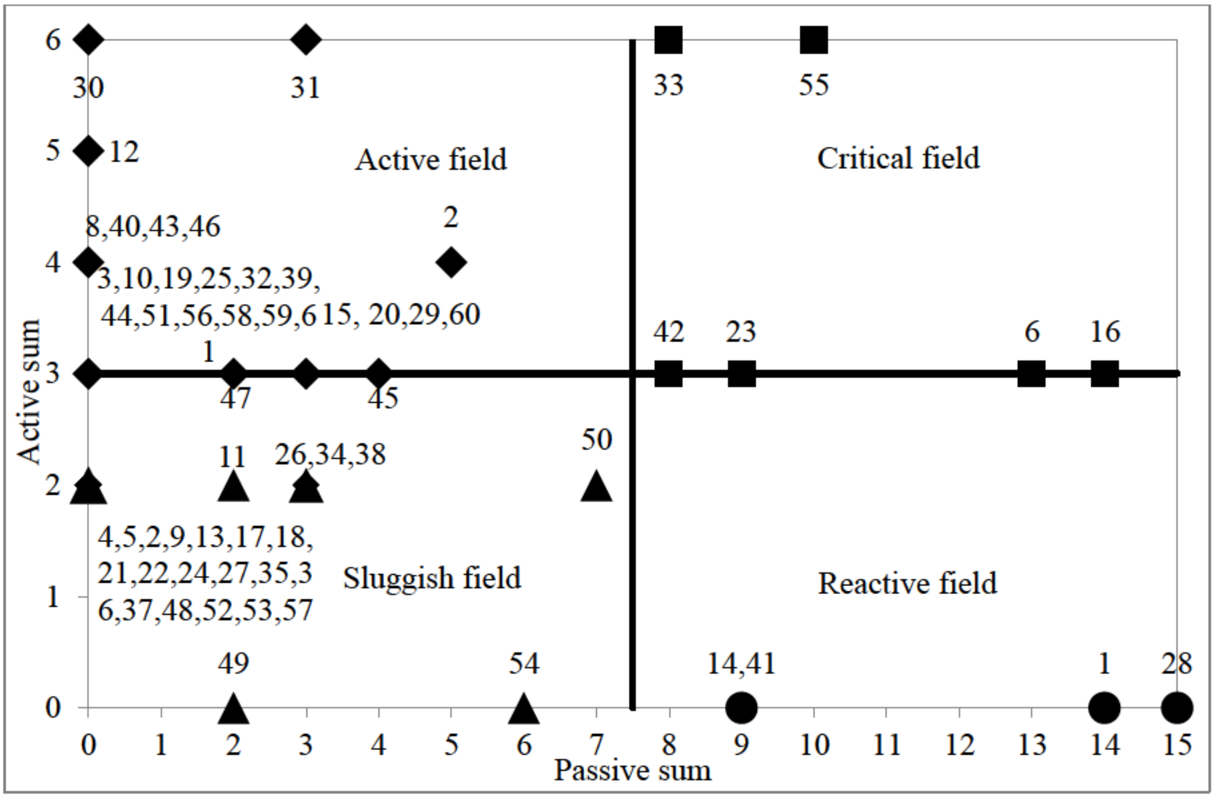

Figure 3.4 Factors causing the decline in productivity in the four fields of a dot-plot-diagram

3.3 Results and Discussion

3.3.1 Effect of sugarcane yield on sugar productivity

The results showed that the productivity of sugarcane per unit area in the whole Sudanese sugar industry has decreased over the past ten years i.e. from 2008 to 2017. The highest production season was in 2008, with approximately 105 tonne of sugarcane per hectare, while approximately 71.51 tonne per hectare were produced in the 2015/2016 season, which was lower than an average of 80.39 tonne per hectare in the preceding crop year. A slight increase (i.e. 4 tonne per hectare) in sugarcane productivity was observed over the preceding season in the past year 2016/2017 (Figure 3.5). On the other hand, the highest sugarcane yield in Brazil reached 72.6 tonne per hectare, and in South Africa it was 64.2 tonne per hectare (SASA, 2015; Statista, 2017). The results revealed that the sugarcane productivity per unit area was higher in the Sudan, compared to the other leading producers (i.e. South Africa and Brazil). However, the results also indicated that there may have been different causes for the declining sugarcane yield. Firstly, it could have been caused by the inadequate application of agricultural inputs. This is in agreement with the findings of Adnan (2013), who stated that the unbalanced and inadequate application of chemical fertilizers was influencing sugarcane productivity in Pakistan, while Zulu *et al.* (2019) concluded that the late application of fertilizers and chemicals is likely to result in the declining sugarcane yield of small-scale sugarcane growers in South Africa. Secondly, the land may not have been prepared sufficiently, due to the deterioration of the implements. Thirdly, there could be problems with the water application in the fields, due to the poor maintenance of the pumps, the improper cleaning of canals, or the insufficient replacement of irrigation systems (Suliman, 2017). A shortage of water for sugarcane irrigation was reported in a study conducted on the Halfa factory, which has access to only 950 m^3 of water per day for irrigation purposes. The quantity of water is not enough to satisfy the daily water requirements of the farm and this limits the expansion of sugarcane production (Bushara, 2016). This has also led to the inadequate application of irrigation water and it has caused droughts to occur in the fields (Obied, 2013; Suliman, 2017). This seems to indicate that the sugarcane yield will continue to be influenced, unless sustainable solutions are found.

In the same context, ignorance regarding the fallow system in the fields has disrupted the subsequent five-year method, and this could have influenced the sugarcane yield. In some cases, sugarcane was grown in poor saline soils, which may have negatively influenced the growth. Moreover, the majority of the sugar factories were found to have depended on the cultivation of one sugarcane variety (i.e. CO 6806) over the past 30 years, which may have contributed to the decline in production. This concurs with the conclusions reached in personal conversations with engineers in the selected sugar industries (Ahmed, 2017; Aradeib, 2017; Elwagiea, 2017; Mohammed, 2017; Suliman, 2017; Yunis, 2017), who stated that the decline in the sugarcane yield in publicly-owned Sudanese sugar factories could be mainly due to them relying only on one cultivar. In China, one sugarcane variety (i.e. ROC 22) has been planted in more than 50% of the growing areas for over 20 years. This continuous cultivation has made the variety more susceptible to a range of different diseases, and it has influenced productivity negatively (Zhang and Govindaraju, 2018). However, many other factors may be causing the decline, such as incompetent management. For example, the lack field monitoring may have led to the improper provision of sufficient agricultural requirements in a timely manner. This concurs with a study conducted by Everlyn (2013), which identified the managerial factors influencing sugarcane production in Kenya. The study concluded that the more well-qualified the field engineers are, the more optimum the management of agricultural inputs is, which will result in a positive increase in productivity. Lawes *et al.* (2002) also indicated that management was a significant factor in the production of sugarcane in Australia.

However, the socio-economic characteristics of a farm were not explored in this study, in order to find out whether the poor sugarcane yield is mainly due to poor management. Further investigations may be warranted, as poor management is influencing the sugarcane yield in Sudan. Moreover, the study revealed that the factory down-times for the Kenana, Gunied, Halfa, Sinnar, Assalaya and White Nile mills, when there were no sugarcane deliveries, were 1.9, 4.9, 1.5, 14.7, 9.2 and 43.4% per season, respectively. The declining sugarcane yield could also be due to an improper sugarcane transportation system (i.e. poor routes, as well as the deterioration and depreciation of trucks). Therefore, the sugarcane yield in Sudan must be improved to increase the productivity of the whole sugar industry. In order to achieve this, a new technique, called the laser land-levelling system, should be used. The hydro-flume irrigation system should be implemented across all sugarcane farms to increase the efficiency of water application and to avoid the problem of labour scarcity. Agricultural inputs (i.e. fertilizers, pesticides, ripeners and flowering inhibitors) should be applied, the mechanical harvesting system must be improved and the capacity of the trucks and the quality of the routes must be improved, to ensure the continuous and efficient flow of sugarcane from the farm to the factory.

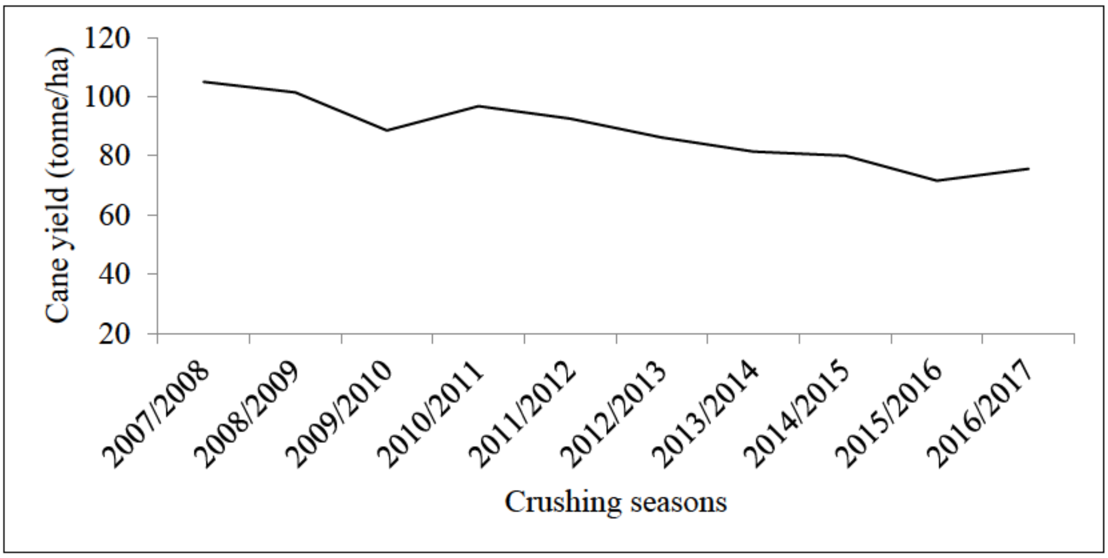

Figure 3.5 Sugarcane production in Sudan from 2008 to 2017

A simple linear regression analysis (Weisberg, 2013) was carried out by using the 10-year data of sugar production (Sp) and sugarcane yields (Cy). The regression equation was as follows:

$$Sp = 20.075 + 6.9739 \times Cy \tag{3.4}$$

The correlation between sugar productivity and sugarcane yield was very strong ($R^2 = 0.9161$), and it accounts for a 91.6% variability in the data. A simple regression model reached a highly significant level ($P < 0.01$), as shown in Table 3.2. The results showed that sugar productivity is directly influenced by the sugarcane yield in the fields. The accuracy of the model was very high and supported the importance of the sugarcane yield. According to the model equation, the sugar production is positively linked to the sugarcane yield, as shown in Figure 3.6. This seems to indicate that sugar productivity can be improved by maximizing the sugarcane yield.

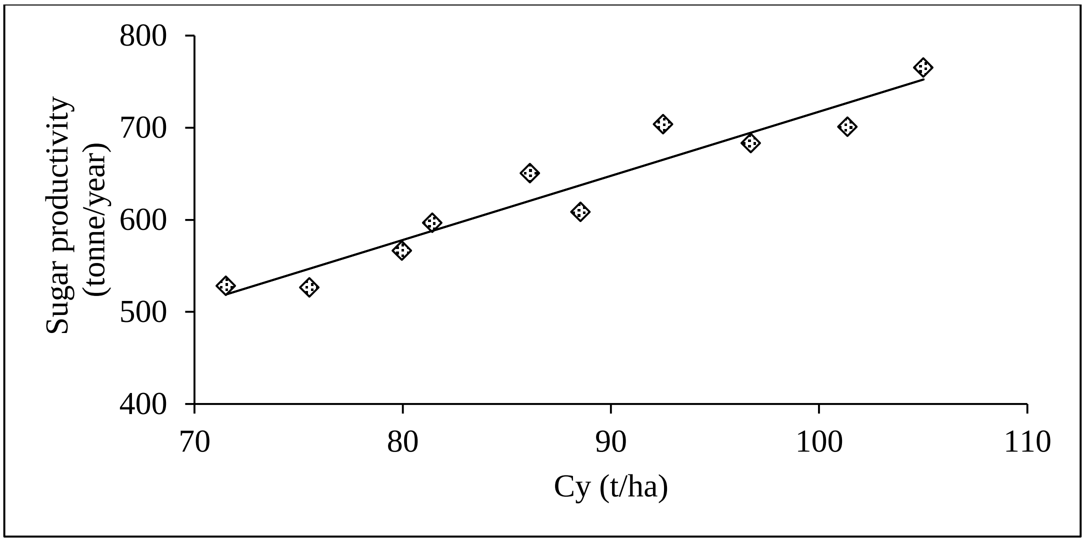

Figure 3.6 Scatter plot between sugarcane yield and sugar productivity

3.3.2 Effect of sugarcane quality on sugar productivity

It is essential to analyse the sugarcane quality, since it is the most fundamental issue for determining the production of sugar per unit area. By using this indicator, management can make a direct comparison of the sugar produced in each field and the rate of sugar production in the factories. The results showed that the average sugar percentages in the sugarcane (S%C) were 12.27%, 12.21%, 12.18%, 12.42%, 12.26% and 11.2% for the Kenana, Guneid, Halfa, Sinnar, Assalaya and White Nile mills, respectively. This seems to indicate that the

S%C was almost the same across all factories in the country. Obeid (2013) indicated that sugarcane in Sudan has almost all the same properties, with very few differences in the soil and agro-climate of the areas where the farms are located. The results revealed that the fiber percentage in sugarcane varied between 15.6% and 20.1% for all the selected farms in the industry. However, the similarity of sugarcane properties may be due to, firstly, to them being cultivated in the same region (belt), namely, the Gazeira, White Nile, Sinnar and Blue Nile states. The location of plain clay soil is between the 10° and 16°N latitude and the 32° and 37°E longitude, which is typical for sugarcane production (Obeid, 2013). Secondly, the same varieties of sugarcane (CO 6806 and CO 997) have been planted for the past 30 years, especially in the Guneid, Sinnar, Assalaya and Halfa states (Arbab, 2009; Ahmed, 2017). Solomon (2009) and Obeid (2013) stated that varieties with a higher proportion of fiber show a higher reduction in the sucrose percentage. It was also revealed that, in most cases, the sugarcane is harvested after, or before, the optimum harvest age (i.e. 12 months). In a study conducted in Ethiopia by Hagos *et al.* (2014), it was concluded that the harvest age significantly influences the sugarcane yield, while Lawes *et al*. (2002) also conducted a study in Australia, which found that it has a significant influence on the sugarcane productivity per unit area. The BFAP (2014) reported that the South African coastal farmers are advised to cut the sugarcane at the mature stage (i.e. 14 months) when the sucrose percentage is high However, this could be due to an imbalance in the scheduling between sugarcane production and the harvest program. The optimum harvest age of sugarcane should be adjusted in the Sudanese sugar factories. The fiber% of sugarcane is an essential factor that must be considered in the field, before the harvest stage. There was also a continuous water shortage due to the improper maintenance of irrigation pumps during the sugarcane production stage. The results indicated that the abovementioned factors have been insufficiently managed in the majority of the sugar-growing areas in Sudan. Therefore, the sugarcane quality in Sudan needs to be sufficiently monitored in the field. This could be achieved by developing a plan that is focused on sustaining an adequate schedule for sugarcane agriculture, by having a stable irrigation program and by adjusting the harvest age.

A regression model was set up between sugar production (Sp) and sugarcane quality (Cq), using the same period of the collected data. The model equation was as follows:

$$Sp = 397.26 \times Cq - 4206.2 \tag{3.5}$$

The model was significant ($P < 0.05$) with an F value of 0.017. The data represented a good correlation (i.e. $R^2 = 0.5294$) between sugar productivity and sugarcane quality, which indicated a good fit. The model was considered to be adequate, as it had an overall regression accuracy of 52.9% and a significant *F* value (Table 3.2). According to Equation (3.5), the sugar productivity could be negatively influenced by the sugarcane quality. This seems to indicate that the sugarcane quality is likely have the same effect on the sugarcane yield and on sugar productivity, as shown in Figure 3.7. However, sugarcane properties are an important factor for regulating the sucrose content, and hence, they influence sugar productivity. Nguyen *et al.* (2019) found that the sugarcane yield and sucrose content are directly impacted by the genetics of sugarcane in Vietnam. Therefore, the quality of the sugarcane should be considered, in order to improve productivity.

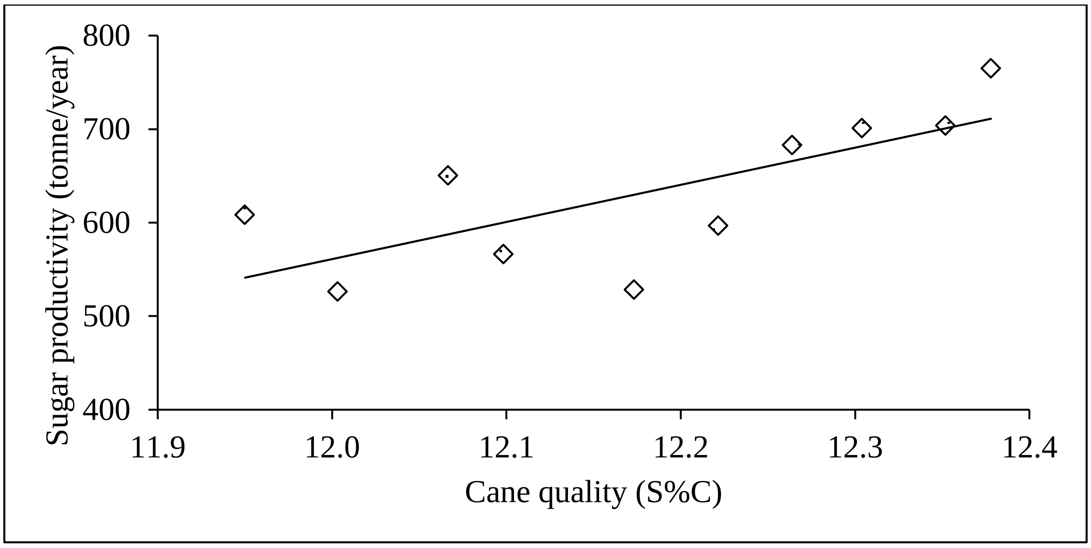

Figure 3.7 Scatter plot between sugarcane quality and sugar productivity

3.3.3 Effect of factory performance on sugar productivity

The factory is the unit that converts the sugarcane stalks into crystal sugar by means of a processing operation. Thus, the performance of the factory must be examined to ensure that the continuity of the recovery process is kept at a standard level. The results showed that the average factory performance was 81.98%, 77.25%, 77.98%, 79.78%, 79.22% and 78.65%, respectively, for the Kenana, Guneid, Halfa, Sinnar, Assalaya and White Nile mills (Figure 3.8). The overall efficiency of sugar processing has not exceeded 80% in the five mills over the past 10 years. The performance of the Kenana mill was about 4% higher than that of the Halfa, Sinnar and White Nile mills and almost 5% higher than the Guneid mill. The average lost time during the crushing season ranged between 5.39% and 19.25% in the five mills, whereas it was about 49% in the White Nile mill. The lost time was caused by technical problems and stoppages, when no sugarcane was fed to the mill. This could be due to the depreciation of the mill, worn-out equipment or the failure to carry out regular maintenance. This concurs with the view of Suliman (2017), who pointed out the imperfections of the equipment and the devaluation of the government-owned sugar mills, in a personal conversation. This could have increased the technical problems and led to prolonged breakdown times during the crushing season.

In the same context, the sugar extraction rate has declined, which reflects a decrease in factory efficiency. Impurities (i.e. mud) were also found to have increased in the extracted juice, which is a common problem in the harvested sugarcane that comes from the field. Kwenda (2015) conducted a similar study in South Africa, which found that the presence of sand in the sugarcane reduced the sucrose recovery rate percentage, and it also caused wear and tear to some mill machinery. The current findings revealed that the problem of mud in harvested sugarcane began in recent years with the introduction of the mechanical harvesting system. This could be due to unbalanced sugarcane cutting caused by the harvester’s knives going unnecessarily deep into the soil. This results in the removal of sugarcane roots, together with some of the soil, which is then loaded and transported to the mill. This may be caused by the uneven field terrain during the preparation stage, when the first ratoons are established. The engineers from the relevant factories in Sudan agree with this view (Yosif, 2017; Suliman, 2017). It was concluded that the rising proportion of clay in the juice in the extraction phase was due to the improper mechanical harvesting of sugarcane. Therefore, the land should be levelled properly, to eliminate the mud problem.

The study also showed that the number of factory stoppages was high, and therefore, no sugarcane was fed into the mill. In the White Nile mill, the stoppages reached a total of 43.3% of the time per season. This seems to indicate that the downtime was higher than the planned standard for the country (i.e. 5.33% of the season) (AbuZeid, 2015). Kbashi (2017) reported that stoppages at the White Nile factory have been continuously increasing, due to sugarcane shortages. This could be due to the main problem, i.e. the declined sugarcane productivity per area, as the harvesters take a long time to load the chopped sugarcane into the trucks, or it could be also due to the poor maintenance of factory machinery. Therefore**,** the scheduled maintenance programs should be carried out efficiently, to avoid any breakdowns and to reduce such stoppages.

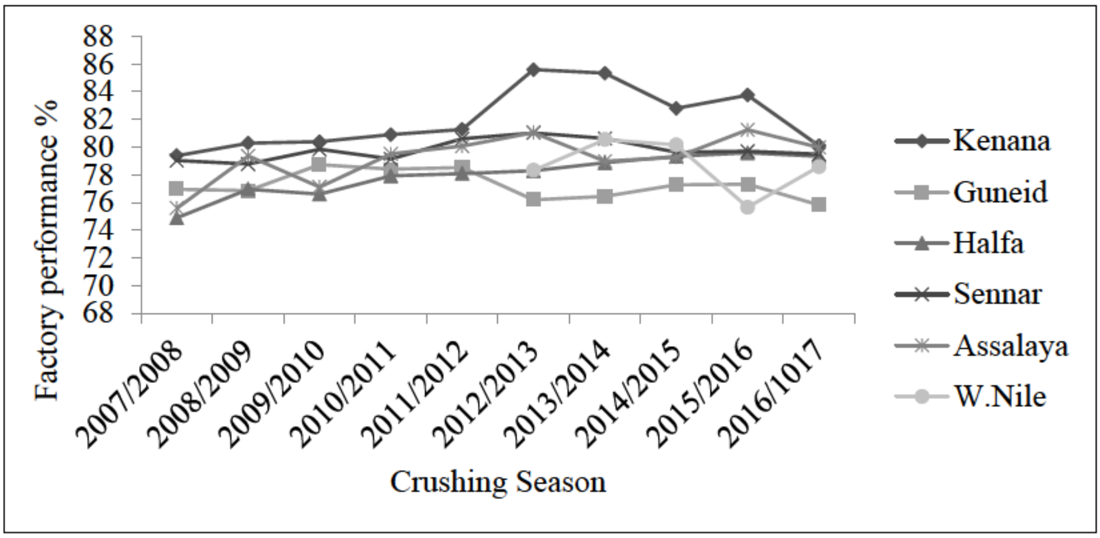

Figure 3.8 The performance of sugar factories over the past ten years

A regression model was conducted between sugar productivity (Sp) and factory performance (Fp). The equation of model is as follows:

$$Sp = -43.267 \times Fp + 4056.9 \qquad (3.6)$$

The correlation between the productivity and efficiency of a factory was weak ($R^2 = 0.2403$). The model was statistically insignificant ($P > 0.05$), as the F value was equal to 0.1503 (see Table 3.2). According to the equation, the industrial efficiency has a negative effect on sugar production, which seems to indicate that the factory efficiency may not necessarily be the main reason behind the decrease in sugar productivity (Figure 3.9).

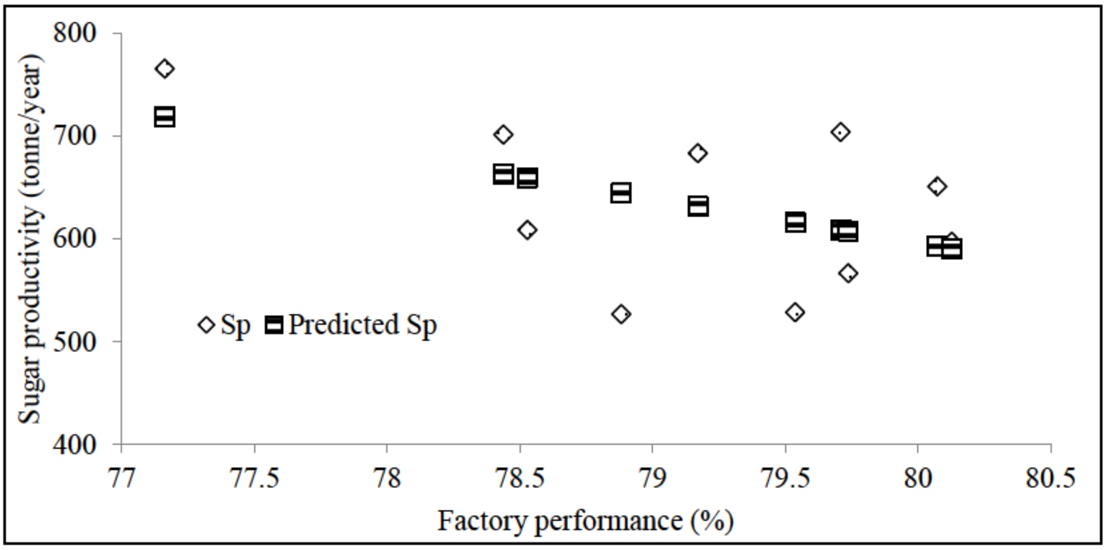

Figure 3.9 Scatter plot between factory performance and sugar productivity

Because of the factors that influence sugar productivity (Sp), the sugarcane yield (Cy), sugarcane quality (Cq) and the factory efficiency (Fp), a multiple linear regression was performed as follows:

$$Sp = -2053.2 + 6.81 \times Cy + 93.41 \times Cq + 12.01 \times Fp \quad (3.7)$$

Equation (3.7) indicates that there is a high degree of fit, which is implied by a 95.2% coefficient of determination (Table 3.2). The model reached a very significant level ($P < 0.01$), and the coefficient and intercept of the regression reached a significant level ($P < 0.05$). Accordingly, sugar productivity increases with the increasing sugarcane yield, sugarcane quality and factory efficiency (Figure 3.10). This indicates that productivity could be increased with an increase in the sugarcane yield, at the current practiced trend of factory efficiency (Fp) and the existing sugarcane quality (Cq).

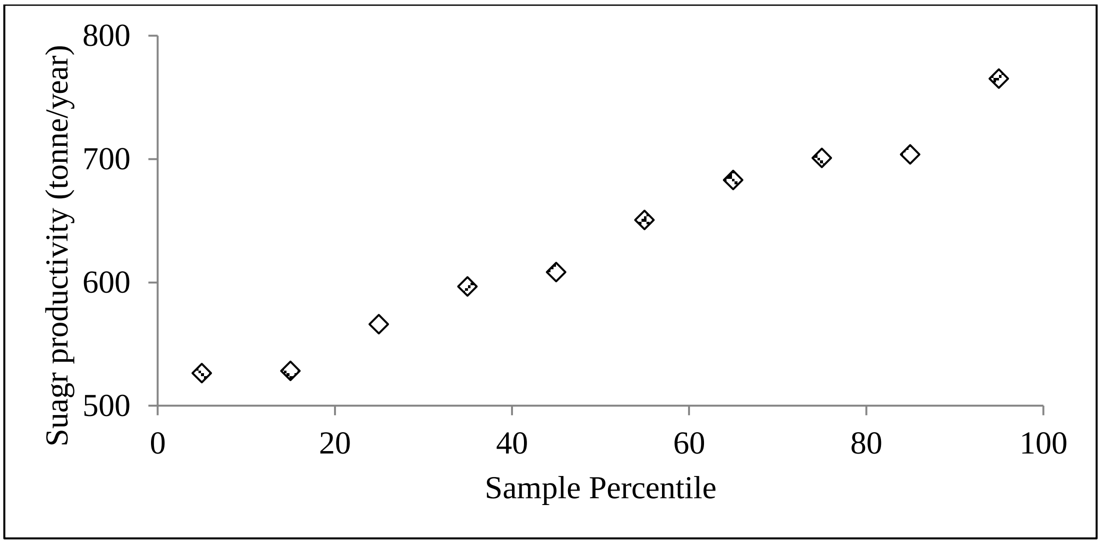

Figure 3.10 Normal probability plot for sugar productivity

Table 3.2 Summary of the output of the regression analysis

Single linear regression between sugar productivity and	Coefficients	R Square	Standard Error	Significance F
Sugarcane yield	6.97	0.92	0.75	0.001
Sugarcane quality	397.6	0.53	132.4	0.017
Factory performance	- 43.3	0.24	27.2	0.150
Multiple linear regression between sugar productivity and				
Sugarcane yield (Cy)	6.81	0.95	1.08	0.001
Factory efficiency (Fp)	12.01	0.95	10.5	0.294
Sugarcane quality (Cq)	93.41	0.95	65.2	0.201

The linear regression analysis indicated that the sugarcane yield is the main contributor to the decreased sugar productivity in Sudan. This seems to indicate that there are sub-factors influencing the main problem. Therefore, what are the factors that cause a decline in the sugarcane yield, sugarcane quality and factory efficiency within the sugar industry in the Sudan? Below is a system analysis technique that was conducted to identify the root problems causing the decline in sugar productivity. Figure 3.2 shows the cause and effect diagram that was built to indicate all the possible factors that contribute to the declining sugar production in the country.

3.3.4 Factors influencing the decline of sugar productivity in Sudan

According to Figure 3.4, the independent factors in the active and critical fields are as follows:

a) Production factors: the lack of production inputs, the inadequate arrival of agricultural inputs, and the insufficient application of agricultural inputs, continuous irrigation water shortages and the frequent failure of irrigation pumps.

b) Processing factors: an insufficient replacement and rehabilitation program, poor maintenance, the low efficiency of machinery, machinery failures, frequent factory stoppages, no sugarcane being fed to the factories, the increased proportion of mud in the harvested sugarcane, improper land preparation, uneven terrain, improper sugarcane transportation, the rugged routes, ignorance regarding the fallow system, the lack of training programs, the lack of experience, the lack of labour, insufficient salaries, a poor working environment, the increased fibre percentage in sugarcane, the lack of funding, the depreciation of the mills, worn out equipment, field droughts, a lower factory efficiency, a decrease in the sugar extraction rate, improper sugarcane harvesting, poor knowledge and skills and the depreciation of the implements.

The lack of production inputs could be due to their inadequate arrival and application; therefore, the following three factors were simplified and called the ‘inadequate application of agricultural inputs’. The continuous water shortages could be controlled by stopping the failure of the pumps; thus, the factor was converted to the ‘frequent failure of irrigation water pumps’. The efficiency of machinery could be improved by introducing an adequate rehabilitation and replacement program. The previous two factors were simplified as follows:

‘the replacement of insufficient equipment and rehabilitation programs’. During the crushing season, the frequent factory stoppages could also be controlled by ensuring that there is continuity in the feeding of sugarcane, efficient sugarcane harvesting and transportation, as well as efficient truck routes. Hence, the five factors were combined to read ‘frequent factory stoppages due to no sugarcane being fed’. Improper land levelling comes from inadequate land preparation and, therefore, both factors were shortened to ‘improper land preparation’. The distinction was difficult between the lack of training programs, the lack of experience and poor knowledge and skills. Therefore, these factors were simplified to ‘the lack of training programs’. The difference between equipment being worn-out and depreciating is confusing. The depreciation of equipment and factory machinery influences the efficiency of the factories. Therefore, these factors were shortened to ‘mill depreciation’. The number of independent factors in the critical and active fields was reduced from 32 to 20 factors. Table 3.3 summarizes the suggested practices for each factor for improving sugar production in Sudan. Therefore, major reforms have to be introduced, in order to secure the future of this sector in the country. This study has created a set of tools that incorporates the engineering principles with which to spur decision-makers on towards improving the efficiency of sugar production.

3.4 Work-plan to increase Sugar Productivity in Sudan

This paper has created a framework for performance improvement, based on statistical thinking, to increase sugar productivity and to support the attempts of decision-makers in the Sudanese sugar industry. The principal concepts of statistical thinking are as follows: all operations inside the system are connected to each other; there are different potential factors inside each operation; identifying, eliminating and analyzing the factors are the key elements of success and enhance performance; and statistical engineering is one of the techniques that is integrally used to implement ideas, measures, tools and technologies to upgrade outcomes (Hoerl and Snee, 2012; Kustiyo and Arheman, 2019). Likewise, it is an integral approach that resolves problems by using the principles of statistical thinking. Accordingly, the following framework of process improvement is set, based on statistical thinking and engineering, to solve the causal factors. The following framework has been constructed with the aim of spurring decision-makers on to increase the sugar productivity in all the mills in Sudan:

3.4.1 Improved sugarcane productivity

The sugar industry in Sudan needs to encourage the vertical increase of sugarcane productivity per hectare. The target should be to expand sugarcane productivity to 105 t per ha across all sugarcane fields within the next ten years. This could be achieved by introducing new varieties of sugarcane with high sucrose content. The provision of adequate and sufficient agricultural inputs needs to be improved, while sugarcane harvesting and delivery practices also need to be improved by aligning the harvesting to the optimal sugarcane maturity and delivering it efficiently, in terms of time and cost. It is essential that agricultural practices are developed to match these changes. The adoption of a uniform agricultural pattern for each farm, without disturbing the fallow system, will help to sustain soil fertility in the long-term, and it will increase productivity. The introduction of a laser system for land-levelling across the farms will help to ensure uniformity in the application of irrigation water across the fields. This will allow the sugarcane maturity stages to be equal. The even terrain will also help to accomplish more effective mechanical sugarcane harvesting, with a minimum amount of mud being transported to the mill. The introduction of trucks with a higher capacity for sugarcane transportation, and the improvement of the routes across the fields, will ensure a steady flow of fresh sugarcane to the mills. The capacity of the trucks should be expanded from 9-16 tonne to 35-60 tonne per truck. The shortage of manpower (i.e. sugarcane cutters, engineers and machine operators) was found to influence the industry. As part of the drive to improve productivity, sugarcane production should, where possible, facilitate a shift towards increasing mechanized harvesting. This can be accomplished by providing the efficient services of well-trained staff. Sufficient funding should be allocated to the industry, in order to achieve and adopt the new system changes and improvements.

3.4.2 Industry solutions

One of the important keys for securing the sugar industry in the Sudan is the creation of a rehabilitation program for the mills. Depreciation has influenced the performance of the majority of the mills in Sudan since the start of the sugar industry, over fifty years ago. These solutions will include the progressive replacement of mill parts (i.e. speed reducers) by using the correct spare parts. The procedure will ensure the increased efficiency of sugar extraction and it will minimize the mud problem that comes with mechanically-harvested sugarcane.

This will require the sufficient and timely provision of production inputs, which must be aligned with the requirements of the productive season.

3.4.3 An enhanced working environment

Workers need their surrounding environment to be comfortable in order to improve their capacity, and hence, their productivity. This will require the relocation of some workshops to outside of the industrial contamination zone, by moving the workers away from the noise and pollutants, such as organic particles and bagasse ash. The introduction of air-cooling units will positively promote the performance of the labourers. The average salary of the majority of the workers was found to be between 50 to 80 US dollars, which is very low. Privileges should be provided for the employees, in order to encourage them. This will positively prevent the manpower in the mills from decreasing, especially during the cane-crushing season.

3.4.4 Developing agricultural machinery

It is important for the sugar industry to be provided with all the necessary machinery and equipment and to keep it all functioning properly. The policy of replacing machinery with the updated ones every year should be adopted. The aim is to purchase new equipment by spending about the same amount of cost annually. This helps to finance the machinery purchases with the minimum amount of money every year. Thus, the approach would ensure keeping the advance and reliable implements to accomplish the required tasks efficiently. The provision of sufficient and original spare parts is also required. A plan must be developed for their replacement, depending on their operating age, which will also help to maintain the performance of the machinery. This could be achieved by creating a database for the implements (i.e. their age, the number of working hours for each machine and its maintenance records). This will ensure better management and the ability to predict depreciation; hence, the right decisions regarding their replacement will be made. Choosing highly-skilled mechanics and operators for every machine is an essential element that should be considered.

3.4.5 Recommendations

The study recommends that major reforms of the different aspects (i.e. agricultural packaging, modern technologies, sugarcane transportation and a reduction of down-time) should be implemented. A work-plan has been strategically designed to be accomplished within the suggested time-frame of ten years. It is recommended that the various arms of the sugar industry in Sudan should apply the framework that is set out in this paper, in order to increase sugar productivity. The authorities should collaboratively commit to carrying out the required objectives of all parts of the work-plan, which has been strategically designed to be accomplished within the time-frame.

Table 3.3 Summary of the influential factors and the potential best practices for sustainable solutions

Factor	Sub-factors	Best practices for development
Methods	The inadequate application of agricultural inputs	Work on providing the agricultural inputs before the beginning of the sugarcane cultivation season.
	The frequent failure of irrigation water pumps	Commitment to a scheduled maintenance program.
	The insufficient replacement of equipment and a rehabilitation program	Set a reliable database of all factory parts and the history of the machines to facilitate the replacement process.
	Ignorance concerning the sugarcane fallow system in the field	Research on the effects of the fallow system on sugarcane productivity.
	Frequent factory stoppages due to no sugarcane being fed	Increase the sugarcane productivity per unit area, double the capacity of the trucks and improve the routes from the field to the industry.
	Field droughts	Proper maintenance by using the original spare parts for the irrigation pumps. Continuous restoration to the canals and ditches by skilled labourers, as well as providing substitute pumps

		to replace those that break down during the season.
Measurement	Improper land preparation	Involve a laser system for land-levelling.
Manpower	Lack of training programs	Consolidation of the training courses.
	Lack of labour	Increase the privileges of the jobs.
	Insufficient salaries	Increase the salaries.
Environment	Poor working environment	Create a healthy workplace environment for the labourers.
Machines	Machinery failure	Import durable brands of machinery and develop a plan of replacement, according to their operating ages. Choose highly-skilled operators for every machine.
	Poor maintenance	Provide adequate and sufficient original spare parts.
	Low machinery efficiency	Develop a plan for a maintenance program and commitment to a pre-set substitution program.
Materials	Increased mud with the harvested sugarcane	Cultivate the sugarcane on an even terrain, in order to maintain a steady sugarcane harvesting height and to avoid lifting portions of soil.
	The lack of production inputs	Provide the production inputs in sufficient quantities.
	Increased fiber% sugarcane	Apply the flowering inhibitors professionally in the cultivation stage and program the field for sugarcane harvesting at the optimum age (12 months).
	The decreased sugar extraction rate	Ensure that mud is not loaded with the harvested sugarcane from the field.
	The lack of funding	Allocate a sufficient percentage of the profits to finance the plant's needs, instead of supplying them all to the state treasury.
	The depreciation of the mills	Develop an annual evaluation program for all parts of the plant machinery, including their rehabilitation and replacement.

3.5 Conclusion

The low sugarcane yield is the main contributor to the declining production of sugar in Sudan. This fluctuation is due to the lack of production inputs, the insufficient provision and replacement of implements and rehabilitation programs, as well as improper land-levelling. The disruption of the fallow sequence, the cultivation of one sugarcane variety, as well as the saline soil may have also contributed to the problem. Although the sugarcane quality in Sudan is almost the same, there are only a few differences in the soil and agro-climate of areas in which the farms are located. However, continuous water shortages during the sugarcane production stage have caused a serious decline in the quality of sugarcane. Sugarcane that is harvested at a non-optimal age negatively increases the fiber percentage and decreases the sucrose percentage. The depreciation of the mills, worn-out equipment and the failure to carry out regular repairs have decreased the performance of the mills. Moreover, impurities have influenced the efficient extraction of sugar. A framework has been created to support the attempts of the decision-makers to improve the productivity of the Sudanese sugar industry. The ten-year work-plan has been set to carry out major reforms, such as the optimization of agricultural package applications and the use of modern technologies. Reducing the down-time during the crushing season is one of the key elements for increasing the efficiency of the factories.

The next chapter will deal with environmental issues, which is essential in the sugar production sector. The chapter evaluates the current management practices of sugar industry waste and assesses its associated environmental impact on the health of the communities, especially those residing in the vicinity of the factories.

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4. THE ENVIRONMENTAL IMPACT OF SUGAR INDUSTRY WASTE IN SUDAN

This chapter is based on the following paper:

Ibrahim, TS and Workneh, TS. 2020. The environmental impact of sugar industry waste in Sudan. *Journal of Environmental Health, Science and Engineering* **[Manuscript submitted]**

Abstract

The purpose of this study was to investigate the impact of Sudanese sugar manufacture waste on the communities surrounding the factories. The study employed a cross-sectional survey approach comprising of 311 (82.5%) of the total 377 respondents living in the vicinity of the factories. The data were analysed by using the Statistical Package for Social Science (SPSS) Version 19. The descriptive statistics (i.e. the percentages, means, standard deviations and standard errors), non-parametric statistics (i.e. the Mann-Whitney test) and logistic regression (i.e. multinomial) were employed. The results showed that the wastewater discharge had a significant ($P < 0.05$) effect on the health of the communities. The multinomial logistic regression model showed that the wastewater creates an off-odor and encourages the breeding of mosquitoes, which has a significant ($P < 0.05$) influence on the creation of a health risk (i.e. malaria) for the people residing in the vicinity of the sugar factories. The study also revealed that the lack of wastewater management in the sugar industry has had a significant influence on crop and animal production. The suspended particles, as well as the bagasse fly, were found to cause a significantly ($P < 0.05$) high rate of eye and respiratory diseases in the region. Therefore, the study recommended that major reforms are required to improve the waste management strategies in the sugar industry and to positively protect the community from the environmental impacts. This study, therefore, designed a framework for enhancing the handling of industrial waste, which can be adopted by the decision-makers in the Sudanese sugar industry.

Keywords: environmental impact, health risks, pollutants, sugar industry, Sudan, wastewater, framework, community, questionnaire, decision-makers

4.1 Introduction

The environment is one of the main elements contributing to the health of individuals and communities. The problem of pollution is considered to be far from satisfactory, especially in developing countries (Sahu, 2015). With the increase in rain-fed and irrigated agriculture, urbanization and industrialization in Sudan, pollution is rapidly increasing (Alim, 2012; Pierre *et al*., 2016). However, the institutional and legislative frameworks are very limited and the pollution control measures need to be more effective. There is lack of knowledge with regards to waste management practices in the country (Robert, 2011). Environmental management strategies were non-existent in the industry management structure before the year 2000. The major challenges need to be identified and an impact assessment needs to be undertaken to improve the operation of the older, government-managed sugar factories (Alim, 2012). The sugar industry is one of the largest sources of industrial effluent and it generates a considerable amount of wastewater, including pollutants, in the form of solids and gases (Sahu, 2015; 2018). The sugar industry in Sudan discharges untreated wastewater containing pollutants that poison the watercourses (Alim, 2012; Anail, *et al.*, 2013). The volume of the discharged effluent varies from one factory to another, depending on its sugarcane-crushing capacity (Sahu, 2015). The estimated daily discharge of wastewater for all the sugar factories in Sudan is about 150 000 m^3. A small proportion of this wastewater is used for crop irrigation, but its impact on the health of the communities is uncertain (Aisha, 2007). A reasonable amount of waste, such as filter cakes and vinasse, also results from the manufacture of sugar (Oboody, 2016), and these pollutants have a harmful effect on humans and the surrounding ecosystem (Oboody, 2016; Sahu 2018); for example, the wastewater that is discharged into open fields has an impact on the environment and the communities residing in the vicinity of the industries. Contamination, such as acidification and the heating of the river water, could also cause a health risk (Günter *et al.*, 2007). This issue needs to be solved in Sudan. The environmental aspects must therefore be analysed by identifying the impact of this effluent on the communities that live in the vicinity of selected sugar factories.

Bagasse is one of the waste products of the sugar industry and it is used for producing steam for cogenerate power in the boilers of the factories (Sahu, 2018). It is combusted during the sugar manufacturing process and produces ash, which influences human health (Mohamed and Samah, 2011; le Blond *et al.*, 2017). Roughly 11 284 tonne of residual ash is produced annually in the Sudanese sugar factories (Cordiero *et al*., 2004). The impact of such pollutants needs to be studied and solutions need to be found; however, the authorities are concerned about the high cost of waste treatment (Oboody, 2016). There is a lack of sufficient data on waste treatment and its impact on the communities residing around these sugar factories, which makes it very difficult to identify the adverse effects of the waste and then to find the proper solutions (Abid, 2008).

Moreover, the sugar industry produces a large amount of different gases , for example carbon (Sahu, 2015; 2018), which influence the health of animals, plants and humans, while dust storms are produced during sugarcane harvesting, which influence the communities residing near the factories (El Chami *et al*., 2020). The sugar factories are also a source of noise, due to the various operations and heavy machinery used during the production process (Abid, 2008). From an environmental perspective, the industry is facing problems related to pollutants because of mismanagement and industrial standardization (Sahu, 2018). However, no clear method has thus far examined the adverse effects of sugar manufacturing pollutants on the communities living in the vicinity of the selected sugar factories in Sudan. Therefore, it is necessary to study their impact on the environment and on these communities.

The waste management strategies of various countries are significantly different, which is why achieving certain objectives remains an important issue. A well-designed framework will steer managers to address the waste issue in a cost-effective and timely manner, and it will encourage the enhancement of existing plans, or assist in the design of new ones (Davidson, 2011). Different techniques have been developed to address the waste problem, such as the Integrated Waste Management (IWM) method, which combines different methods, technologies and management strategies. A systems analysis provides useful information for defining, evaluating and adapting waste management systems (Pires *et al*., 2010). The sugar waste could also be used as source of energy and as a raw material for environmentally-friendly products (Evgeniya *et al*., 2017). The aim of this study is to evaluate the impact of waste on the environment and on the communities surrounding the selected industries in Sudan. The study also aims to create a framework for the integral handling of industrial waste, in order to spur decision-makers on towards enhancing the environment of the sugar industry in Sudan.

4.2 Data Collection

This study uses the cross-sectional survey approach to conduct self-administered and semi-structured questionnaires (Mengistu *et al.,* 2016). A questionnaire containing close-ended questions was developed and pre-tested by experts, to avoid ambiguity and to refine the categories. Pre-testing was done by questioning about five to 10 of the non-targeted respondents. The questions were structured in a way that they allowed and considered very detailed insights, for example, the different types of pollutants and their impact on the surrounding environment and the degree of satisfaction to the health services presented to the communities living in the vicinity of the selected factories (Hind, 2015). The effects of the factory interventions on the incomes and lifestyle of the people was also considered. Appendix A summarizes samples of the survey questions in the questionnaire. The interviews were carried out from January 2017 to March 2017. The questions used a three-point Likert Scale, namely, 'Agree', 'Disagree' and 'Neutral'. The reason for choosing only three-points was because of simplicity of the majority of the people living in the vicinity of the industries. The researcher understood that the answers to the questions should be set in the easiest way for the respondents, which has enabled the researcher to collect clear-cut information from the respondents. The degree of complaints was set to four levels (i.e. No complaints, Low, Medium and High) to measure the effect of the stated pollutants on the surrounding communities. The targeted population were the families who live in the campuses and villages close to the selected factories. The sample of this study comprised of 377 respondents (families) from the selected residential areas, who were randomly selected by using the lottery method. The number of samples was determined by using Equation (4.1), as shown below (Taro, 1967). The questionnaire was divided into nine main questions.

$$n = \frac{N}{1+N(e)^2} \tag{4.1}$$

Where: n = sample size, N = population size, e = 0.5, 0.3, 0.7

4.2.1 Sampling techniques

The random sample technique was used for this study and the sample unit was the respondent's family, so as to be more representative (Mengistua *et al.*, 2016). Questionnaires were distributed randomly to the families who live within a radius of 20 kilometers of the selected factories. There were three targeted locations around each factory, and the questionnaires covered about 21 respondents for each location. The questionnaire was to be filled in by all the family members. The main reason for selecting respondents in the vicinity of the factories was to allow very detailed insights and to acquire clear-cut information about the issues that were raised in the questionnaire.

4.3 Data Analysis

The Statistical Package for Social Science (SPSS) was used to analyze the data obtained from the questionnaires. SPSS 19 is a well-known computer software programme that supports the statistical analysis of survey data. The descriptive statistics included the percentages, means, standard deviations and standard errors. The non-parametric statistics encompassed the Mann-Whitney test and the chi-square test, which were used to compare the mean values of the variables and to identify the significant differences. For example, the diseases caused by the pollutants were identified and the relationships between the other parameters were found by using the correlation coefficient test. Furthermore, multinomial logistic regression was employed to identify the important factors influencing the surrounding environment. Multinomial logistic regression is a probability estimation model that is used when the dependent variable has more than two categories (i.e. Agree, Disagree and Neutral) and the independent variable is categorical or continuous (John *et al.*, 2017). Table 4.1 shows the dependent and independent variables that are associated with influencing the environment, as well as their definitions. The output was discussed and further interpretations are reached in the Results and Discussion section.

If Y is the dependent variable, it can take values of either 1, 2 or 3.
Yi = 1 if the respondent (i) agrees with a certain question
Yi = 2 if the respondent (i) disagrees with a certain question
Yi = 3 if the respondent (i) has a neutral reaction to a certain question

Hence, the multinomial logistic regression model for estimating the influence of wastewater on the community health is as follows:

$$ln\left[\frac{\rho_h}{\rho_j}\right] = \beta_{0h} + \beta_{1h}x_1 + \beta_{2h}x_2 + \cdots + \beta_{kh}x_k \qquad (4.2)$$

Where:
ln = the log of the odd ratio

P = the probability of community health effect

j = the number of categories (3)

h = 1 to j -1

β = a constant

β_1, β_2 and β_k = the estimated parameters corresponding to each predictor

X_1, X_2 and X_k = the explanatory variables (predictors)

k = the number of predictors

To compare the probability of one of the categories, the odd ratios are all compared to the reference outcome, by using the following equations:

$$ln\left[\frac{\rho_1}{\rho_3}\right] = \beta_{01} + \beta_{11}x_1 + \beta_{21}x_2 + \cdots + \beta_{k1}x_k \quad (4.3)$$

$$ln\left[\frac{\rho_2}{\rho_3}\right] = \beta_{02} + \beta_{12}x_1 + \beta_{22}x_2 + \cdots + \beta_{k2}x_k \quad (4.4)$$

Equation 4.3 represents the probability of respondents who agree (P_1) compared with those who are neutral (P_3) to the issue of health risks caused by wastewater. Equation 4.4 illustrates the probability of respondents who disagree (P_2) compared with those who are neutral (P_3) (Grace-Martin, 2018).

Table 4.1 Variables influencing the environment of the Sudanese sugar factories and their description

Variable	Description	Type
Wastewater creates off-odor	Agree = 1, Disagree = 2 and Neutral = 3	Nominal
Wastewater creates mosquitoes		
Wastewater mixes with the water source		
*People's health (i.e. malaria)		
Particulates contaminate the air		
Particulates pollute the floors and clothes		
Lack of visibility due to smoke		

clouds		
*Health risks to human	Stomach ache = 1, Vomiting = 2, Diarrhoea = 3 and Other = 4	Nominal
*The infection (eye disease, heart attack, respiratory disease, asthma, chronic bronchitis and irregular heartbeat)	Yes = 1 and No = 2	Ordinal (Binary)
*Disease cases among the animals		
*Death cases among the animals		
*Risk to crops		
*People complain	High = 1, Medium = 2, Low = 3 and No complain = 4	Ordinal

* = Dependent variable

4.4 Effect of Wastewater on People Residing in the Vicinity of the Factories

The descriptive statistics of the variables associated with the effects of wastewater on the surrounding community are displayed in Table 4.1. It was found that wastewater had a statistically significant ($P < 0.05$) effect on the mean differences in the creation of an off-odor and mosquitoes, as well as mixing with the water sources and causing health risks (i.e. malaria). Figure 4.1 shows that the wastewater creates a suitable environment for the reproduction of parasites in one of the selected sugar industries. The non-parametric statistics showed that the creation of parasites and an off-odor by wastewater, significantly influenced human health ($P < 0.01$), while the wastewater was significantly ($P < 0.05$) responsible for contaminating the water sources that were used for drinking purposes. In a study conducted in the Assalaya area, water-related diseases (i.e. vomiting, diarrhoea and allergies) were observed among the people who used the surplus irrigation canals that contained factory effluent (Ahmed *et al.,* 2017). This may have been due to a lack of health awareness among the villagers near the sugar industries. It might also be because most of the sugar industries in the country are located near the Nile River, which increases the chance of water-source contamination. Figure 4.2 shows the wastewater being released into open drains in one of the selected sugar factories. This was in agreement with the findings of Hind (2015), who concluded that the simple and undeveloped lifestyle of the communities living near the factories may have endangered their health. It also concurred with the conclusions of Elhag (2010), who indicated that a lack of awareness of the impact of pollution is one of the problems facing the Sudanese sugar industry.

Moreover, the complaints of the respondents were found to have a significant ($P < 0.05$) effect on the mean differences of the off-odor, mosquitoes and health risks caused by the wastewater, as shown in Table 4.2. The health of the surrounding communities may have been affected by the pollutants. The main reason for this may be the inadequate treatment of industrial effluent in the sugar industry. This result concurs with the conclusions of Mohamed *et al.* (2017), Alnail *et al.* (2013) and Pradeep and Omprakash (2017), which indicated that the pollution of waterbodies was due to the disposal of waste by the sugar industry when it was discharged without being treated, and which had an influence the water quality and the ecological system. Oboody (2016) and Alnail *et al.* (2013) also observed the creation of insects, parasites and off-odors caused by the stagnancy of the sugar industrial wastewater. Therefore, the authorities in the country should find an effective means of treating wastewater in the sugar industry.

4.5 Impact of Wastewater on Animal Production

One-hundred-and-forty-three respondents (43%) were involved in activities like animal and crop production. Their water sources were the sugarcane irrigation drainage canals, the wastewater streams, the Nile River, water tanks, wells, lakes and sugarcane irrigation canals. Wastewater was used by 3.1% of the respondents, compared to other available water sources. The water sources were found to have statistically significant ($P < 0.05$) mean differences in animal production. Symptoms of sickness were observed in some animals, while cases of animal deaths were found by 90 (30%) of the 205 respondents, as shown in Table 4.1. In a study conducted in Pakistan, animals suffered different diseases and, in some cases, deaths were recorded due to the consumption of sugar industry effluent that was discharged into the drains near the villages (Qureshi *et al.*, 2015). The descriptive statistics revealed that the wastewater caused significant ($P < 0.05$) mean differences in animal production. The non-parametric statistics showed that wastewater had a significant ($P < 0.05$) effect on animal health, when compared with other water sources (i.e. sugarcane irrigation canals), while the chemicals in the wastewater may also have caused a health risk to animals. These results concur with those of other researchers who have analyzed the wastewater from the sugar industry, both locally and globally, and found that the Chemical Oxygen Demand (COD) was extremely high, resulting in the contamination of the water (Reddy *et al*., 2014; Awasare *et al.*, 2015; Oboody, 2016; Asmah, 2017). These results are in agreement with the findings of Mohamed *et al.* (2017), who concluded that the wastewater from the Assalaya sugar factory caused a threat to the agricultural environment and the animals.

4.6 Impact of Wastewater on Crop Production

Crops like vegetables, cereals and fruits, were planted on small-scale farms (0.4 ha). Vegetables were the main cultivated crop (69%), compared to 28% and 3% that were under cereals and fruit trees, respectively. Figure 4.3 illustrates some crops that are produced by using the wastewater from the Kenana sugar industry. Of the total of 177 respondents, 44 (25%) used wastewater without pretreatment for crop irrigation, whereas 133 (75%) used sedimentation pans. Wastewater pre-treatment (i.e. sedimentation pans) was found to have a statistically significant ($P < 0.01$) effect on the mean differences in crop production. However, the non-parametric statistics revealed that there was an insignificant difference ($P > 0.05$) in the effect of using pre-treated wastewater for crop irrigation on human health, compared to using non-treated wastewater. One of the many reasons for the utilization of wastewater for crop irrigation is the proximity of the streams to the fields, and secondly, it might also be due to the unavailability of an alternative water source for irrigation. This finding concurs with the findings of Saranraj and Stella (2014), who concluded that sugar mill effluent was used for plant irrigation in India because there was a lack of other water sources. Although there is consensus that wastewater is enriched with nutrient elements, the present findings showed that the health risks were not considered by producers, even though the wastewater had significant ($P < 0.05$) mean differences in causing a risk to the crops. It was found that the consumption of vegetables irrigated with untreated wastewater significantly ($P < 0.01$) increased the susceptibility of infections and diseases (i.e. stomach aches and diarrhoea). Aisha (2007) concluded that there was uncertainty about the consumption of healthy crops irrigated with effluent from the sugar industry. However, Kumar (2014) found that such effluent can be used for crop irrigation, under very strict conditions, if appropriate dilution takes place. A risk may be caused by the accumulated chemicals, such as heavy metals, which will influence human health. This is in agreement with the findings of researchers like Kumar (2014), Reddy *et al.* (2014), Sahu (2015) and Alnail *et al.* (2013), which indicated that untreated sugar industry effluent contained a significant proportion of chemicals that contaminate the land, water, crops and the air, and may negatively influence the quality of water used for drinking and irrigation purposes. Another study conducted in India found that the long-term usage of contaminated sugarcane irrigated with industrial effluents in rural areas results in a health risk for humans (Bhawna *et al.,* 2016).

Table 4.2 Descriptive statistics of the variables illustrating the environmental impact of sugar industry waste

Variables	N	Agree (%)	Disagree (%)	Neutral (%)		Mean	S.D.	S.E.	Sig.
Wastewater creates off-odor	311	196 (63)	87 (28)	28 (9)		1.43	.628	.036	.000
Wastewater creates mosquitoes	311	209 (67.2)	77 (24.8)	25 (8)		1.40	.608	.035	.000
Wastewater contaminates water	311	121 (38.9)	160 (51.4)	30 (9.6)		1.44	.634	.036	.000
*People's health (malaria)	311	206 (66.2)	70 (22.5)	35 (11.3)		1.45	.689	.039	.000
Particulates contaminate the air	305	260 (83.6)	34 (10.9)	11 (3.5)		1.18	.47	.027	.000
Particulates dirty the floors and clothes	305	278 (89.4)	21 (6.8)	6 (1.9)		1.11	.369	.021	.000
Lack of visibility due to smoke clouds	305	236 (75.9)	49 (15.8)	20 (6.4)		1.29	.582	.033	.000
Loud-sounds	305	204 (65.6)	70 (22.5)	31 (10)		1.43	.671	.038	.000
	N	Stomach ache (%)	Vomiting (%)	Diarrhea (%)	Other (%)	Mean	S.D.	S.E.	Sig.
*Health risks to humans	108	38 (12.2)	3 (1)	54 (17.4)	13 (4.2)	2.39	1.09	.105	.000

* Infection:	N	Male (%)		Female (%)		Mean	S.D.	S.E.	Sig.
Eye diseases	125	82 (26.4)		43 (13.8)		1.34	.477	.043	.000
Heart attacks	10	6 (1.9)		4 (1.3)		1.40	.516	.163	.527
Respiratory diseases	62	40 (12.9)		22 (7.1)		1.35	.482	.061	.022
Asthma	40	30 (9.6)		10 (3.2)		1.25	.439	.069	.002
Chronic bronchitis	65	42 (13.5)		23 (7.4)		1.35	.482	.060	.018
Irregular heartbeat	18	13 (4.2)		5 (1.6)		1.28	.461	.109	.059
	N	Yes (%)		No (%)		Mean	S.D.	S.E.	Sig.
*Diseases to animals	204	90 (28.9)		114 (36.7)		1.56	.498	.035	.093
* Animal deaths	205	94 (30.2)		111 (35.7)		1.54	.499	.035	.235
*Risk to crop	206	124 (39.9)		82 (26.4)		1.40	.491	.034	.003
Variables	N	High (%)	Medium (%)	Low (%)	No (%)	Mean	S. D.	S.E.	Sig.
Off-odor	309	137 (44.1)	60 (19.3)	42 (13.5)	70 (22.5)	2.15	1.212	.069	.000
Mosquitoes	309	194 (62.4)	61 (19.6)	36 (11.6)	18 (5.8)	1.61	.908	.052	.000
Flies	309	148 (47.6)	83 (26.7)	48 (15.4)	30 (9.6)	1.87	1.005	.057	.000
Sugarcane-burning particles	309	193 (62.1)	74 (23.8)	29 (9.3)	13 (4.2)	1.55	.830	.047	.000
Bagasse particles	309	155	67	46	41	1.91	1.085	.062	.000

	(49.8)	(21.5)	(14.8)	(13.2)

* Dependent variables

Figure 4.1 Wastewater creates parasites in the sugar industry

Figure 4.2 Wastewater released into open fields in the sugar industry

Figure 4.3 Crop and animal production influenced by wastewater in the sugar industry

4.7 Impact of Pollutants on the Communities surrounding the Factories

The processing operation of the sugar industry in Sudan has been found to release huge quantities of pollutants (i.e. organic particles, noise and smoke clouds). According to the respondents' perceptions, people suffer from the massive spread of organic pollutants and particles (Figure 4.4). The descriptive statistics have shown that the pollutants significantly ($P < 0.01$) contaminate the air and pollute the clothes and floors of the communities living in the vicinity of the sugar factories. The non-parametric statistics revealed that the respondents suffered significantly ($P < 0.05$) from the suspended particles that resulted from sugarcane- and bagasse-burning. This could be because no anti-pollution measures are taken by the sugar industry sector in the country. However, the study was limited to the agricultural engineering aspects, this categorical statement needs to be supported by diagnostic medical data. Figures 4.6 and 4.7 show the smoke and ash resulting from burnt bagasse and filter cake in the dumping area of one of the factories, which is emitted and could drift into the air. It was reported by TIFAC (2019) that the installation of air pollution control equipment would help to prevent pollutants (i.e. ash) from fully escaping into the atmosphere through the chimneys. Table 4.1 also shows that loud sounds, due to the operations taking place during the sugar-processing season, significantly ($P < 0.05$) influence the people living in the nearby villages.

This might be due to their proximity of the factories (i.e. a distance of one kilometer, on average). Moreover, it was observed that large amounts of pollutants were released from the chimneys of sugar factories. The non-parametric statistics showed that the depreciation of the sugar factories in Sudan, as well as the old-fashioned approaches that are practiced, significantly ($P < 0.01$) increased the off-odors and parasites (i.e. mosquitoes and flies). This concurs with the findings of engineers Yosuf (2017) and Yassir (2017), who stated that the publicly-owned factories in the country had depreciated and that the technology had not been updated, which may have an effect on the surrounding environment. This was in agreement with a report by the TIFAC (2019), which stated that there was a reduction in visibility in the areas surrounding the sugar mills because of the massive release of pollutants into the air. The present findings indicated that there are aspects (i.e. noise pollution) that influence the communities in the areas surrounding the factories. Although the effects of pollutants resulting from sugar manufacture are inevitable, Wada *et al.* (2017) stated that they can be minimized. For instance, villages should be kept far away from the industrial areas, and the authorities should embark in a rehabilitation program to improve the performance of industrial chimneys, so as to reduce the effects of the emissions.

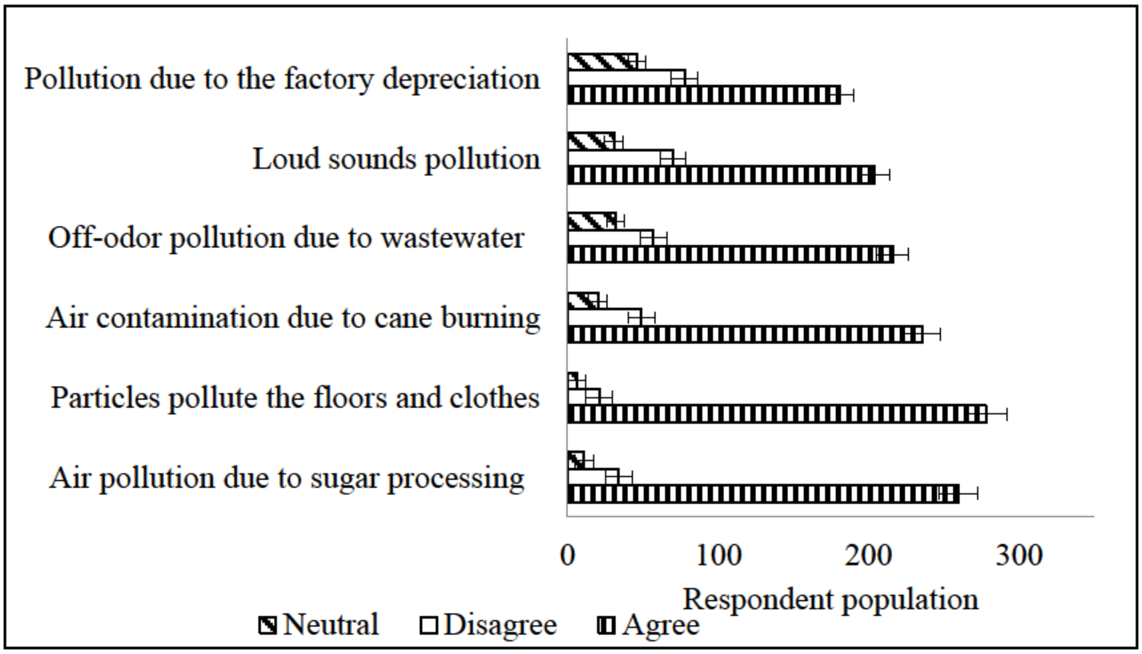

Figure 4.4 People suffering from pollutants in the environment

4.8 Health Risks of Pollutants on the Communities living in the Vicinity of the Factories

The responses to questions about their health were relatively low, compared to the total targeted population. Out of a total of 311 respondents, only 151 (48%) answered the questions relating to health issues. This might, firstly, be due to the sensitivity of the issue and to this particular society wanting to avoid conflict with the authorities. Secondly, it might be due to a lack of the health awareness among the communities living in the vicinity of the factories. This concurs with the findings of Hind (2015), who highlighted the simplicity of the community living near the Kenana factory, which might have made the people reluctant to respond to questions dealing with both environmental and health issues. Nevertheless, the authorities should take effective measures to deal with this issue in a transparent manner, in order to develop a viable solution for mitigating the health risks that may be caused by industrial pollutants.

The pollutants caused diseases, such as eye allergies and infections, chronic bronchitis, respiratory infections, asthma, an irregular heartbeat and heart attacks for 125 (82.7%), 65 (43%), 62 (41%), 40 (26.5%), 18 (12%) and 10 (6.6%) of the respondents, respectively (Figure 4.5). Eye diseases (i.e. allergies and infections) were found to have a highly significant ($P < 0.01$) mean difference on the health of the community. Table 4.1 also shows that respiratory diseases (i.e. asthma and chronic bronchitis) were significantly ($P < 0.05$) widespread among the residents. Paula *et al.* (2017) found that people who resided close to the sugarcane-burning areas in Brazil were significantly susceptible to cardiovascular morbidity. The study estimated that the effect of exposure to air pollutants on people with cardiovascular disease was evidence of the health risks caused by sugar manufacturing pollutants. The present findings have revealed that the impact of the sugar manufacturing pollutants on human health can cause a wide range of diseases for those living in the vicinity of these factories. However, a diagnostic medical data is needed to support these study findings. Qureshi (2015) reported that the waste discharged by sugar mills in Pakistan was found to cause asthma and various skin diseases, whereas dizziness and physiological effects, such as irritation in the eyes, nose, throat and lungs, were recorded among people living in areas surrounding the sugar mills in India, (TIFAC, 2019).

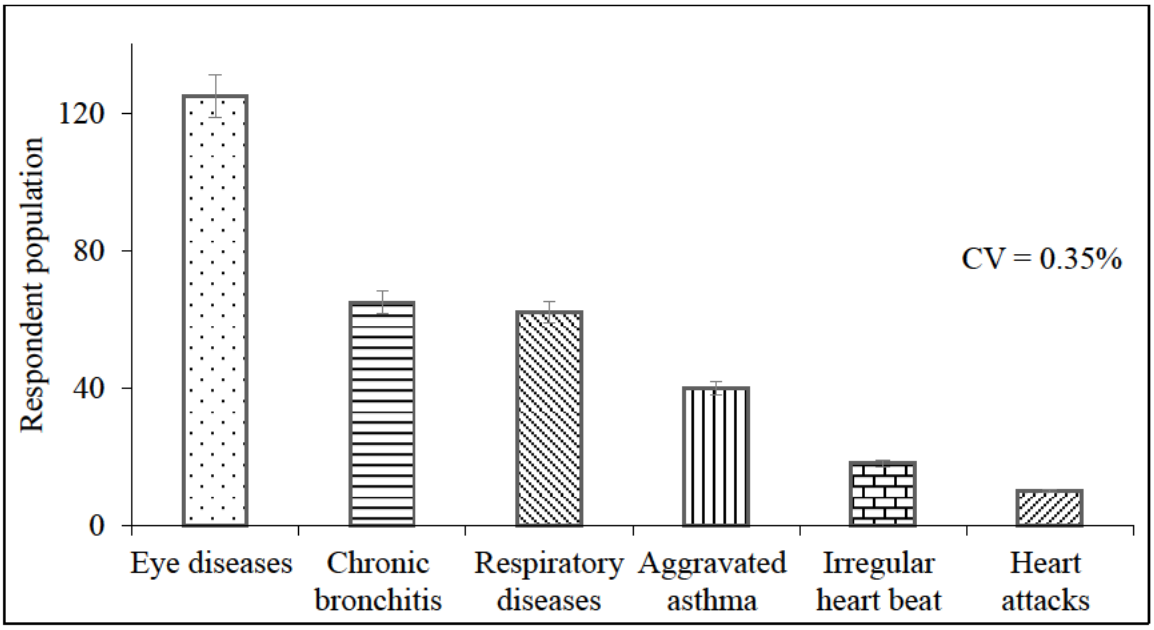

Figure 4.5 Diseases caused by sugar manufacturing waste

Figure 4.6 Emissions from bagasse and filter cake in the sugar industry

Figure 4.7 Bagasse and filter cake ash in the sugar industry

4.9 Industry Participation in the Communities

It was found that the sugar industry in Sudan provides services to its communities (i.e. access to hospitals, medical aid, the availability of qualified staff and scheduled prevention rotations). The hospitals were found to have a statistically significant ($P < 0.05$) mean difference in their closeness to the villages, and the availability of doctors and medical teams in the hospitals significantly ($P < 0.01$) influenced the people's satisfaction. The people were significantly ($P < 0.05$) satisfied with the regular prevention work (i.e. the spraying of pesticides against parasites) (Figure 4.8). In a South African study, some cases of medical shortages were found in hospitals in the vicinity of the communities, and there was dissatisfaction with the health services, due to shortage of doctors and the necessary medical equipment (Takalani, 2013). This may be due to the people not having a scientific background on what constitutes a healthy environment. It could also be because the authorities are ignorant about the issues of community health and their surrounding environment. The survey results showed that there was no centre for monitoring the effects of sugar manufacturing waste on human health. This concurs with a study by Elhag (2010) on the Halfa sugar factory, which concluded that the sugar industry authorities were unaware of the impact of waste products on both the environment and on human health.

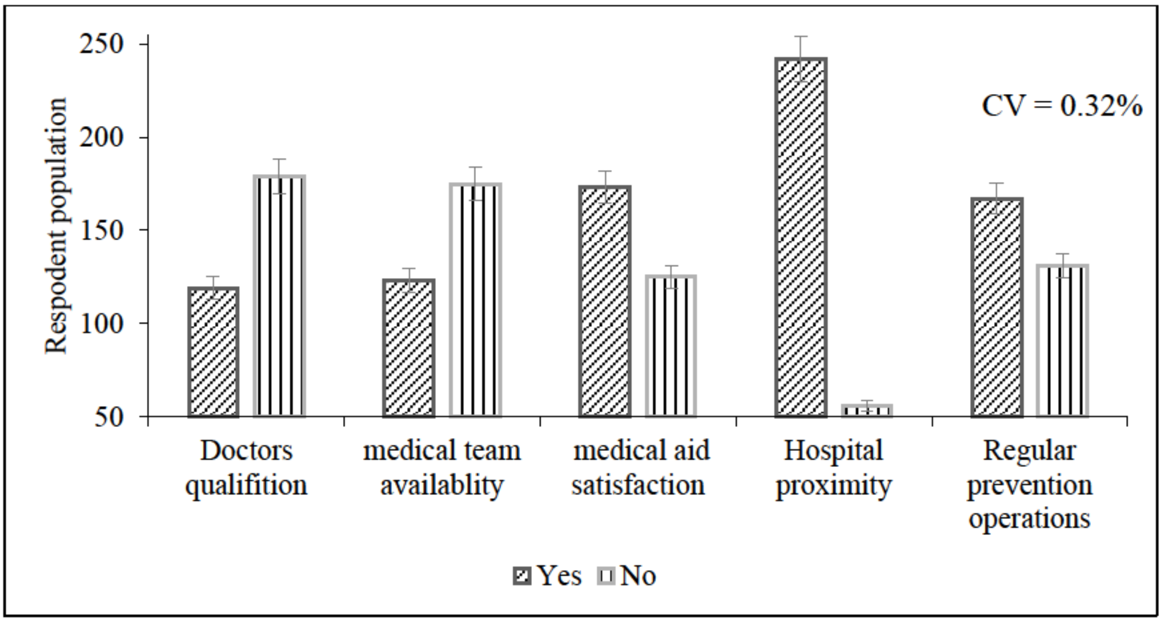

Figure 4.8 Satisfaction of the population with health services.

4.10 Issues that should be taken into Consideration

It was revealed that there were serious issues threatening both the environment and the health of the communities surrounding the selected factories. Out of 300 respondents, the majority 268 (89%) agreed that the management was inefficient and that the communities were not protected against the sugar industry waste. The people's responses were found to have significant ($P < 0.01$) mean differences regarding the importance of protecting the community from the effluents, improving the air and water quality, as well as enhancing the waste management and the surrounding environment (Figure 4.9). This may be due to the fact that the same old-fashioned practices have been followed since the inception of the majority of the Sudanese sugar factories. The conventional approach of sugar producers in Sudan seems to be to focus on the economic benefits, rather than on the environmental impacts. In a study conducted by Elhag (2010), it was concluded that the sugar industry in Sudan was facing environmental problems due to its old practices. However, the authorities within the sugar industry should undertake effective strategies to decrease the environmental impact on the surrounding communities. Günter *et al.* (2007) reported that sugar factories in Brazil are obliged to use waste-reducing technologies and water recycling plants to protect the environment and the water sources.

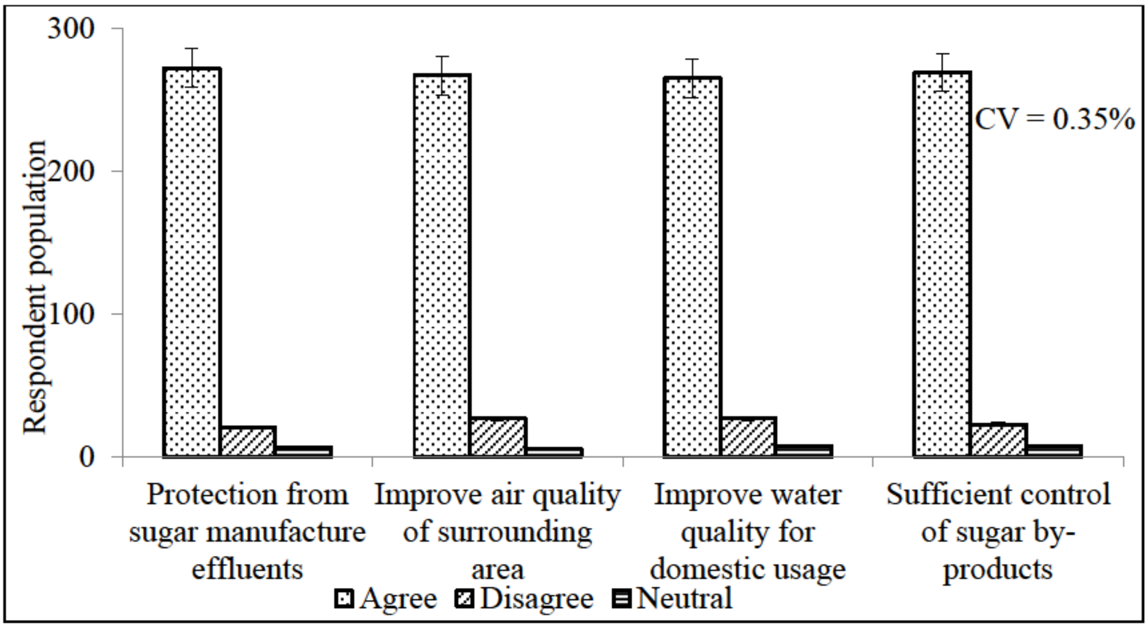

Figure 4.9 Response to the important issues that should be considered

4.11 Factors Influencing the Health of the Communities

The multinomial logistic regression model was used to identify the main factors influencing community health (i.e. malaria). The results of the analysis showed that the model fitted well with the observed data set. A statistically significant improvement in the fit of the model was found, where chi-square = 247.12, df = 32 and $p < 0.001$. The Pseudo R-Square (i.e. Cox and Snell R-squared, Nagelkerke R-squared and McFadden R-square) values were 0.55, 0.66 and 0.46, respectively, which merely mimicked the R-squared value in the linear regression (Pallant, 2011). The value of the McFadden R-Square, which is often reported in research, was 0.46, which indicated a good fit of the data and supported the quality of the model.

Eight independent variables were included in the multinomial logistic regression test, in order to define their effect on people's health. Wastewater that created an off-odor, as well as the breeding of mosquitoes, significantly ($P < 0.05$) influenced the health of people residing in the vicinity of the sugar factories by causing diseases, such as malaria. The distance of wastewater streams from the villages, the flow season, the mixing of waste with the water source, water source contamination, the creation of swamps and the breeding of flies, were found to be statistically insignificant ($P > 0.05$) predictors in Table 4.3. The results revealed that untreated wastewater encourages the creation of off-odors and parasites (i.e. mosquitoes). Hence, it critically influences the surrounding environment and people's health. Many studies have indicated the relationship between the untreated wastewater of the sugar industry and the breeding of parasites (i.e. mosquitoes), which cause various diseases (Mohamed *et al.*, 2017; Ahmed *et al*., 2017; Sahu, 2019). Therefore, the industrial wastewater from sugar factories has a major effect on the surrounding community and areas, unless it is treated.

Table 4.3 Multinomial logistic regression model results for the effect of wastewater on community health

I have had malaria several times	Parameter Estimate	Standard Error	Wald	P-Value	Odd Ratio
Wastewater stream is close (Agree = 1)	0.528	1.419	0.139	0.710	1.696
Wastewater flows all year (Agree = 1)	1.033	0.956	1.168	0.280	2.810
Wastewater mixed with the water body (Agree = 1)	1.664	1.036	2.580	0.108	5.280
Wastewater contaminates the waterbody (Agree = 1)	1.118	0.972	1.323	0.250	3.058
Wastewater creates swamps (Agree = 1)	0.085	0.898	0.009	0.925	1.089
Wastewater creates an off-odor (Agree = 1)	0.436	0.869	0.251	0.616	1.546
Wastewater creates flies (Agree = 1)	1.503	0.713	4.449	0.035*	4.495
Wastewater creates mosquitoes (Agree = 1)	2.534	0.813	9.712	0.002**	12.61
Constant	- 3.911	1.603	5.950	0.015	0.021
Wastewater stream is close (Disagree = 2)	- 1.271	1.499	0.719	0.397	0.281
Wastewater flows all year (Disagree = 2)	0.630	1.343	0.220	0.639	1.877
Wastewater mixed with the water body (Disagree = 2)	2.074	1.242	2.790	0.095	7.956
Wastewater contaminates the waterbody (Disagree = 2)	- 0.653	1.226	0.284	0.594	0.520
Wastewater creates swamps (Disagree = 2)	- 0.834	1.114	0.560	0.454	0.434
Wastewater creates an off-odor (Disagree = 2)	1.131	1.150	0.969	0.325	3.100
Wastewater creates flies (Disagree = 2)	0.862	0.986	0.764	0.382	2.367
Wastewater creates mosquitoes (Disagree = 2)	1.094	1.058	1.069	0.301	2.986
Constant	- 2.799	1.677	2.786	0.095	0.061

*and ** Significant at $P < 0.01$ and $P < 0.05$, respectively. -2 log likelihood = 221.351; Chi-square = 247.117 and p = 0.000. Pseudo R-Square (Cox and Snell, Nagelkerke and McFadden) = 0.548, 0.669 and 0.465, respectively.

4.11.1 Wastewater is responsible for flies

Sugar industry wastewater causes the breeding of flies and it was found to have a positive and statistically significant ($P < 0.05$) relationship with the endangerment of community health. The breeding of flies is more likely to influence the health of the people living close to the sugar factories. The fact that more flies are created by the wastewater is more likely to fall under the 'Agree' category than the 'Disagree' or 'Natural' categories. The probability of the respondents agreeing to the issue of health risks appears more likely to increase by a factor of 4.5, as the level of flies increases. This seems to indicate that the wastewater of the sugar industry in Sudan is discharged without being treated, which mediates the reproduction of parasites. This result concurs with the findings of Mohamed *et al*. (2017) and Ahmed *et al.* (2017) on their analyses of the wastewater at the Assalaya sugar factory in Sudan. This result also agrees with the findings of a study conducted in Ethiopia on the treatment of sugar industry wastewater containing ferrous materials (Sahu, 2019). However, further investigation is required to support the positive relation between wastewater and parasites.

4.11.2 Wastewater is responsible for mosquitoes

Wastewater from the sugar industry was a positive predictor and a highly significant ($P < 0.01$) indicator for the breeding of mosquitoes and for influencing the health of the surrounding communities. The probability of the reproduction of mosquitoes in the wastewater was more likely to be supported by the respondents than to fall into the other categories (i.e. 'Disagree' and 'Neutral'). This means that the more wastewater that is created, the more a median of diseases caused by mosquitoes is created, which increases the probability of endangering the health of the surrounding communities by a factor of 12.6. These results revealed that sugar industry wastewater is the main contributor to the breeding of mosquitoes in Sudan. This concurs with a study by Sahu (2019) in which the untreated sugar industry wastewater in Ethiopia was found to be the source of mosquitoes. However, further exploring is needed to prove the positive relationship between wastewater and mosquitos.

4.12 A Prospective Framework for Handling Sugar Manufacturing Waste in Sudan

The communities surrounding the selected sugar factories in Sudan are facing unavoidable danger because of contamination. These contaminants could be minimized to the lowest levels by making a sustained effort to use efficient tools for managing the waste, thus mitigating the environmental impact. This study has therefore designed an integrated framework to conserve the bio-network of the sugar industry in the country. The framework is based on a collaborative effort between the sugar industry and the surrounding communities to improve waste management.

The concept of this framework depends on the industrial ecology, and it focuses on integrating and adapting technologies in order to sustain the improved management of sugar manufacturing waste (Davidson, 2011). This prospective industrial waste handling framework for the selected sugar industries aims to do the following: (1) to maximize the re-use and recycling of sugar industry waste, (2) to support decision-makers in achieving sustainable sugar production, and (3) to achieve zero waste from the Sudanese sugar industry. These goals can be achieved by introducing new technologies which can transform the raw materials of sugar manufacturing waste into ecofriendly products. For instance, the building of wastewater treatment plants, as well as the idea of the green harvesting of sugarcane, will help to minimize the impact of pollution on the people who live in the vicinity of the industry. The existing practices that are used to treat sugar by-products and waste are not environmentally-friendly. The surplus bagasse, filter cake, wastewater and vinasse are improperly managed, and they produce pollutants, such as suspended particles, an off-odor and parasites. The pollutants are a health risk to humans and animals in the surrounding areas (Figure 4.10). It is clear that the authorities within the industry need to collaborate on the environmental aspects and the protection of society, in order to maintain a sustainable bio-network within the sugar industry in Sudan.

The prospective strategy is to target specific by-products and waste and to use them as raw materials for producing ecofriendly products (Figure 4.11). The surplus bagasse could be used to produce paper, the wastewater could be recycled and re-used, and the vinasse and filter cakes could be used to produce fertilizers, such as potassium and phosphate (Prado *et al*., 2013; Nakhla, 2014; Evgeniya *et al.,* 2017). The efficiency of on-site treatment plants could also be increased, by initiating a wastewater recycling program (Oboody, 2016). Moreover, effective bodies must be sustained to work integrally with industrial, social and environmental bodies, to preserve the bionetwork of the sugar industry. Institutions should be created that are responsible for the implementation of extensive environment, pollution and waste management legislation. It is essential to collect information about pollution and waste monitoring, in order to implement pollution-reducing measures. Sharing information is an important element for creating awareness about the effects of waste on human health. This framework is the first of its kind for the Sudanese sugar factories. The strategy aims to steer the decision-makers to reduce the environmental effects of sugar processing waste and pollutants. This will enable them to gain a better understanding of the relationship between pollution, waste management and the healthy lifestyle of the surrounding communities.

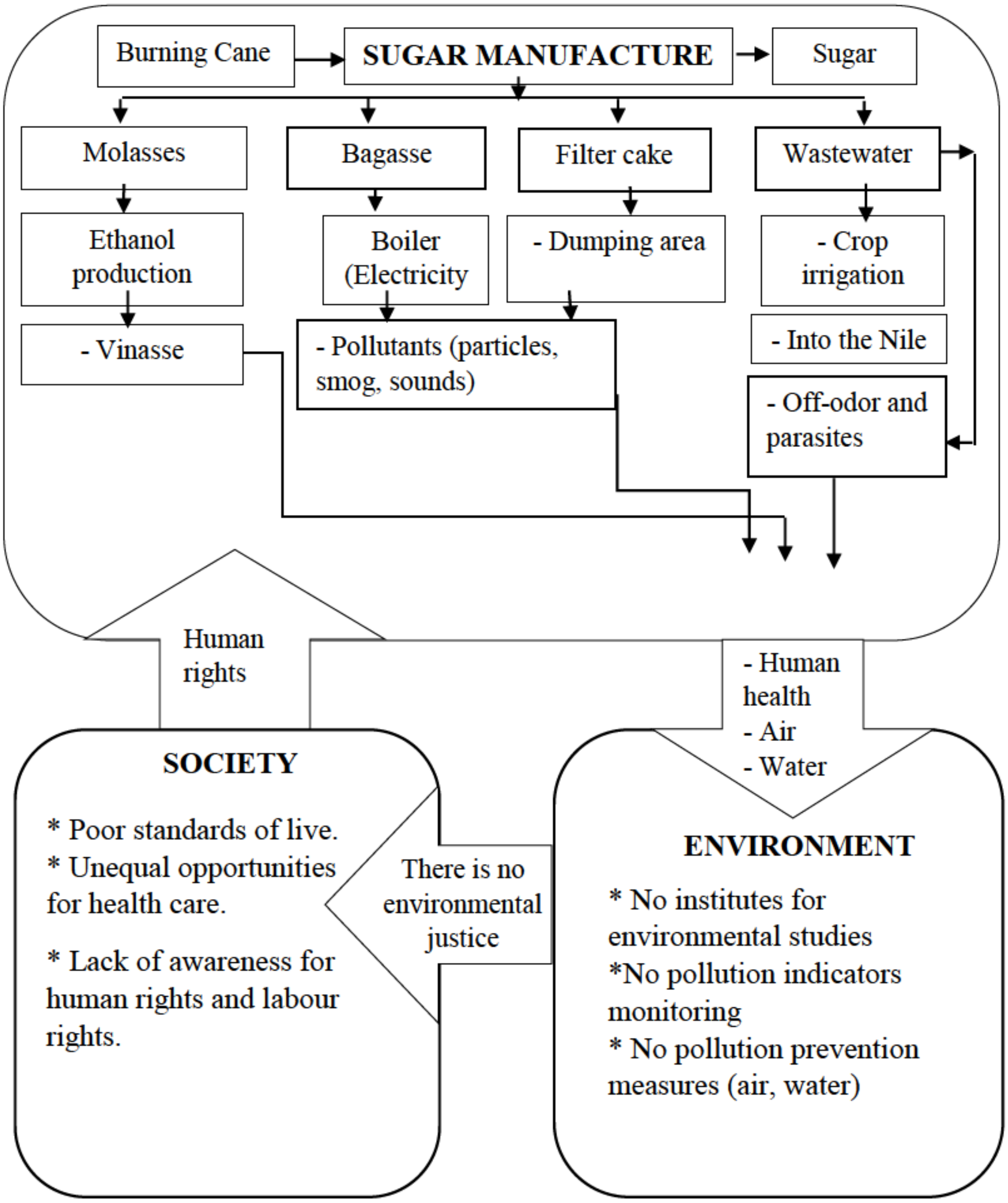

Figure 4.10 Current sugar waste management system

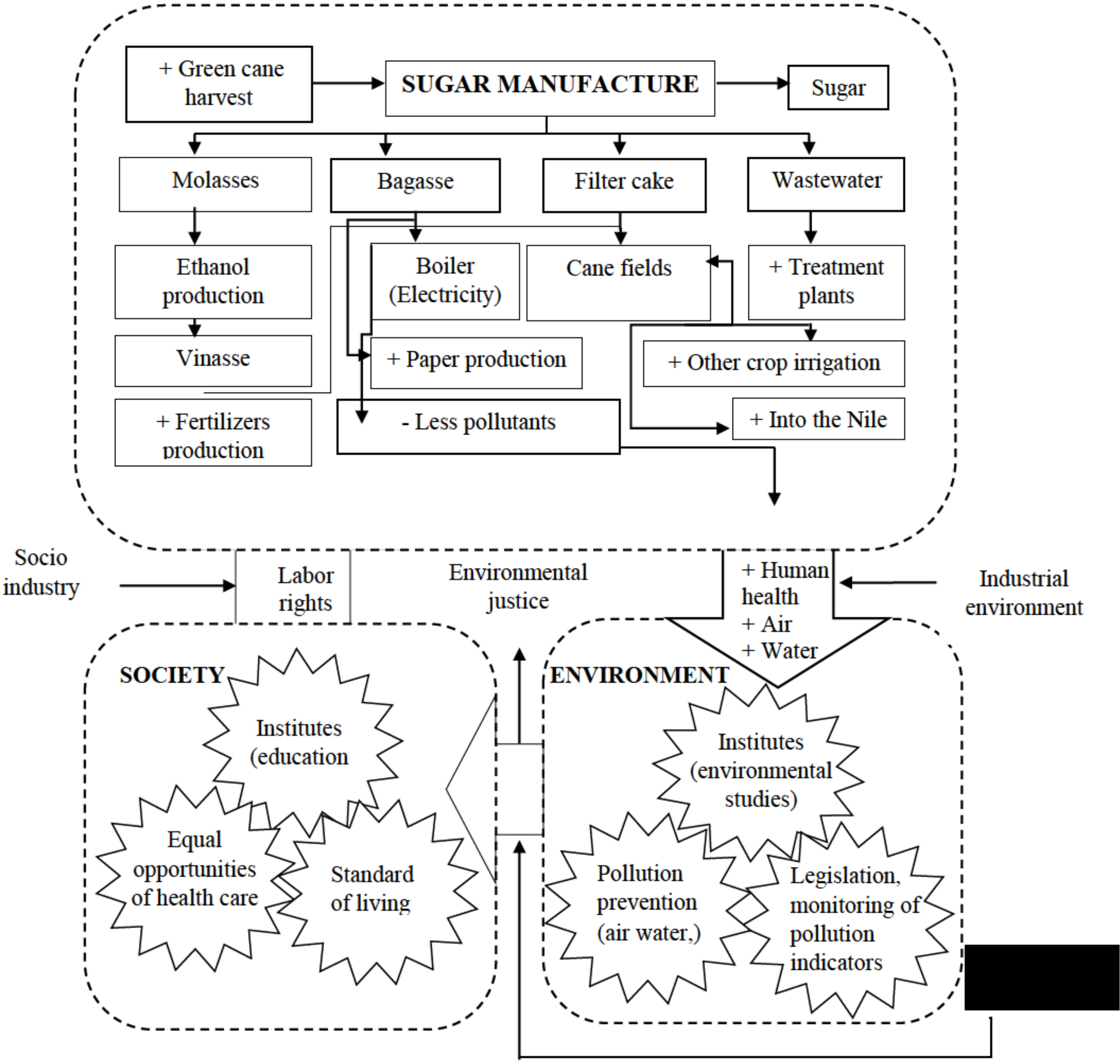

Figure 4.11 Prospective framework for the sugar waste management

Where: [-] = Negative impact on the environment, [+] = Positive impact on the environment

4.13 Conclusion

The Sudanese sugar industry has identified waste disposal problems that influence the surrounding communities and environment. The wastewater has created significant ($P < 0.05$) off-odors and mosquitoes, and has been mixed with the water sources, which is causing a health risk. It has also significantly ($P < 0.05$) influenced crop and animal production. The appearance of disease and death has been observed in some animals and plants that use the wastewater. The sugar industry pollutants (i.e. suspending particles and gases) have caused significant ($P < 0.05$) eye diseases and respiratory infections. The majority of respondents (85%) agreed that the sugar manufacturing waste needs to be effectively managed and that the quality of the water and air needs to be improved. However, people were unsatisfied with the health services. Therefore, major reforms are required to manage the sugar manufacturing waste, and to put an end to its environmental impacts. However, base-line information especially the medical diagnostic data is required to better understand the human health risks of the waste and to support the findings of this study. This study has designed a framework for enhancing the handling of the sugar industry waste, which will positively affect the environment of the communities residing in the vicinity of the sugar factories. It will spur the decision-makers on to enhance the bio-network of the sugar industry in Sudan.

The next chapter shows how people who reside close to the sugar factories are subject industrial waste disposal. The chapter gives detailed data on the effects of wastewater and other pollutants on the health of people living in the vicinity of sugar factories.

4.14 References

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5. DATA FOR UNDERSTANDING THE HEALTH RISKS OF SUDANESE SUGAR INDUSTRIAL WASTE: WASTEWATER AND SUSPENDED PARTICULATES

This chapter is based on the following paper:

Ibrahim, TS and Workneh, TS. 2020. Data for understanding the health risks of the Sudanese sugar industrial waste: wastewater and suspended particulates. *Data in Brief* **[Manuscript submitted]**.

Abstract

This article describes the data on the health risks of the Sudanese sugar industrial waste, which was gathered from 311 respondents who reside in the vicinity of the factories. These data have been used in “The Environmental Impact of Sugar Industry Waste in Sudan” and they provide a useful insight into the impact of sugar industry waste on the environment and human health. The data were collected by using structured survey questionnaires, which were administered in June 2017. Moreover, these data will serve as a reference source for further research, in order to understand the risks posed by sugar industry waste in developing countries.

Keywords: health risk, waste, environment, sugar industry

Table 5.1 Specification table

Subject	Health Risk
Specific subject area	Questionnaire data to assess the health risks of industrial sugar waste on human
Type of data	Table
How data were acquired	Self-administrated questionnaire
Data format	Analysed and formatted in raw form
Parameters for data collection	They were randomized
Description of data collection	Data were randomly collected from the community living in the vicinity of the six Sudanese sugar factories, using a

	questionnaire.
Data source location	Sudan / Africa
Data accessibility	With the article
Related research article	TS Ibrahim and TS Workneh (2020). The Environmental Impact of Sugar Industry Waste in Sudan. Under review in *International Journal of Environmental Health Science and Engineering.*

5.1 Value of the Data

The valuable information provided in this chapter can benefit the sector of sugar industry in Sudan. The authorities of sugar factories can use this baseline data in different ways as follows:

(a). These data about understanding the health risks of industrial waste on the communities were collected from all the Sudanese sugar factories, and are is the first of its kind

(b). Decision-makers in the country can benefit from this data; it will help them to understand the problem and spur them on to develop solutions for containing the risks.

(c). These data can be used to explore and develop the sector's environmental measures further.

(d). A framework can be designed, based on these data, to improve the handling of industrial sugar waste.

5.2 Data Description

Pollution is rapidly increasing with the increase of rain-fed and irrigated agriculture and industrialization in Sudan (Alim, 2012; Pierre *et al.*, 2016); however, there is a lack of scientific data on the waste management activities in the country (Robert, 2011). Environmental management strategies were non-existent in the industry's management structure until the year 2000. Therefore, this dataset provides insightful information that is based on survey data for assessing the risks of Sudanese sugar industrial waste on the communities. The platform for data collection was a cross-sectional survey that employed self-administered and semi-structured questionnaires. In total, 311 Sudanese respondents were interviewed for assessing the risks of industrial sugar waste. Table 5.1 shows the data characteristics for nominal variables, with designated intervals, which the respondents needed to answer in the questionnaire. A questionnaire was developed with survey questions that used a three-point Likert Scale: ‘Agree,’ ‘Disagree’ and ‘Neutral.’ Table 5.2 represents a data summary of the health risks that industrial sugar waste pose to humans. The table includes the intervals for the answers of the respondents, which are divided into two variables that are based on gender: Male and Female. The targeted population was those people who live in the villages close to the selected factories. The data highlighted the effects of industrial sugar waste on the health of people residing in the vicinity of the Sudanese sugar factories (Table 5.3).

Table 5.2 Data summary of variables influencing the surrounding environment

Variables	Obs.	Agree (%)	Disagree (%)	Neutral (%)	Mean	Std. Dev.	Std. Err.
Wastewater creates off-odour	311	63	28	9	1.43	0.628	0.036
Wastewater creates mosquitoes	311	67.2	24.8	8	1.40	0.608	0.035
Wastewater contaminates water	311	38.9	51.4	9.6	1.44	0.634	0.036
Malaria	311	66.2	22.5	11.3	1.45	0.689	0.039
Particulates contaminate the air	305	83.6	10.9	3.5	1.18	0.47	0.027
Particulates dirty the floors and clothes	305	89.4	6.8	1.9	1.11	0.369	0.021
Lack of visibility due to smoke clouds	305	75.9	15.8	6.4	1.29	0.582	0.033
Loud-sounds	305	65.6	22.5	10	1.43	0.671	0.038

Notes: The observation number varies for each question, due to respondents’ reluctance to answer uncomfortable questions.

Table 5.3 Health effects of the sugar industrial pollutants on the residents

Infection	Obs.	Male (%)	Female (%)	Mean	Std. Dev.	Std. Err.
Eye diseases	125	26.4	13.8	1.34	0.477	0.043
Heart attacks	10	1.9	1.3	1.40	0.516	0.163
Respiratory diseases	62	12.9	7.1	1.35	0.482	0.061

Asthma	40	9.6	3.2	1.25	0.439	0.069
Chronic bronchitis	65	13.5	7.4	1.35	0.482	0.060
Irregular heartbeat	18	4.2	1.6	1.28	0.461	0.109

The observation number varies for each question, due to respondents' reluctance to answer uncomfortable questions.

Table 5.4 Codebook of the questions

Codebook	Question
Wastewater creates off-odours	The wastewater disposal creates unfavourable odours because of its stagnancy.
Wastewater creates mosquitoes	The wastewater disposal creates mosquitos and they spread massively all the year.
Wastewater contaminates water	The wastewater disposal contaminates our water source
Malaria	We have experienced malaria disease several times because of the mosquitoes.
Particulates contaminate the air	Substantial particulate matter is suspended in the air during the harvest season, which contaminates the air we breathe.
Eye diseases	Have you been infected with an eye disease while living in the vicinity of the factory?
Respiratory diseases	Have you been infected with respiratory diseases while living in the vicinity of the factory?
Particulates dirty the floors and clothes	The bulk of organic pollutants that result from cane burning during the harvesting season dirties the floors and clothes.
Asthma	Have you been infected with asthma while living in the vicinity of the factory.
Chronic bronchitis	Have you been infected with chronic bronchitis while living in the vicinity of the factory.
Heart attacks	Have you been infected with heart-attacks while living in the vicinity of the factory.
Irregular heartbeat	Have you experienced irregular heartbeat while living in the vicinity of the factory.
Invisibility due to smoke clouds	Substantial smoke clouds cover the sky during the cane harvesting season, which hinders visibility.
Sound pollution	Noisy sounds come from the factory during the harvesting season, which ruins the mood.

5.3 Experimental Design, Materials and Methods

The self-administered questionnaire was developed and pre-tested to refine the categories. The sample was comprised of 311 randomly-selected respondents from the selected residential areas in the vicinity of the factories, by using the lottery method (Mengistu *et al.*, 2016). The questionnaires were distributed randomly to the respondents living in the vicinity of the six selected sugar factories, namely, the Guneid, Halfa, Sinnar, Assalaya, Kenana and White Nile mills. The questionnaire was to be filled in by all the family members. The main reason for selecting the respondents that had settled in the vicinity of the industries was to allow for their very detailed insights and to acquire clear-cut information. The data were obtained from the first survey of all the sugar factories in Sudan, which is a developing country. The significance of the data is based on the crucial issue of the effects of waste on peoples' health. SPSS Version 19 was used to analyze the data obtained from the questionnaire.

5.4 Conclusion

This chapter highlighted the health risks associated with the sugar industrial waste. The study involved a cross-sectional survey for the collection of data, and SPSS was used to analyse the data. Waste disposal was found to develop a favorable environment for the breeding of mosquitoes. This has a significant ($P < 0.05$) influence on the incidence of malaria among the residents living close to the selected factories. The industrial sugar pollutants were also found to cause human eye and respiratory infections in the region. The results of this study represent a useful source for understand the health risks posed by sugar industrial waste. The sugar processing industry also releases toxic gases, which damage the environment. Therefore, it is necessary to assess the greenhouse gas emissions and the energy consumption of sugar production.

The next chapter shows a life-cycle assessment of sugar processing and the associated environmental impacts. The chapter measures the industrial energy use and emissions and their effect on the environment.

5.5 References

Alim, EAE. 2012. Assessment of the liquid and solid waste from Guneid sugar factory. Unpublished MSc Dissertation, Medical and Health Studies Board, University of Khartoum, Khartoum, Sudan.

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Pierre, F, Patrick, K and Wondwosen, S. 2016. *Assessment of the environment pollution and its impact on economic cooperation and integration initiatives of the IGAD region*. National Environment Pollution Report – Sudan. Sudan Country Report. The European Union's EDF Programme for Eastern, Southern Africa and the Indian Ocean, Brussels, Belgium.

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6. LIFE-CYCLE ASSESSMENT OF SUGAR PRODUCTION IN SUDAN: GREENHOUSE GAS EMISSIONS AND ENERGY USAGE

This chapter is based on the following paper:

K,/.Ibrahim, TS and Workneh, TS. 2020. Life-cycle assessment of sugar production in Sudan: greenhouse gas emissions and energy usage. *Journal of the Air and Waste Management Association* **[Manuscript submitted]**.

Abstract

This study aims to analyse the impact of Sudanese sugar production waste on the environment by using a Life-Cycle Assessment (LCA). The systems that were studied included the following: sugarcane agricultural production (i.e. land preparation and cane planting), sugarcane cultivation (i.e. the manufacture of fertilizers and herbicides), sugarcane harvesting and transportation, as well as sugar milling. The study used the SimaPro Software Version 9.0.0.49 and Ecoinvent Version 3 databases, and characterization was performed by using the methods of ReCiPe 2016 and the Intergovernmental Panel for Climate Change (IPCC) 2007. The total fossil energy consumption was about 3651 MJ. t^{-1} sugar. The most significant energy consumer in the life-cycle of the sugar industry was sugarcane production, with 2166 $MJ.tonne^{-1}$ sugar (39%). Sugar processing was the second highest contributor to fossil energy consumption with a share of 26.6%, while sugarcane cultivation (i.e. the manufacture of fertilizers and herbicides) and sugarcane harvesting with transportation consumed 20.7% and 13.7%, respectively. The greenhouse gas emissions over the selected stages of sugar production were about 271.2 kg CO_2-equivalent t^{-1} sugar. The emissions in kg of CO_2-e t^{-1} sugar from sugarcane production, harvesting with transportation, cultivation and sugar processing were 160.5, 57.2, 35 and 18.5, respectively. However, the potential contributions to global warming, based on 100-year time period, were 51%, 27%, 12% and 10% for sugar processing, sugarcane production, sugarcane cultivation and sugarcane harvesting with transportation, respectively. The principal contributors to ozone depletion were sugarcane production and sugar processing, with 44% and 22%, respectively. The sugar-processing stage has significantly contributed to eutrophication, acidification,

particulate matter and ecotoxicity. The study recommended the enhancement of the sugar industry operations to substantially improve their environmental performance.

Keywords: life-cycle assessment, life-cycle inventory, energy consumption, greenhouse gas emissions, sugarcane, sugar industry

6.1 Introduction

The process of sugar production consumes large quantities of resources, such as water and fossil energy (Nakhla, 2014; Sahu, 2018). The process generates a considerable amount of waste and pollutants, in gaseous and solid form. Debris and contaminants harm the surrounding environment; for example, fossil fuel utilization releases harmful gases that pollute the air and cause environmental problems, such as global warming (Ramiro *et al*., 2019). In addition, the combustion of bagasse for electricity to supply the system generates ash, which could influence human health (Cordiero *et al*., 2004; Mohamed and Samah, 2011; le Blond *et al*., 2017; Sahu, 2018). Intensive sugarcane production requires chemicals, such as fertilizers and herbicides, to raise the yield and control diseases. However, the residue of these chemicals could influence the soil and environment.

Machinery is also involved in almost all the stages of sugarcane agriculture, which produces large emissions (Ramiro *et al*., 2019). Therefore, from an environmental point of view, the gaseous emissions, effluents, and energy use of the sugar industry should be monitored to minimize the environmental impact. Therefore, it is necessary to identify the energy usage and to assess the emissions and their effects on the Sudanese sugar industry environment. Because the sugar production process could adversely create an impact on the environment, the Life-Cycle Assessment (LCA) method can be useful to calculate, analyse and interpret these environmental impacts. The LCA has become a familiar tool throughout the sugar production chain for undertaking systematic environmental assessments (Livison *et al*., 2010; Astuti *et al*., 2018; Ramiro *et al*., 2019). This methodology has been used to conduct many studies in different countries around the world, such as Brazil, South Africa, Egypt and Mauritius. Due to the lack of data for Sudan, the application of LCA has not been conducted to assess the sugar industry sector. The objective of this study is to quantify the greenhouse gas emissions into the air and the amount of energy used for the production of sugar in Sudan. The research applied the life-cycle assessment principles to assess the environmental damage attributed to sugar production, and to identify at which stage of the sugar production life-cycle it has a significant environmental impact. The study identified opportunities for improving and developing the environmental performance, which will assist decision-makers in the Sudanese sugar industry to achieve sustainable production and services.

6.2 Data Collection

Sugar is one of the most strategic products produced in Sudan. However, the industry is considered to be a source of pollution, due to its massive resource consumption and effluent discharge. The LCA methodology was applied to quantify the energy use and the environmental impact of Sudan's six sugar factories. The case study included the country's annual data averages on sugar production activities for the past ten years, namely, from 2007 to 2016. Data were collected from the relevant databases of the selected sugar factories, i.e. field reports and annual records. Information relating to the agricultural fields and sugar mills was obtained from personal contact with engineers, managers and administrators. A survey (i.e. by means of an interview) was conducted with several agricultural engineers from the factories, as well as the farmers. Relevant sources, such as dissertations, books, magazines and manuals were also considered. Some of the data comprised several technical parameters relating to sugarcane cultivation, sugarcane harvesting, sugarcane transportation and sugar processing, were collected from the Ministry of Mining and Energy in Sudan. The fossil fuel energy consumption was calculated per Mega-Jules (MJ) per tonne of produced sugar. The process was conducted by summing up the quantity of the consumed fuel during sugarcane production, sugarcane burning, sugarcane harvesting, transportation and sugar processing. Data on the use of fertilizers and herbicides were obtained from the relevant departments and laboratories. Assumptions were made for some of the calculations, due to a lack of information on the GHG that is relevant to agricultural management in the sugarcane production stage (i.e. the effects of irrigation water, vinasse and filter cake). Table 6.1 contains the mean values of the parameters considered in sugarcane production for the past ten seasons, from 2007/2008 to 2016/2017, while the sugar-processing parameters are presented in Table 6.2. The sugar production system for the selected stages was modeled to represent the current use of technologies in Sudan (Figure 6.1). A Life-Cycle Assessment (LCA) was applied based on the International Organization for Standardization (ISO) standard 14044. By using the SimaPro software version 9.0.0.49, the LCA was involved in the goal definition, inventory analysis, impact assessment and interpretation (Livison *et al.*, 2010). The standard unit used for calculations in this study was the average tonnes of sugarcane that are used to produce one tonne of sugar in Sudan.

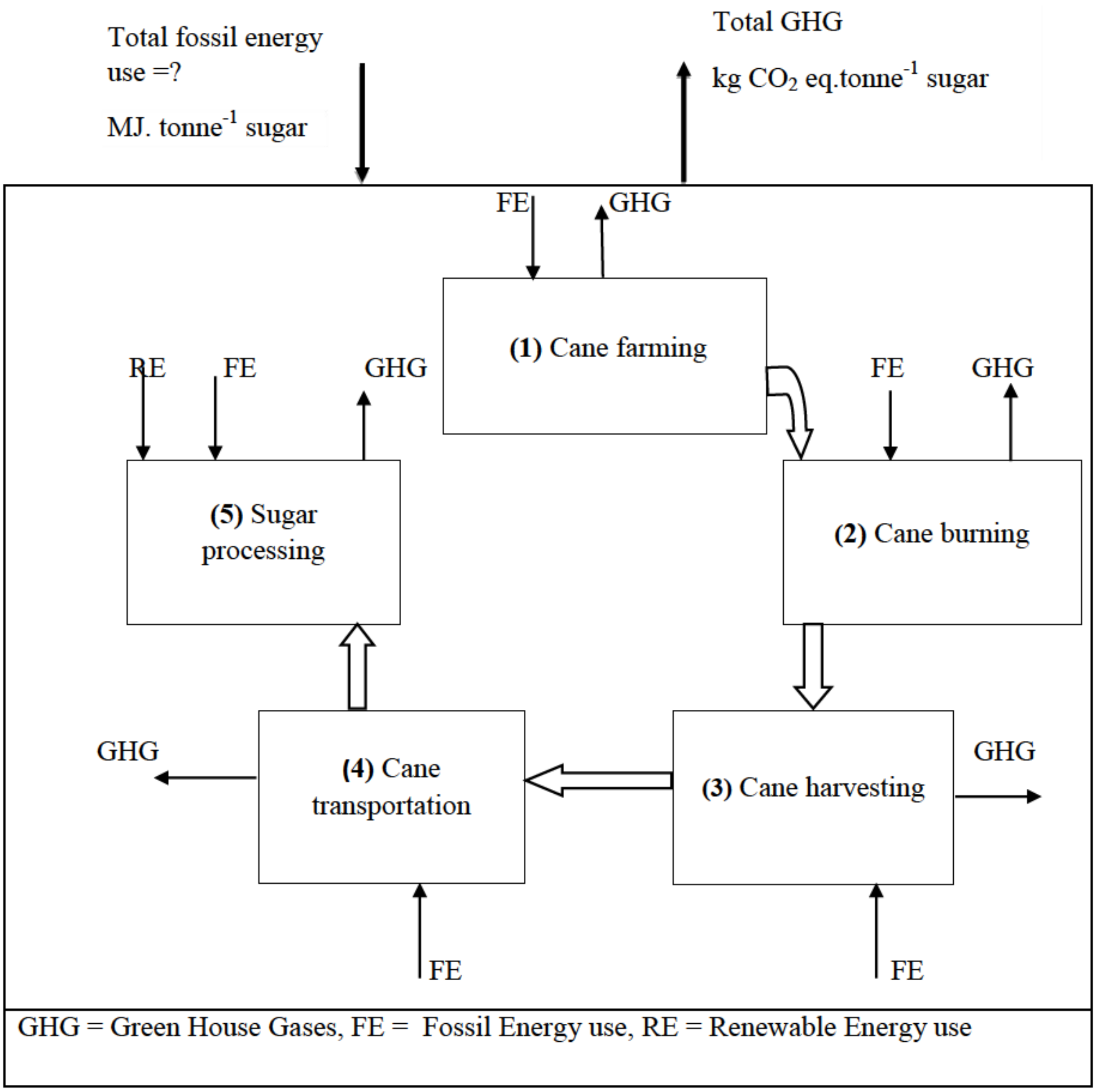

Figure 6.1 Selected stages of the sugar production process

6.2.1 System boundaries

The selected stages in the system boundaries are sugarcane production, sugarcane harvesting, sugarcane transportation and sugar processing, as well as power generation from bagasse. The boundaries end at the phase of sugar production within the factory gates (Figure 6.2).

The considered sub-systems consist of the following four stages: (1) Sugarcane cultivation in the four provinces, namely, at the White Nile, Gazeira, Sinnar and Kassala mills. The sugarcane is irrigated by using the surface irrigation system (Obeid, 2013; Suliman, 2017). The application of fertilizers and herbicides to the sugarcane depends on the soil type and the growth stage. The average fertilizer application rate was adopted for this study. (2) The transportation of sugarcane to the mill by using trucks, with a capacity ranging between 9 to 35 tonne per vehicle and an average distance of 14 kilometers (Adam *et al*., 2015). (3) The energy used in sugar manufacture and the impact of fertilizers and herbicides are included; and (4) Sugar milling, which was considered to be within an average sugarcane throughput of 308 tonne per hour or 1.27 mn tonne of sugarcane per annum at each mill. The rate is estimated for the sugarcane crushing season (i.e. over five to six months), during which the mills operate continuously (Ibrahim and Workneh, 2019). The study excluded some sub-systems, such as building production and machinery maintenance. The study also excluded the distribution and transmission of power that is generated in the powerhouse. The route infrastructure for sugarcane transportation, as well as the transportation of sugar to the storage depots and to the consumers, were also exempted.

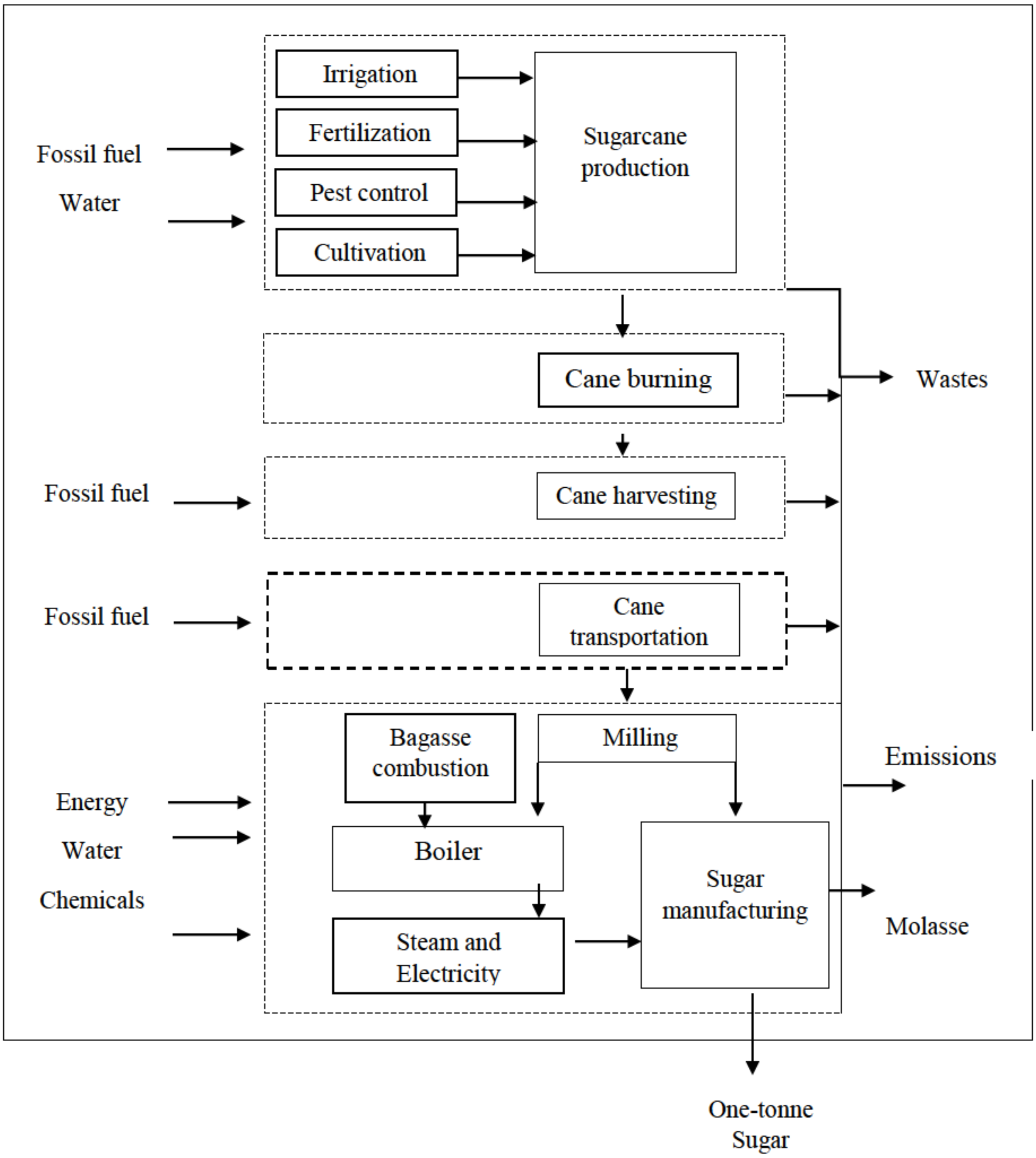

Figure 6.2 System boundaries

6.2.2 Life-cycle inventory

The life-cycle inventory for input data was obtained from the databases of the Sudanese Sugar Company (SSC), which includes four sugar factories, namely, the Guneid, Halfa, Assalaya and Sinnar factories, as well as the Kenana Sugar Company (KSC) and the White Nile Sugar Project (WNSP). Some information related to sugarcane burning and emissions from the soil was assumed, due to a lack of data. In 2016/2017, the total cultivated sugarcane area was approximately 69 500 ha, with an average of 88 tonne sugarcane per ha. About 6 mn tonne of sugarcane was crushed at a rate of 42 266 tonne per day to produce around 720 000 tonne of sugar. The Kenana factory produces more than half (about 56%) of the sugarcane and sugar in the country. This sugar mill was taken as a reference, due to the availability of information, compared to the other sugar factories in this study. At this sugar mill, approximately 14.5% of the cultivated sugarcane was harvested mechanically, and 85.5% was harvested manually. About 90% of the developed sugarcane areas were burned, before commencing the harvesting operation. Table 6.1 shows the data and assumptions used for the life-cycle inventory.

In terms of fertilization, an average of about 26 kg, 16 kg and 0.5 kg of nitrogen (N), phosphorus (P_2O_5) and potassium (K_2O), respectively, were applied to produce one tonne of sugar. The average amounts of herbicides, pesticides, and flowering controllers and ripeners that were applied were 2.09 kg, 0.5 liter and 0.01 kg, respectively, for every one tonne of sugar. Table 6.1 shows the average consumption of diesel in sugarcane cultivation, as well as the amount of fertilizers, herbicides and pesticides used. The average oil fuel consumption for sugar milling was about 87 tonne per tonne sugar. Sugarcane transportation in private companies, such as the Kenana factory, is carried out by using trucks, and wagons pulled by tractors are used in the publicly-owned factories. The capacity of the vehicles varied from 35 tonne to 70 tonne of sugarcane per tuck. The designed capacity for the trailers pulled by tractors was 9 tonne of sugarcane. The average distance of sugarcane transportation from the farm to the mill was 16.8 km. The total diesel fuel consumed for sugarcane harvesting and transportation was estimated to be about 2.2 kg per tonne of sugarcane. Table 6.2 illustrates the average values of the resource inputs and output data, as well as the chemical materials used for sugar production. About 16 991 tonne of bagasse is used to cogenerate electricity at the power stations of the selected factories. Data were calculated according to the input and output values obtained at the stage of sugar processing. Table 6.3 shows the annual amounts (average values) of by-products and residues, per one tonne of raw sugar.

Table 6.1 Data for sugarcane production, burning, transportation and processing parameters

Resources	Amount	Unit	Reference
1) Sugarcane agriculture			
Cultivated area	69492 ha	ha	KSC, 2016 and SSC, 2016
Average sugarcane harvested	88	tonne/ha	KSC, 2016 and SSC, 2016
Irrigation water requirement	24269	m^3/ha	KSC, 2016 and SSC, 2016
Electricity consumption (for irrigation)	3600	kWh/ha	KSC, 2016
Fertilizers application N P_2O_5 K_2O	 261 146 5	 kg/ha kg/ha kg/ha	KSC, 2016 and SSC, 2016
Herbicide use	19	kg/ ha	KSC, 2016 and SSC, 2016
Pesticide use	5	L/ha	KSC, 2016 and SSC, 2016
Flowering control and ripening	0.9	kg/ha	KSC, 2016 and SSC, 2016
2) Sugarcane cultivation			
Diesel input to produce herbicides and pesticides	9	litter/ha	WNSP, 2012 and SSC, 2016
Diesel input to produce fertilizers	4	litter/ha	WNSP, 2012 and SSC, 2016
3) Sugarcane burning			
Sugarcane area burnt before harvesting	90% (62543)	ha	Livison *et al.*, 2010
Leaves and tops burnt per hectare	280	kg/ha	
4) Sugarcane transportation			
Average distance	16.8	km	KSC, 2016

5) Sugar processing			
Sugar produced per hectare	8.5	tonne/ha	KSC, 2016 and SSC, 2016
Bagasse produced	40.2	% cane	KSC, 2016 and SSC, 2016
Molasses produced	3.6	% cane	KSC, 2016 and SSC, 2016
Filter cake produced	3.1	% cane	GSF, 2016 and ASF, 2016
Steam consumed	751	kg/tonne cane	KSC, 2016
Electricity consumption	11	kWh/tonne cane	KSC, 2016 and WNSP, 2012
Water used for sugarcane and sugar processing	0.8	m^3/tonne cane	KSC, 2016
Diesel consumption	0.66	litter/tonne cane	KSC, 2016 and WNSP, 2012

Table 6.2 Average amount of resources used for sugar production

Resources	Unit	Amount
Total sugarcane	$tonne.year^{-1}$	6 962 480
Sugarcane crushed	$tonne.day^{-1}$	42 266.9
Extraction efficiency	%	79.1
Sucrose % cane	%	12.1
Sucrose loss % cane	%	2.5
Total sugar produced	tonne / day	4 186
Industrial efficiency	%	77.3
Total sugar	$tonne.year^{-1}$	720 027.3
Molasses produced	$kg.tonne^{-1}$ sugar	25 921
Electricity surplus	$kWh.tonne^{-1}$ bagasse	89.7
Electricity consumption	$kWh.tonne^{-1}$ sugar	65.3
Bagasse burnt / total produced	%	92
Steam consumed	$kg.tonne^{-1}$ sugar	7 286.3
Sugarcane	tonne cane / tonne sugar	9.7
Water	m^3 / tonne sugar	2 669.7
Land	ha / tonne sugar	0.11

Fuel	Liter / tonne sugar	87
sSepran	$kg.tonne^{-1}$ sugar	0.07
Hodag	$kg.tonne^{-1}$ sugar	0.01
Blankit	$kg.tonne^{-1}$ sugar	0.04
Caustic soda	$kg.tonne^{-1}$ sugar	0.10
Bosan	$kg.tonne^{-1}$ sugar	0.02
Alcohol	$kg.tonne^{-1}$ sugar	0.003
Filter aid	$kg.tonne^{-1}$ sugar	0.01
Soda	$kg.tonne^{-1}$ sugar	2.07
Phosphate acid	$kg.tonne^{-1}$ sugar	0.76
Soda ash	$kg.tonne^{-1}$ sugar	0.07

Table 6.3 Annual mean values of by-products and waste per t sugar

By-product	Unit	Quantity
Filter cake	$kg.tonne^{-1}$ sugar	300
Boiler ashes	$kg.tonne^{-1}$ sugar	15.3
Wastewater	$m^3.tonne^{-1}$sugar	29.6

6.2.3 Calculations of fossil fuel energy consumption

The total energy required for sugarcane production was calculated in mega-joules (MJ) per tonne of produced sugar. The calculation included fossil fuel energy used for the application of fertilizers and herbicides during the stage of sugarcane cultivation. The calculation process was done by using the energy requirements to produce the fertilizers and herbicides used in Sudan and their application rates. The application rates of fertilizers per hectare were 261 kg, 146 kg and 5 kg for N, P_2O_5, and K_2O, respectively. The area required to produce one tonne of sugar was 0.11 ha (KSC, 2016; SSC, 2016). Fossil fuel energy for sugarcane transportation was calculated in MJ per one tonne of sugar. The fuel consumption for one truck was determined in liters per tonne cane per km, and the energy content of the diesel fuel was taken as MJ per liter. Thus, the energy consumption of trucks in Sudan was found per $MJ.tonne.km^{-1}$. The energy used during sugar manufacture ($MJ.tonne^{-1}$ sugar) was calculated by quantifying the amount of diesel consumed per kilogram to produce one tonne of sugar. The Net Calorific Value (NCV) of diesel per $MJ.kg^{-1}$ was determined (Livison *et al*., 2010).

6.2.4 Calculations of renewable energy consumption

A survey was made of the power departments of the selected factories by collecting the relevant data from the record sheets, and by conducting personal interviews with specialists. The considered parameters were as follows: the bagasse combusted per tonne per day, the Net Calorific Value (NCV) of bagasse, which was assumed to be 7.8 MJ/kg (Rakesh *et al*., 2016; Livison *et al*., 2010), and the electricity in kW per day that was generated to supply the sugar processing system. In addition, the renewable energy required to produce one tonne of sugar, the total renewable energy consumption for the system in kWh per tonne sugar, and the energy efficiency index were calculated by using Equation 6.1 as follows:

$$EI = (Et - E_D)/S_J \qquad (6.1)$$

Where: EI = energy efficiency Index, ET = total energy, ED = Diffuser energy usage and SJ = volume of sugar in all final products (Hocking *et al*., 2015).

6.2.5 Calculations of greenhouse gas emissions

Due to the lack of activity data, single Tier 1 methods of the Intergovernmental Panel for Climate Change [IPCC] (2006) were used for the calculations. The calculation methods were based on the fuel used in the selected life-cycle stages of sugar manufacturing in Sudan. Data on the consumed fuel were collected, and the emissions were estimated by using Equation 6.2 (IPCC, 2006). The calculation of emissions was done by summing up the emissions at each stage of the sugar production life-cycle. The emissions represented in the carbon dioxide equivalent per one tonne of sugar produced were compiled for all the selected stages, namely, sugarcane production, fertilizer and herbicide use, sugarcane harvesting with transportation and sugar manufacture. The CO_2-e emission from fossil fuel combustion during sugarcane burning was excluded because of the lack of relevant empirical data in the Sudanese sugar factories. Therefore, it was assumed that sugarcane releases the same amount of CO_2 that is absorbed in photosynthesis during the growing stage (Livison *et al*., 2010). The CO_2-e emission was calculated based on the diesel density of 0.845 kg per liter, the net calorific value of 43 TJ per Gg, and the emission factor of 43.1 t CO_2-e per TJ. The three most important greenhouse gases (GHG), namely CO_2, CH_4, and N_2O, are calculated for the selected stages of the sugar life-cycle. The Global Warming Potentials (GWPs) were used to quantify the GHG, which is expressed as CO_2–equivalents. The GWPs developed by the Intergovernmental Panel on Climate Change (IPCC) were quantified for a period of 100 years. Accordingly, equivalent factors for the three essential gases are defined as follows: 1g CO_2 = 1 g CO_2-eq, 1 g CH_4 = 23 CO_2-eq and 1 g N_2O = 296 g CO_2-eq

$$E_{GHG,\,fuel} = FC_{fuel} \bullet EF_{GHG,\,fuel} \qquad (6.2)$$

Where:

$E_{GHG,\,fuel}$ = emissions of a given GHG by type of fuel (kg GHG)

FC_{fuel} = amount of fuel combusted (TJ)

$EF_{GHG,\,fuel}$ = default emission factor of a given GHG by type of fuel (kg gas/TJ).

The amount of fuel of a particular kind combusted per one tonne of sugar expressed in terajoules (TJ) can be estimated by using Equation 6.3.

$$F_{a,f} = l_{fuel\ a,f} * D_{fuel\ a} * NCV_{fuel} \div 10^6 \qquad (6.3)$$

Where:

$F_{a,\,t}$ = amount of fuel type a consumed in TJ

$L_{Fuel\ a,\,t}$ = quantity of fuel of the type consumed (litre)

$D_{Fuel\ a}$ = density of fuel type (kg/litre)

$NCV_{Fuel\ a}$ = net calorific value of fuel type (TJ/Gg)

A calculation of the total emissions of gas from Equation 6.2 was made by summing up the overall fuels, by using Equation 6.4 (IPCC, 2006).

$$Emissions_{GHG} = \sum_{fuels} Emissions_{GHG,\,fuel} \qquad (6.4)$$

The approach used for this methodology is summarized in five steps, as follows:

(a). The amount of fuel consumed at all the sugar factories was determined.

(b). The amount of fuel consumed into energy flow was converted by using the heating value of the fuel type.

(c). The EF of a given GHG was determined by the type of fuel expressed as kg gas / TJ. For CO_2, which includes the carbon oxidation factor, is assumed to be 1.

(d). GHG emitted calculation was expressed as kg CO_2 equivalent.

(e). The total GHG emissions were summed up according to the fuel type.

The global warming potential of fossil fuel energy is then estimated by quantifying the total GHG emissions of the selected sugar production stages. Hence, the GHG emissions are multiplied by their equivalent factors and the results are summed up (Francesco, 2010). The GHG emissions calculated below are related to the defined functional unit, namely, one tonne of sugar. Figure 6.1 shows the sub-systems that are included in this study.

6.2.6 Life-cycle assessment

A LCA was carried out by using the SimaPro 9.0.0.49 Software. The results were described by using ReCiPe 2016 v1.1 endpoint methodology. The interpretation was carried out to identify which stage of the sugar life-cycle has the most significant impact. The method of IPCC 2007 GWP 100a v1.01 was used for the global warming category. The identified impacts were global warming "in terms of greenhouse gas emissions (CO_2-equivalent) based on the 100-year Global Warming Potential (GWP)", the fossil fuel use, ozone depletion, acidification and ecotoxicity.

6.3 Results and Discussion

There is a need to effectively analyse the environmental impacts generated by a production system, for example sugar production, by using efficient tools. There was no previous LCA study has been conducted on the sugar industry in Sudan. However, the environmental effects of the sugar manufacturing in Sudan that were studied in this paper were enormous. This study is the first of its kind that has applied the LCA approach to the six selected sugar factories of the Sudanese sugar industry. This research studied four stages of the sugar-processing life-cycle, namely, sugarcane production, sugarcane cultivation, sugarcane harvesting and transportation and sugar processing. The results showed some similarities to other studies conducted in the sugar industry, especially in the Life-Cycle Inventory phase (LCI).

6.3.1 Fossil energy consumption

Data on energy consumption was accumulated for the selected stages of the sugar production life-cycle, namely, sugarcane production, sugarcane transportation, fertilizer and herbicide usage and the sugar processing per one tonne of produced sugar. The calculation of fuel consumption was done by summing up the quantities that were consumed for each of the selected stages. The results showed that 9.7 tonne of sugarcane is the average weight required to produce one tonne of sugar. Hence, the total energy required for sugarcane production was 2 166 MJ.tonne^{-1}sugar. This amount of energy indicated that the stage of sugarcane production is the highest (39%) consumer of fossil fuel resources in the sugar production life-cycle. The sugar-processing stage was considered to be the second contributor to fossil fuel energy consumption, with a percentage of 26.6%, while sugarcane cultivation and sugarcane harvesting with transportation contributed significantly to the use of fossil fuel resources, with percentages of 20.7% and 13.7%, respectively. Figure 6.3 shows the use of fossil fuel resources use for the selected stages of the sugar production life-cycle. When a comparison of the results was made with other studies conducted in Mexico, South Africa and Mauritius, this study showed that about 39% of the fossil fuel energy was consumed in the sugarcane production stage, compared to 60.3%, 34% and 75% in sugarcane production stages in Mexico, South Africa and Mauritius, respectively. The total fossil energy consumed to produce one tonne of Sudanese sugar was about 3651 MJ. The amount indicated in this study is lower, compared to that of Ramiro *et al*. (2019), who found it to be about 8,572 MJ, and Livison *et al*. (2010), who estimated it to be 5350 MJ.

Nevertheless, the amount of consumption is higher than the estimation of Ramjeawon (2008), namely, 1 995 MJ for South Mauritius. However, Ramiro *et al*. (2019) calculated 60.3% for both the sugarcane production and sugarcane harvesting stages. This result indicates the high dependence and usage of diesel fuel in the phase of sugarcane production. The reason for this is that the stage of sugarcane production includes different agricultural activities, such as soil preparation and the establishment of sugarcane fields, which consumes large amounts of diesel fuel. In Sudan, the land required to produce one tonne of sugar is 0.11 ha, compared to 0.15 ha for South Africa and 0.12 ha in Mauritius. This seems to indicate that Sudan has the highest sugarcane productivity per smaller unit area, compared with South Africa and Mauritius. However, the land size of the sugarcane of Sudan and Mauritius is relatively the same, but smaller than that in South Africa. The reason for this is that the sugarcane farms in both countries are mainly fully-irrigated, while 80% of the South African sugarcane is rainfed. Generally, the uncertain rainfall severely impedes the agricultural productivity in rainfed areas (Tilahun *et al*., 2011). Liu *et al*. (2016) found that the sugarcane yield, under rainfed conditions, is influenced by the variation of available water. Hence, this illustrates the higher sugarcane productivity per unit area in the fully irrigated farms, compared to the rainfed fields.

The total amount of energy consumed for fertilizer and herbicide application was 472 MJ per ton of produced sugar. The energy consumption in sugarcane harvesting and transportation was calculated after considering the distance between the factories and the farms. The average length of the roads for sugarcane transportation is 16.7 km and trucks are used (Ibrahim and Workneh, 2019). The total fossil fuel energy consumption for sugarcane transportation per one tonne of sugar was 770 MJ. Fuel oil and diesel are used during the manufacture of sugar to supply the boilers and to supplement the power cogeneration from bagasse during the off-season. The amount of consumed fuel oil and diesel was multiplied by their net calorific values (TJ/Gg). Sugar industry data showed that approximately 0.18 liters of fuel oil and 6.65 liters of diesel were required to produce one tonne of sugar. The net calorific value of fuel oil and diesel was 43 and 42.3 TJ/Gg, respectively (IPCC, 2006). The total energy from both fuel oil and diesel used for sugar processing was 249 MJ per one tonne of sugar. The total fossil fuel energy used for all the stages was 3 978 MJ per tonne of sugar.

6.3.2 Renewable energy consumption

The renewable energy consumption was calculated after identifying the bagasse Net Calorific Value (NCV), which was assumed to be 7.8 MJ/kg (Rakesh *et al*., 2016; Livison *et al*., 2010). The results showed that the total energy generated from bagasse was 33 969 MJ per one tonne of sugar. The total energy consumption (i.e. renewable and fossil fuel sources) for the system was about 37 947 MJ. t^{-1} sugar.

6.3.3 Global warming potential

The Global Warming Potential (GWP) is known as climate change, which is caused by the trapping of heat in the atmosphere (Zahedi *et al*., 2018). Global warming potential is emission of the GHGs into the atmosphere and is expressed as kg CO_2-eq (Chandra *et al*., 2018). The results showed that the total fossil fuel emissions over the selected stages of the sugar production life-cycle in Sudan were estimated to be about 271.2 kg CO_2-equivalent per one tonne of sugar. The emissions from the sugar processing, sugarcane production, sugarcane cultivation and sugarcane harvesting with transportation stages were 18.5, 160.5, 35 and 57.2 kg CO_2-eq.tonne^{-1} sugar, respectively. The contributions of the global warming potential, based on a 100-year period, were 51%, 27%, 12% and 10% for sugar processing, sugarcane agriculture, sugarcane cultivation, and sugarcane harvesting and transportation, respectively. The sugar processing stage is the greatest contributor (51%) to gas emissions. The contribution to the global warming of sugarcane agriculture, cultivation, harvesting and transportation was 49%. This indicator was lower than that of Ramjeawon (2008), who estimated 80%, and Livison *et al.* (2010), who estimated 74% for the same stages. In those cases, the stage of sugarcane transportation is the most significant (50.6%) contribution to global warming. In comparison, both phases of sugarcane growing and harvesting contribute 90.1% of the CO_2-equivalent of the LCA. Chandra *et al*. (2018) found that most of the GWP is due to the direct and indirect usage of fossil fuels, for example, during the fertilization. In this study, the low value was due to the moderate use of chemicals, such as pesticides and herbicides. The transport of sugarcane from the field to the factory represents a small load of emissions, and the two main reasons for this are the modern trucks models and the short distances that are travelled for sugarcane transportation, which is about 16.5 km, on average.

Consequently, the relatively low fuel consumption in these stages has lessened their contribution to global warming. This finding concurs with that of Ramiro *et al*. (2019), who found that the sugarcane production and harvesting stages contribute 39.5% to global warming (the climate change endpoint category). Figure 6.3 shows the contribution of the selected stages of the sugar life-cycle to the global warming potential, based on a 100-year period.

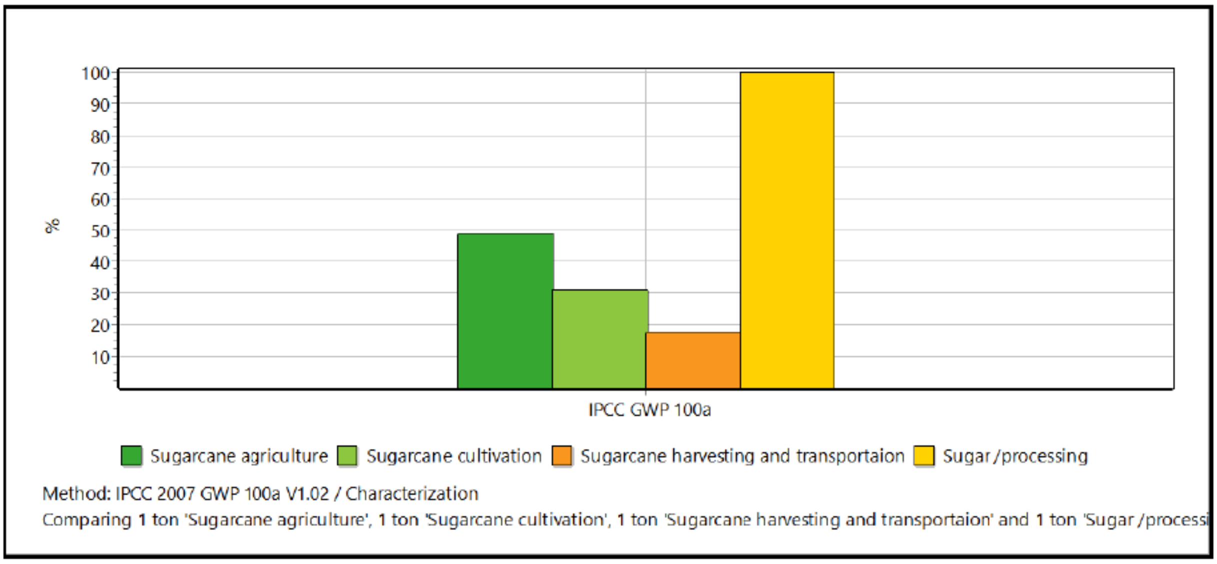

Figure 6.3 Greenhouse gas emissions, based on a 100-year GWP

6.3.4 Ozone depletion and acidification

The principal contributor to ozone depletion was sugarcane production (44%), followed by sugar processing, sugarcane cultivation and sugarcane harvesting, with a record of 22%, 18%, and 15.5%, respectively. This is because there are massive emissions during sugarcane production, due to fossil fuel consumption in essential operations, such as land preparation and and the planting of sugarcane. During sugar processing, power cogeneration represents the second contributor to ozone depletion because of the bagasse combustion in the factories. These findings agree with those of Ramiro *et al*. (2019), who found that sugarcane production has a very severe impact on the environment in Mexico. Sugar processing contributed significantly to eutrophication, acidification, particulate matter and ecotoxicity. The factors attributed to this stage were the use of chemicals, such as lime, for the refining of sugar, as well as the use of fuel oil and bagasse burning for power generation. These processes release a huge amount of greenhouse gases, which have an adverse effect on the environment. Figure 5.4 shows the impact assessment of the sugar life-cycle stages in the environment.

6.3.5 Human toxicity

One of the definitions of human toxicity is the effect of poisonous materials on the social environment. It is interpreted as the Disability-Adjusted Life Years (DALY) and is one of the quantitative severity-based indicators yield measures. The DALY approach attempts to account for the years of life lost. The total human carcinogenic toxicity for the whole process of sugar production was 15.5×10^{-3} DALY. Sugarcane production has a higher 6.6×10^{-3} (43%) contribution to the human toxicity, compared to the other stages of the sugar production life-cycle. The human toxicity for sugar processing, sugarcane harvesting, transportation and sugarcane cultivation was 4.2×10^{-3}, 2.4×10^{-3}, and 2.3×10^{-3} DALY, respectively. Human toxicity is not limited to the processes of supplying capital goods, emissions from machinery and production, and the use of agrochemicals. Human health is affected because these processes produce heavy metals. The comparable impact in Figure 6.4 shows that human toxicity is the highest in the sugarcane production stage. These results are in agreement with the findings of Chandra *et al*. (2018) and Silalertruksa *et al.* (2017).

6.3.6 Terrestrial eco-toxicity

The term of eco-toxicity includes the terrestrial eco-toxicity and the marine eco-toxicity. The unit for the impact of eco-toxicity is expressed as species per year (species.yr) - time-integrated loss of species (Bałdowska-Witos *et al*., 2020). The term of terrestrial eco-toxicity refers mainly to emissions into the atmosphere, water and soil. These emissions represent the release of heavy metals, in solution form. However, the impact of eco-toxicity is only useful in the soil when it interacts with the water. The terrestrial eco-toxicity for sugarcane agriculture, sugar processing, sugarcane cultivation, and sugarcane transportation and harvesting was 1.49×10^{-8}, 1.16×10^{-8}, 1.14×10^{-8} and 5.28×10^{-9} species. yr, respectively.

However, the marine eco-toxicity was 1.15×10^{-5}, 1.01×10^{-5}, 9.47×10^{-6} and 4.07×10^{-6} species.yr for sugarcane production, sugar processing, sugarcane cultivation, and sugarcane harvesting and transportation, respectively. As shown in Figure 6.4, marine eco-toxicity has a relatively higher impact, while terrestrial eco-toxicity has a lower effect on the sugarcane agriculture stage. However, both terrestrial and marine eco-toxicities have the highest impact during sugarcane production, compared to the other life-cycle stages of sugar production. This result is in line with the findings of Chandra *et al*. (2018), who concluded that the terrestrial eco-toxicity has the highest impact during sugarcane production, while Prasara and Gheewala (2016) found that sugarcane cultivation had a significant effect on marine eco-toxicity.

6.3.7 Eutrophication potential

Eutrophication is known as the over-enrichment of the aquatic environment with nutrients (Carpenter, 2005). This condition depletes the oxygen in the water, which causes algal blooms and anoxic events (Carpenter, 2005; Chandra *et al.*, 2018). The eutrophication is the circumstances of the surface waters and is a widespread environmental problem. It is classified into two impact categories, namely, marine eutrophication and freshwater eutrophication. Marine eutrophication includes the nitrogen enrichment of seawater and freshwater, while freshwater eutrophication considers only the phosphorous-enrichment of freshwater (Morao and de Bie, 2019). The main factors influencing eutrophication include emissions from agricultural operations, such as fertilizer run-off, leaching, the denitrification of nitrogen oxide, and ammonium. There are other factors that make a smaller contribution to eutrophication, such as transportation and the operation of machinery. Freshwater eutrophication was 1.1×10^{-7}, 7.5×10^{-8}, 4.5×10^{-8} and 2.6×10^{-8} species.yr for sugar processing, sugarcane agriculture, sugarcane cultivation, and sugarcane harvesting and transportation, respectively, while marine eutrophication was 2.02×10^{-9} 1.45×10^{-11} 7.2×10^{-12} and 5.15×10^{-12} for sugar processing, sugarcane agriculture, sugarcane cultivation, and sugarcane harvesting and transport, respectively. Figure 6.4 shows the contribution of the stages of the sugar manufacturing life-cycle to marine and freshwater eutrophication. As noted in Figure 6.4, the potential for freshwater eutrophication has a relatively higher effect on the environment, compared to marine eutrophication. However, marine eutrophication recorded 98% and freshwater eutrophication recorded 41.5% during sugar processing. This result is mainly due to the NOx emissions into the air, which generally result from the combustion processes, and which include power generation and the production of chemicals (i.e. lime) used in a sugar refinery.

6.3.8 Acidification potential

Acidification is defined as the comparative effects of SO_2 and is mainly affected by the emission of ammonia NH_3, nitrogen oxide NO_2, and sulfur oxides SO_x into the air. When these substances are deposited into the soil, they change the soil acidity, which leads to acidification. The acidification potential was 1.3×10^{-6}, 3.9×10^{-7}, 2.6×10^{-7} and 1.4×10^{-7} species.yr for sugar processing, sugarcane agriculture, sugarcane cultivation and sugarcane harvesting and transportation, respectively. As noted in Figure 6.4, the impact of terrestrial acidification is relatively high in sugar processing, compared to the other life-cycle stages. Other factors influence the acidification potential, such as emissions from the usage of fertilizers. However, the impact of acidification does not appear to be extensive in sugarcane agriculture. This result is in agreement with the findings of previous studies (Renouf *et al*., 2010; Prasara and Gheewala, 2016; Chandra *et al*., 2018), which concluded the insignificance of terrestrial acidification in the stage of sugarcane agriculture.

6.3.9 Particulate matter

The environmental damage of particulate matter formulation is the amount of suspended particles that are harmful to human health. The particulate matter potential was 8.4×10^{-4}, 6.3×10^{-4}, 2.9×10^{-4} and 2.2×10^{-4} DALY for sugar processing, sugarcane agriculture, sugarcane cultivation, and sugarcane harvesting and transportation, respectively. Figure 6.4 shows that sugar processing is the highest contributor to the emissions that form the particulate matter, such as bagasse combustion, during power generation and transport.

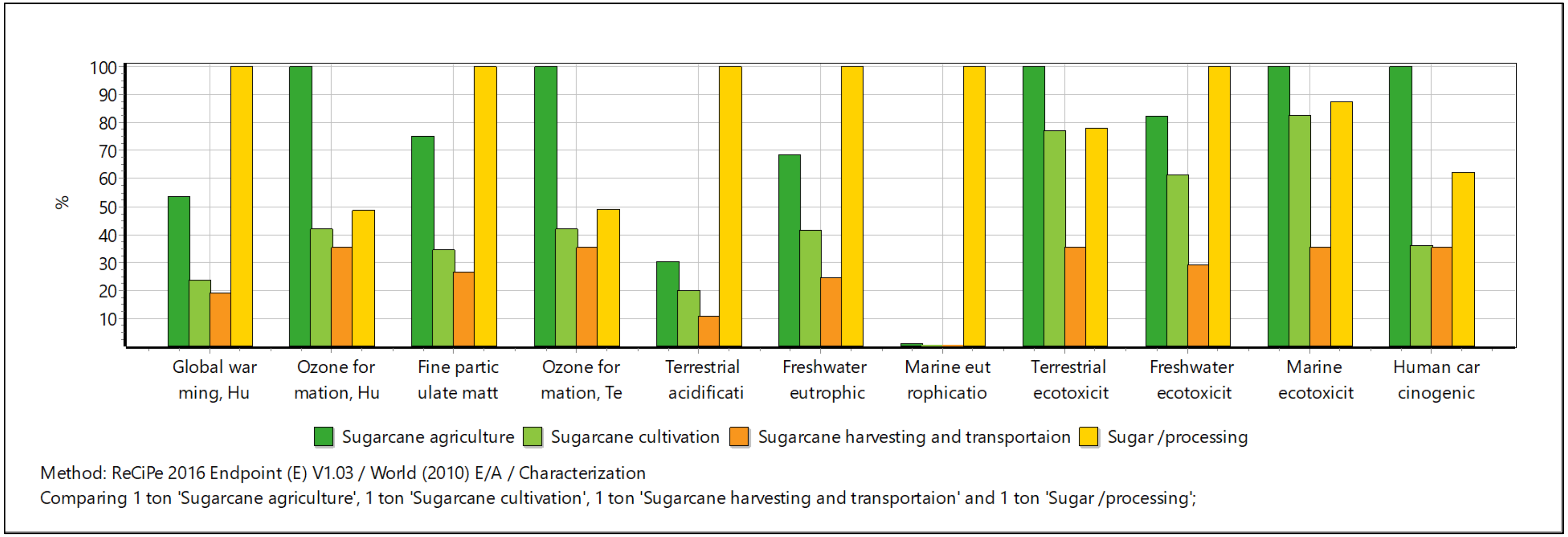

Figure 6.4 Results of characterization and damage assessment

6.4 Conclusion

This study identified the main contributors to the environmental impact of the sugar production stages, by using the life-cycle assessment method. The study revealed that the sugarcane production stage used about 2166 $MJ.tonne^{-1}$ sugar of energy, which is the highest consumer of fossil fuels. Sugar processing was the second-highest consumer of fossil fuel energy, with a share of 242 $MJ.tonne^{-1}$ sugar, and it was the main contributor to the global warming potential i.e. 18.2 kg CO_2-eq.$tonne^{-1}$ sugar, due to the huge gas emissions. The principal contributors to ozone depletion were sugarcane production, sugar processing, sugarcane cultivation and sugarcane harvesting and transportation, with percentages of 44%, 22%, 18% and 15.5%, respectively. The sugar processing stage has a significant impact on eutrophication, acidification, particulate matter, ozone depletion and eco-toxicity. However, improvements in the sugar production techniques i.e. cleaner production technology, are required in order to significantly improve the environmental performance of the industry.

The next chapter is a synthesis of the four journal papers that are included in Chapters Two to Six, and it includes the Conclusions and Recommendations for future researchers.

6.5 Recommendations

The utilization of fertilizers and herbicides represents a pollution load to the environment, due the chemical materials that they contain and the fossil fuels that are used for their application. The farmers must minimize the chemical application as much as possible, to avoid them having a negative impact.

The agricultural practices must be improved to increase the sugarcane yield per unit area and to effectively use the land. Therefore, accurate measures, such as a decision support system that is based on artificial intelligence, should be used to effectively monitor the fertilisation process. The organic matter that results from sugar processing, such as filter-cake, can be used as an alternative fertilizer. This approach will positively reduce the application rate of fertilizers and herbicides per hectare.

The sugarcane in Sudan is fully irrigated from the River Nile, mostly by using traditional irrigation methods. The surface irrigation technique (i.e. hydro-flume) should be implemented on all the sugarcane farms. The irrigation system should be improved and well-managed to increase the efficiency of the irrigation water application. Modern irrigation systems (i.e. centre-pivot) should also be adopted, which will positively improve the efficiency of water application.

Cleaner technology should be implemented, for example, using new models of harvesters with efficient fuel consumption, in order to minimize the emissions that are generated by mechanization, while manual sugarcane harvesting should be considered as an alternative to mechanized harvesting.

It is imperative that sugarcane transportation should operate efficiently, while ensuring a minimum impact on the environment. The sugarcane transportation routes should be improved, in order to mitigate the emissions, while the fleet of trucks should be renewed to improve the efficiency of fuel consumption per trip, which would positively benefit the environment.

New technology in power generation should be adopted in both the private- and government-owned sugar factories. This new technology will increase the generating efficiency and reduce the energy use in sugar processing, which will lead to a reduced fossil fuel consumption and the minimization of emissions.

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7. CONCLUSIONS AND RECOMMENDATIONS

This chapter includes the conclusions and recommendations, based on the results that were obtained in the previous chapters.

7.1 Conclusions

As one of the largest agricultural countries, Sudan could lead the African continents from the expansion of its sugar industry; however, it has not been growing as planned. The factors that have stunted the pace of its development are its lower production, poor waste management, and its associated impact on people's health and the environment. The Sudanese sugar industry has experienced complications in its product supply chain, which has negatively influenced the sector for a long time. This study aimed to identify firstly, the factors that influence the sugar productivity. Secondly, to find the stages of the sugar manufacturing life-cycle that has the most impact on the environment. Thirdly, to assess the impact of the industry's waste products on the communities living in the vicinity of sugar factories. Finally, to develop a framework to improve the productivity, enhance the management of sugar industrial waste and to minimise the associated impact on the environment and the health of the people.

The documentary review method and a cross-sectional survey approach were used for data collection. The techniques used for data analysis included a qualitative content analysis technique (i.e. a textual analysis), a linear regression analysis, the intensity relation matrix technique, the descriptive statistics, non-parametric statistics, logistic regression analyses, characterisation methods of ReCiPe 2016 and the Intergovernmental Panel for Climate Change (IPCC) (2007). The study involved the use of software i.e. the SimaPro version 9.0.0.49, the Statistical Package for Social Science (SPSS) Version 19 and Microsoft Excel 2010.

The results revealed that the sugarcane yield was the main contributor to the decline in productivity. The most influential factors contributing to the decline in sugarcane yield were the lack of agricultural inputs, the insufficient provision and replacement of implements, inadequate rehabilitation programs and improper land preparation. The soil salinity on the farms and the agro-climatic conditions also contributed to the decrease in sugarcane production, while the continuous shortage of irrigation water also influenced the yield, and the harvesting of sugarcane at a non-optimal age decreased the sucrose present in the extracted juice. The abovementioned factors have negatively influenced the efficiency of sugar extraction. The worn-out equipment and failure to carry out maintenance have affected the milling performance, which has remained at 78%. The study recommends reforms for spurring the decision-makers on to solve the causes of this decline, in order to significantly improve the sugar productivity.

Also, this study revealed that wastewater was released without any pre-treatment in most of the selected sugar industries, which significantly ($P < 0.05$) endangered the health of humans. This wastewater has created significant ($P < 0.05$) swamps, which are a suitable environment for the reproduction of mosquitoes and off-odours. In some cases, the wastewater was mixed with water sources, causing a health risk and influencing crop and animal production. The pollutants have significantly ($P < 0.05$) caused eye and respiratory diseases to the communities living in the vicinity of the selected industries. A framework based on the collaborative efforts between the society, environmental authorities and the decision-makers in the industry, was designed to minimise the environmental impact and health risks.

The results of life-cycle assessment showed that 39% of fossil energy was consumed during the sugarcane production stage and that this was the main contributor (59%) to the greenhouse gas emissions and ozone depletion. The sugar-processing stage was the principal contributor to damaging the environment (i.e. global warming). Sugar processing also contributed significantly to ecotoxicity, acidification, eutrophication and particulate matter formulation. The study recommended an improvement in the environmental performance of sugar production in Sudan.

However, this study provided new knowledge to improve productivity and to solve the identified causes of the problem. The study also provided baseline information on the impact of sugar industrial waste and built a well-structured plan to minimise this risk. Moreover, for the first time, this study assessed the environmental performance of sugar production in Sudan by using the LCA approach.

The novel aspects of the research can be summarised as follows:

(a) The most influential factors leading to the decline in productivity of the Sudanese sugar factories were identified and evaluated by using the system analysis method i.e. the cause and effect diagram and the intensity relation matrix.

(b) The linear regression function was used in (Eqs. 3.4, 3.5, 3.6 and 3.7) based on the relationship between factors Cy, Cq and Fp, to provide an independent estimation of the effect of each variable on the productivity (Sp).
(c) The health risks and the environmental impact of exposure to sugar industrial waste were assessed and identified.
(d) A framework was developed, which incorporates the environmental authorities, the social efforts and the industry's decision-makers, to improve the handling the sugar industrial waste and to minimise its associated impact.
(e) A life-cycle assessment of the Sudanese sugar production was applied to calculate the energy consumption and its associated impact on the environment.

Based on the results that were obtained, this research will contribute to both the rectification of sustainable productivity and the preservation of the environmental health of the Sudanese sugar industry. It represents an appropriate model for the improved management of sugar industrial waste and for minimising the associated emissions and impacts.

7.2 Recommendations

This section includes recommendations based on the observations of the researcher during conducting this study. The recommendations that can be made are listed as follows:

(a) The sugarcane yield can be greatly increased by optimizing the agricultural application package and using modern technologies. The sugarcane transportation system can be developed by introducing higher-capacity trucks to decrease the stoppages during the crushing season. Hence, the efficiency of the factories will be increased, as well as the sugar productivity.
(b) A rehabilitation program should be carried out for most of the government-owned mills. The plan should ensure the provision of new spare parts for the sugar processing supply chain, by using modern technology. This procedure will ensure the increase of the sugar extraction rate, as well as the milling efficiency.
(c) It is a well-known fact that the more sugar that is produced, the more waste is generated. Consequently, if the waste is not appropriately managed, environmental problems will appear and affect the surrounding communities. Therefore, it is recommended that sugar industrial waste should be appropriately handled and treated.

The provision of new techniques (i.e. sedimentation pans) for wastewater treatment should be considered for all the sugar factories.

(d) New technologies should also be adopted to reduce the greenhouse gas emissions. The current jimmies of the factories should be provided with the appropriate technology for filtering the carbon.

(e) The energy policy in the sugar industry should be reconsidered immediately, in order to minimize the usage of fossil fuel resources.

(f) Power generation turbines with a high efficiency that can consume only 6.5 tonne of steam to produce one MWh, should be adopted in all sugar factories. Another alternative is for the decision-makers to incorporate bio-fuel technology by creating plants that use the molasses as the raw material for bio-ethanol production.

(g) The use of machinery that uses renewable energy sources should be encouraged. This trend will maximize the efficiency of energy usage and minimize the consequent environmental impacts.

(h) Effective measures should be taken to ensure the integration of the industrial, social, and environmental sectors in order to conserve the bionetwork of the sugar industry. Institutions should be created that are responsible for the implementation of a widespread environment, pollution, and waste management legislation. This approach will provide an excellent background for better understanding the relationship between infection, waste management, and a healthy life for the communities surrounding the sugar factories. It is also essential to develop health services for the population living in the vicinity of the selected sugar industries.

(i) It is essential to collect information about pollution and waste monitoring, in order to implement pollution reduction measures. Sharing knowledge is vital for creating an awareness of the effects of sugar industry waste on the environment and human health.

(j) The provision of appropriate training for each job involving technicians and engineers should not be compromised. The education level of the labourers must be considered, and the wages should be given attention and increased. This approach will improve the workers' performance in all departments of the sugar industry, which will, in turn, positively increase sugar productivity.

(k) The suggested topics for further research are as follows: further life-cycle assessments of the sugar industry in Sudan should be undertaken, a standard of the national specific greenhouse gas emissions factors for various potential sources should be developed, further analyses should be undertaken on sugar manufacturing waste and its effect on the environment, and an integral program for monitoring the efficiency of sugar production should be developed.

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9. APPENDICES

9.1 Appendix A: Questionnaire

Dear Respondent, I am a PhD student at the *Department of Bioresources Engineering*, *University of KwaZulu-Natal*, *South Africa*. My research project is entitled as an evaluation of the production and environmental performance of the Sudanese sugar industry. The aim of the research is to carry out research on the evaluation the impacts of waste disposal, particle pollutants and toxic gases on the communities residing around the six sugar factories in Sudan. I kindly request that you to respond to the questionnaire below. The information you provide will contribute to important environmental measures for Sudan. All responses will be handled confidentially and be used only for research purposes.

Background information

(1) Gender: Male ( ) Female ( )

(2) Age: ………………………….

(3) Location………………………………………………………………………………

(4) Education: Primary school ( ) Secondary school ( ) University ( ) Postgraduate ( )

(4) Period of residing: 0- 10 years ( ) 10-30 years ( ) 30- 50 years ( ) more than 50 years ( )

1. Family information					
No	Gender	Age	Education	Occupation	Annual income (1US$ = 17,5 SDG)
1					
2					
3					
4					
5					

2. Effects of wastewater disposal resulting from sugarcane manufacturing on the populations living around the selected factory			
	Disagree	Agree	Neutral
(a) The wastewater stream is close to where I live			
(b) The wastewater stream in running all year round			
(c) The wastewater is disposed to a water body (Nile)			
(d) The wastewater disposal contaminates our water sources			
(e) The drinking water we use is crystal clear			
(f) The drinking water we use tastes normal			
(g) The drinking water we use has no a distinctive unpleasant smell			
(h) The wastewater disposal creates swamps near where we live, which insects inhabit			
(i) It creates unfavorable odors because of its stagnancy			
(j) It creates mosquitoes, which massively spreading all the year			
(k) It creates flies, which spread all the year			
(l) We have experienced malaria disease several times because of the mosquitoes			

3. Degree of family complaining towards:				
	High	Medium	Low	No complain
(a). The odours of wastewater				
(b). Mosquito				
(c). Fly				
(e). Suspending particles resulting from cane burning				
(f). Suspending particles resulting from bagasse burning				
4. Effects of wastewater disposals resulting from sugarcane manufacturing on animal				

production		
	Yes	No
(a) Do you have a farm or work on a farm?		
(b) Is there any livestock in your farm (cattle, sheep, poultry, horses)?		
(c) What is the source of water for your livestock? Choose from the options below: i. Cane irrigation canal ii. Cane drainage canal iii. Wastewater stream from the factory iv. River Nile v. Overhead tank vi. Ground water (well) vii. Natural trenches		
(d) Are there any cases of illness among the animals because of the water source (if it is the wastewater)?		
(e) Are there any death cases among the animals because of water source (if it is the wastewater)?		

5. Effects of wastewater disposal resulting from sugarcane manufacturing on crop production		
	Yes	No
(a) Do you have any crop plantation activities in your farm		
(b) If yes, what type of crop are you used to planting 1. Vegetables 2. Cereal crop 3. Fruit trees		
(c) Do you use any kind of pre-treatment to the wastewater before you use it, such as sedimentation tank?		

(d) Why did you choose to use the wastewater for irrigation? Because: a) There is no other option b) It is enriched with nutrients c) Its low cost d) Other reasons ………………………….		
(e) According to your knowledge and experience, do you know the health risks of using the industrial wastewater for crop plantations?		
(f) Have there been any health problems coming from customers because of your products?		
(g) If **yes,** what kind of health problems did they informed you of? 1) Stomach ache 2) Vomiting 3) Diarrhea 4) Other reasons ………………………….		

6. Environmental effects of organic and particulate pollutants resulting from cane burning and processing on the communities residing around the factory			
	Disagree	Agree	Neutral
(a) There is a large amount of particulate matters suspended in the air during the harvesting season, which contaminates the air we breathe			
(b) The bulk of organic pollutants result from cane burning during the harvesting season create dirt on the floors and clothes			
(c) There are huge smoke clouds covering the sky during the harvesting season which contaminates the air we breathe			
(d) There are off-odors during the harvesting season, which contaminate the air we breathe			

(e) There are noisy sounds coming from the direction of the factory during the harvesting season, which spoils the atmosphere.			
(f) These problems have existed since the factory was established, but they have become worse with the aging of the industry			

7. Health effects of the pollutants resulting from cane burning and processing operations on the residents living near the selected factories									
Infected members in the family				The infection					
No	Gender		Age	Eye disease	Heart attach	Respiratory disease	Asthma	Chronic bronchitis	Irregular heartbeat
	Male	female							

8. Health services presented by the industry towards the surrounding communities		
	Yes	No
(a) There are rotational prevention procedures (pesticides spray) conducted by a specialist health team		
(b) There is a hospital nearby where I live		
(c) There is available medical aid in our hospital		
(d) There are enough medical teams in our hospital		
(e) The available doctors are well-qualified to assist		

9. Important issues that should be considered			
	Disagree	Agree	Neutral
(a) Protecting the residents from the dangerous influences of the sugar factories			
(b) Developing innovative technologies to improve the surrounding air quality, such as stopping cane burning			
(c) Developing innovative technologies to enhance the water quality for domestic usage, such as establishing wastewater treatment plants			
(d) Sufficiently controlling the sugar by-products and its recycling techniques			