INVESTIGATION OF THE ENVIRONMENTAL IMPACTS OF BIOETHANOL PRODUCTION: A CASE FOR BIOETHANOL FROM SUGARCANE IN KWAZULU-NATAL, SOUTH AFRICA

By

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I declare that the above thesis is my own work and that all the sources that I have used or quoted have been indicated and acknowledged by means of complete references.

I further declare that I submitted to originality checking software and that it falls within the acceptable requirements for originality.

I further declare that I have not previously submitted this work, or part of it, for examination at UNISA for another qualification or any other higher education institution.

05/11/2021

SIGNATURE DATE

DEDICATIONS

This study is wholeheartedly dedicated to my beloved late dad, Mr. Isaac Mbamuku-Nduku. He was keen on sustainable environments through his published works in Geography and Economics and his passion for sustainable agriculture. He had always encouraged us to lead sustainable lives.

This thesis is also dedicated to my lovely mum, Mrs. Rose Kah Nduku, who has been on a sickbed for more than 10 years and has not stopped seeking God's blessings upon me. She always encourages me to study until I am tired of studying.

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ABSTRACT

At the current global population growth rate, the world is experiencing an unprecedented demand for natural and processed resources such as energy resources. Bioethanol being a comparatively sustainable source of energy has gained global traction as one of the suitable replacements for fossil fuels. However, the production of bioethanol has contributed to several environmental issues globally. This study was done based on specific objectives which include the evaluation of the environmental impacts in clearing natural vegetation for the purpose of sugarcane agriculture in uMlalazi, KwaZulu Natal (KZN), to evaluate how three different scenarios of sugarcane agricultural practices contribute to the emission of GHG and to identify GHG emission hot spots, to assess the environmental impact of sugarcane production for bioethanol on water catchments of uMlalazi in KZN, South Africa, and to analyse the wastes, waste management issues, gaseous emissions and their impacts from case studied sugar and bioethanol plants in KZN, South Africa. These objectives were motivated by the need to assess the environmental impacts of bioethanol production across its value chain in the KwaZulu Natal province of South Africa. Environmental impacts of bioethanol production through the analysis of waste generation in relation to potential environmental issues in some significant stages of the production value chain of bioethanol was the focus of this project.

Various methods and models were incorporated in this study. GIS models helped with the analysis of the impact of land use changes versus sugarcane farms size changes over time. The Cool Farm Tool was used to analyse the amounts of greenhouse gasses emitted throughout sugarcane farming activities while identifying emission hotspots. Both GIS models and Water Quality Index (WQI) modelling techniques were used in analysing the quality of the water within the catchment areas under study. Secondary data on individual water quality parameters were sourced from the Department of Water Affairs (DWA). The DWAF (1996) guidelines for aquatic ecosystem standards were compared with the measured water quality. Finally, document analysis that followed observations and informal interviews were employed to analyse the waste generated from a case studied sugar mill and a bioethanol plant. The impact of such waste was analysed following the collection of primary and secondary data.

It was noted in this study that although the overall sugarcane farm size in uMlalazi has reduced since 1985, the conserved ecosystems are seen to have increased in sizes between 1985 and 2020.

Findings from the CFT model, present emission hot spots which include fertilizer production, fertilizer use in the soil, residue management, and diesel use in the various farm machinery. While single case studied emerging sugarcane farms from KwaDukuza (KDZ), Richards Bay (RB), Pietermaritzburg (PMB), and Port Shepstone (PS) all emit an average of about 550 000 kg CO_2eq per farm, per farming cycle, their counterpart commercial sugarcane farms in the same regions emitted 1295970, 210310 and 10024970 kg CO_2eq from KDZ, RB and PMB, respectively. Water pollution was confirmed in parts of the catchments. The results show very poor to poor water quality. For the 2014 scenario, 20% of the catchment contains water unsuitable for aquatic ecosystems, 33% is very poor and 47% shows poor to good water quality. While the 2018 scenario shows 15%, 10% and 75% for unsuitable, very poor and poor to good water qualities respectively. The sugar mill presented an average effluent production from 2010 to 2019 amounted to 310061.2 tons, 67318.79 tons filter cake, 37302.83 tons molasses, and 306349.2 tons bagasse. With no reference to the waste management strategy and effluent treatment employed at this mill, its high COD levels of 13023 mg/L, will negatively impact nearby aquatic ecosystems. On the other side, the bioethanol mill was also seen to generate waste in which the management strategies could not be accounted for during this study.

In conclusion, the value chain of bioethanol therefore presents several environmental issues of concern that range from land use change impacts to both air and water pollution. Sugarcane agricultural practices have contributed to both air and water pollution likewise the sugar and bioethanol milling processes. It is therefore recommended that waste minimization and mitigation strategies be put in place in these sectors.

Keywords:

Bioethanol, Land use change, Ecosystem services, Sugarcane agriculture, Fertilizer, Irrigation, Surface water pollution, Greenhouse gases, Environmental Impact, Cool farm tool, Molasses, Satellite images, Water quality index, Vinasse, sustainable energy.

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LIST OF ACRONYMS

Acronyms	Meaning
AHP	Analytical Hierarchy Process
BE	Bioethanol
BF	Biofuel
C_2H_5OH or EtOH	Bioethanol
CFT	Cool Farm Tool
COVID 19	Corona Virus Disease of 2019
CR	Consistency ratio
CSIR	Council of Scientific and Industrial Research
DAFF	Department of Agriculture, Forestry and Fishery (SA)
DED	Department of Economic Development (SA)
DME	Department of Mineral and Energy (SA)
DRDLR	Department of Rural Development and Land Reform (SA)
DWAF	Department of water, agriculture, and forestry (SA)
DWS	Department of water and sanitation (SA)
EC	Electrical conductivity
EPA	Environmental Protection Agency
eq	equivalent
FAO	Food and Agricultural Organization
Gg	Giga gram
GHG	Greenhouse gas
GIS	Geographical Information Systems
ICP-OES	Inductively coupled plasma - optical emission spectrometry
IDW	Inverse distance weighted
IPCC	International Panel on Climate Change mitigation
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
KCl	Potassium chloride
KZN	KwaZulu Natal

LC	Life Cycle
LCA	Life Cycle Assessment
LCAM	Life Cycle Assessment Model / Modelling
LULCC	Land use and land cover change
MLA	Machine Learning Algorithms
mS	Milli Siemen
OECD	Organization for Economic Co-operation and Development
RAMSAR	The first conference on wetland protection that took place in an Iran City called Ramsar.
REN21	Renewables 2021
SA	South Africa
SACGA	South African Cane Growers' Association
SAFDA	South African Farmers Development Association
SANS	South African National Standards
SASA	South African Sugar Association
SASRI	South African sugarcane Research Institute
SASS	Stream assessment scoring system
SOC	soil organic carbon
US EPA	The United States Environmental Protection Agency
VESS	visual evaluation of soil structure
WHO	World Health Organisation
WQI	Water quality index
μS	Micro Siemen

CHAPTER 1: BACKGROUND TO THE STUDY

1.1 INTRODUCTION

Global population has increased about 4.25 times in the last century (Zhang and Lis, 2020). This increase contributes to the demands for energy resources such as oil and balanced growth of oil production of about 21 times (Zhang & Lis, 2020). Oil production leads to hydrocarbons production and the depletion of fossil fuels. Fossil fuels are a huge contributor to climate change through the emission of air greenhouse gasses (GHG) during their extraction and burning (Perera,2018; Yadav et al., (2020). Fossil fuels also pollute water bodies with acidic effluents during their extraction (Union of concerned scientists, 2017; Stewart, 2020). With the quest to shrink the environmental footprint of fossil fuels, most global economies are now opting to become bio economies (Kohler, 2016; Jones et al., 2017). The 2018 statistics from the international energy urgency show a biofuel production forecast of a 25% increase over the next five years (https://www.iea.org/fuels-and-technologies/bioenergy). A decline is also evident in the available net liquid oil from 2014 to 2015 (Solé et al., 2018). However, with the current global health turbulences due to the COVID 19 pandemic, the global population has turned to hand sanitizers with about 70% alcohol (Ethyl Alcohol). This has increased the demand for bioethanol.

A macro-regional bioeconomy strategy for 7 Eastern African countries, including Burundi, Ethiopia, Kenya, Rwanda, Tanzania, South Sudan, and Uganda, was published, and applauded for it is the first of its kind on the African continent (International Advisory Council on Global Bioeconomy, 2020). This strategy encourages the use of bioresources to address shared regional problems. South Africa also published a dedicated bioeconomy strategy in 2013 and again in 2020 (International Advisory Council on Global Bioeconomy, 2020). With one of the problems being the increasing need for energy, green energy/bioenergy was the favored alternative to fossil fuel due to its renewable and more sustainable nature more than eight years ago (Huang et al., 2012; Raman & Mohr, 2014, Bušić et al., 2018). Moreover, changing the energy mix with bioenergy introduction will break the connection between GHG emissions and economic activities (United

Nations, 2020). Bioethanol, therefore, has strategic importance in reducing environmental degradation and, in effect, a reduction in global climate changes (Popp et al., 2014; Souza et al., 2017). Being produced from renewable feedstocks such as sugarcane, bioethanol production produces a smaller GHG footprint compared to other fossil fuels. This aligns with the principles of sustainable development. Projections for global bioethanol production will increase to 134.5 billion litres in 2024 from 100.2 billion liters in 2016 (Bušić et al., 2018), with two-thirds of this increase originating from Brazil. Bušić et al. (2018) also noted that about 40% of the global bioethanol production is from sugarcane.

South Africa (SA) has been encouraged to use biofuels such as bioethanol to run their economic activities such as blended with petrol to be used in cars engines. The SA government estimated that GHG emissions could be reduced by 30% using bioethanol (Pradhan & Mbohwa, 2017). According to Pradhan and Mbohwa (2017), the use of ethanol also creates job opportunities along its value chain. They, Pradhan & Mbohwa (2017), also mention that ethanol is not a taxable fuel for biofuel's industrial strategy, and thus it is 100% exempted from fuel tax. Therefore, it was placed under the regulation that 2 – 10% ethanol blends were allowed in South Africa.

Liquid biofuels such as bioethanol's contribution to the entire nation's fuel supply in South Africa was expected to be at least 2% by 2013 (Blanchard et al., 2011). The South African government also recommended that 20–50% of biofuel renewable energy be implemented by 2013, using sugar cane and sugar beet as bioethanol feed stocks (Deenanath et al., 2012). According to Blanchard et al. (2011), concerning the South African Biofuel Industrial Strategy of 2007, incentives were provided for reaching this 2% biofuel supply rate by 2013. Bioethanol is one of the most used liquid biofuels blended with petrol in the transport industry (Dufey, 2006; Tesfaw and Assefa, 2014, Bušić et al., 2018). Bioethanol can also be converted into alcoholic beverages (Kubo et al., 2014; Okoye and Eboatu, 2016). Bioethanol is also used as solvents in varnishes and perfumes (Okoye and Eboatu, 2016). Some countries, including Brazil, have granted licenses for the use of bioethanol to power vehicles. Over the years, Brazil has issued many vehicles with permits to be powered by bioethanol. This record is presented in Table 1.1.

Table 1.1: Licensing of Ethanol Powered Vehicles (pure ethanol & flex-fuel units) Global Agricultural Information Network (GAIN) Report Number: BR11016 for Brazil Sugar Annual Reports (2012) – (Barros & Giles 2012)

2006	2007	2008	2009	2010	2011	2012
1,432,197	2,003,197	2,329,331	2,652,368	2,876,223	2,848,122	414,392

Although these figures are decreasing, this puts Brazil as one of the leading countries using this sustainable biofuel in their transport sector. Although some African countries are still lagging, according to Gasparatus et al. (2012), biofuel is being given increasing attention due to the uneven distribution of energy resources in African countries, and the experience of frequent blackouts (IRENE, 2020). However, some countries, including South Africa, have been hesitant to fully embrace the biofuel option because of insufficient information on the sustainability of its production (Brent, 2009; Mukunza, 2017) and poor government intervention (Funke, 2010). According to Pradhan and Mbohwa (2014), as of 2014, the biofuel development in South Africa has stalled in the legislative process. As a result, there is no evidence of large-scale commercial biofuel projects yet. However, due to favourable climatic conditions and arable land and water availability, the Southern African region has been identified as a region with high potential for biofuel production (Arndt et al., 2019). Although there are concerns about the usage of biofuels from stakeholders, the policies and institutions developed will promote biofuels production and distribution in South Africa (Mukunza, 2017).

As much as biofuels have been suggested to substitute fossil fuels due to their comparatively lower levels of environmental degradation such as using a renewable feedstock (sugarcane, sugar beets) for its production, biofuels such as bioethanol still create environmental degradation along their production chain. Thus, this study evaluates the phases and activities along its value chain that contribute to environmental degradation with the aim of recommending more sustainable practices that are required to meet the energy demand of future generations.

According to Owusu and Asumadu-Sarkodie (2016), several practices along the production chain of bioethanol makes it unsustainable. Air, water, and land pollution are experienced along the production value chain of bioethanol (Lui et al., 2019). The conversion of agricultural land and coastal forests into sugarcane agricultural land for bioethanol production poses environmental risks. Such land use and cover change (LULCC) lead to anthropogenic environmental degradation (Hitayezu et al., 2015). Adding soil nutrients to the soil without proper soil tests with contribute to impacts such as the nitrous-oxide emission and the leaching of nitrate into water bodies leading to eutrophication. Such anthropogenic practices thus need attention through proper environmental management systems (Sharma et al., 2021). Water pollution resulting from fertilizer use on agricultural lands also impacts LULCC (Chmielewski et al., 2018).

Sugarcane agriculture, molasses extraction during sugar production, and the conversion of molasses to bioethanol are the major phases of the bioethanol production chain that contribute to environmental degradation. While molasses is a by-product from sugar production, bioethanol is produced by fermenting sugar or molasses or starch components of plants or plant by-products (De Oliveira et al., 2005; Bušić et al., 2018). Different plant-based raw materials can also be used to produce bioethanol, an example being lignocellulosic biomass such as agricultural and forestry residues and herbaceous energy crops (Bušić et al., 2018). However, in this study, sugarcane has been considered the first raw material to produce bioethanol (Dufey, 2006; Bušić et al., 2018).

Sugarcane is becoming one of the world-leading crops produced for bioethanol, sugar, bagasse, and other lignocellulose (Dias De Oliveira et al., 2005; Figueroa-Rodríguez et al., 2019). The year 2016, saw a global sugarcane agriculture on 26,774,304 ha with a 1,890,661,751 tons production (Figueroa-Rodríguez et al., 2019). South Africa has cultivated sugarcane on 23 658 hectares of land (Mohlala et al., 2016). This has placed South Africa as the 15th highest sugarcane producer globally, and it contributes about 28.13 % of the total contribution of sub-Saharan African sugarcane production (Mohlala et al., 2016). According to 2019 statistics, South Africa is the 11th top sugarcane producing country globally (OECD, 2020, FAO, 2020) with a total cultivated land of 253912ha and full production of 1607 million tons in 2017 (Pradhan & Mbohwa, 2017; OECD, 2020) and total cane production of 2250 million tons in 2019 (FAO, 2020). With the increase in sugarcane agricultural land over the years, on the one hand, GHG emission has also felt a proportionate increase. On the other hand, water resources are polluted due to chemical fertilizers on the farms. The various practices that contribute to sugarcane production such as, burnt harvesting, the use of farm machineries that burn fossil fuels, the use of chemical fertilizers and the transport trucks running on fossil fuels all contribute to the generation of GHG during sugarcane agriculture as a phase in bioethanol production.

The top nine global sugarcane producing countries' GHG emission has increased from 475.269 Giga gram (Gg) CO_2 eq in 2000 to 534.3714 Gg CO_2 eq in 2017 (FAOSTAT, 2020). South Africa saw a marginal decrease to 13.4792Gg CO_2 eq in 2017 from 16.4528 Gg CO_2 eq in 2000 (FAOSTAT, 2020). However, these figures do not provide us with what each farm produces per hectare of farmland, as is the case in this study. With SA sugarcane agriculture increasing, it was necessary to study how the sugarcane farm practices influence GHG emissions. Part of the discovery during this study is that a single emerging sugarcane farm in SA can emit up to 26 099.93kg CO_2 eq.

Therefore, this research has assessed some of the environmental impacts associated with the bioethanol production chain. The study evaluated the effects of LULCC on ecosystem services in parts of KZN, the types of waste generated, and gaseous losses emitted along the production chain of bioethanol, and finally, the effects of such waste on the biophysical environment. Therefore, this study is imperative as environmental management practices will not remain stagnant, likewise the expansion of bioethanol production moving to new frontiers as biofuel demands increase with population increase.

1.2 JUSTIFICATION OF THE STUDY

South Africa depends mostly on fossil fuels such as coal as its source of energy (Department of Minerals and Energy, 2003; Owusu et al., 2016) due to the availability of this natural resource. A 5% of its population consumes about 40% of the electricity used in Africa (Owusu et al., 2016). South Africa imports most of its oil, but it also has the world’s largest coal-to-liquid plant (McSweeney and Timperley, 2018), contributing to its carbon emissions. According to the Council of Scientific and Industrial Research (CSIR)

report by Roos (2009), most (87.2%) of Eskom's electricity is generated from coal-fired stations, and Sasol produces about 30% of their liquid fuel from coal with the use of the Fischer-Tropsch process. This renders this single point CO_2 source of the Sasol Secunda plant the largest in South Africa (SA). Globally, South Africa is in the 12th position concerning CO_2 emission (Roos, 2009), despite SA being the 30th largest economy globally (Roos 2009). According to the 2018 Carbon brief profile, South Africa is now placed at the 14th position globally with respect to GHG emissions (McSweeney and Timperley, 2018). According to the Carbon brief profile for SA (2018), with this position, SA has pledged to peak its GHG emission by 2025 before stepping it down by 2030.
There are various sources of GHG emission that have been identified in South Africa. These include but are not limited to land-use change, unsustainable agricultural practices, and inadequate waste management systems at the industrial level (McSweeney and Timperley, 2018). These issues were considered, and the recommendations for renewable energy and their sources were made in the white paper for renewable energy (2003). Because global bioethanol production has increased by 67% between 2008 and 2018 (Jeswani et al., 2020), it is reasonable to state that bioethanol has the potential to lessen GHG emissions in South Africa due to its renewable feedstock and if sound environmental management is employed alongside its production chain (Tomaschek et al., 2012; Wang et al., 2012; Lewandrowski et al., 2020).

It is stipulated that biofuels should have at least 50% lower emissions than their fossil fuel alternatives for installations in operation before October 2015 and 60% for installations starting after this date (Jeswani et al., 2020). However, it is not clear what the actual GHG emission reduction rate is, especially considering other environmental impacts of bioethanol. Several authors argue that bioethanol produces a reduced GHG emission as compared to fossil fuels (Bastos & Mairon, 2009; Achten &Verchot, 2011; Janssen et al., 2014), because of the net absorption of CO_2 by sugarcane plants themselves, while other recent researchers argue through the provision of evidence that bioethanol has a higher environmental degradation potential when a full life cycle assessment is carried out on sugarcane bioethanol (Aquila et al., 2011; German et al., 2011; Guariguata et al. 2011; Gasparatos et al., 2012; Walter & Machado, 2014; Jeswani et al. 2020).

1.2.1 Global bioethanol demands increase with the outbreak of COVID 19 pandemic from 2019 – 2021

There has been a general increase globally with ethanol consumption from 2007 to 2010, with the USA and Brazil championing a 28.5% increase and China with an 8.6% increase (The Global Ethanol Market Overview, 2010). Ethanol is one of the major components used in the production of hand sanitisers. According to Singh et al. (2020), hand sanitisers came into practical use in health care in 1966 and became popular globally in the early 1990s.

In the wake of the global health pandemic caused by the coronavirus (COVID-19) in 2019, the World Health Organisation recommended using alcohol-based hand sanitisers and other preventative measures to combat the deadly virus. Hand sanitiser contains ethanol, isopropyl alcohol, n-propanol and, water and generally have 60 – 70% ethanol ethyl alcohol (Golin et al., 2020).

According to market research conducted by the Nielsen Holding Inc., the sale of hand sanitisers increased by 300% and 470% in February and March 2020, respectively and in Italy, this increase was marked at 561% from 24th February-15th March 2020 (Berardi et al.2020). This increase was noted to have occurred during the first three weeks of the pandemic.

The COVID-19 outbreak has caused run-on hand-sanitisers, which has, in turn, created excessive demand for alcohols required to produce hand sanitisers and disinfectants, says the SASOL CEO in their media release (SASOL, 2020). This media report also mentions that Sasol has experienced an increase in demand of nearly 400% for an alcohol-based product due to the COVID-19 pandemic. Therefore, it can be inferred from such quantitative evidence that the COVID-19 pandemic has contributed to the increase in ethanol demand globally.

1.3 THE PROBLEM STATEMENT

Bioethanol offers a good alternative to fossil fuels to at individual or group production levels, it is however noted that bioethanol still creates environmental degradation along its production chain although at a comparatively reduced rate compared to the fossil fuels. In this study, a systemic thinking approach was incorporated such that the whole production chain of bioethanol was analysed in KZN with the aim of identifying the hotspots practices that make the production unsustainable. In illustration, Chingono and Mbohwa (2015) reported, in their study about the production of bioethanol, environmental impacts associated with the bioethanol system were discovered. Figure 1.1 demonstrates that effects such as land conversions, biodiversity loss, GHG emissions, soil erosion, water pollution, and air pollution can all be associated with bioethanol production (Chingono & Mbohwa, 2015).

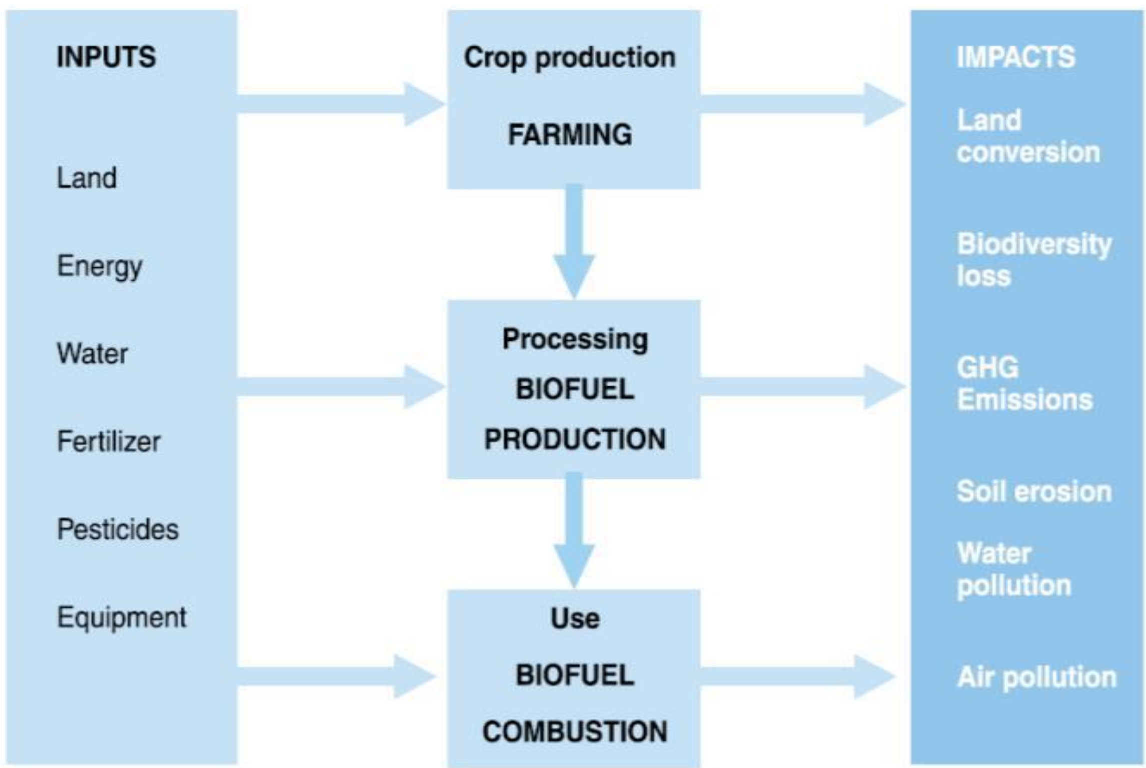

Figure 1.1: General LCA and value chain of BF (Chingono & Mbohwa, 2015)

With wetlands and tropical forests are fast becoming endangered due to the agricultural expansion needed to produce sugarcane for bioethanol, there is an offset in the benefit of substituting fossil fuels with biofuels (Marcelo, 2015). However, bioethanol production at commercial levels requires large-scale commercially cultivated sugarcane. Furthermore, according to Wessels et al. (2016), although there has been increasing urbanisation and conversion of natural land coverage to agricultural land use, contributing to environmental pressures in South Africa, the national land cover map was most recently updated in 2014 for the first time since 2000. This makes it challenging to methodically examine and conclude on the impacts of LULCC.

Maximising output thus comes with the requirement of using inputs that are not environmentally friendly such as LULCC, the excessive use of chemical fertilizers, pesticides, or the use of diesel-operated machines, and the practice of burnt harvesting. It is thus a worrying fact that large-scale sugarcane agriculture for bioethanol production causes serious environmental problems such as GHG emission that contributes to global warming and climate change. On another note, effluents from sugarcane farms can alter water's chemical and physical characteristics, in the process causing water pollution (Tawati et al., 2018). Furthermore, the excessive use of chemical fertilizers and other pesticides becomes cause for run-off into water bodies that lead to a chemical imbalance in the aquatic ecosystem. This causes eutrophication and a damaged or compromised ecosystem.

The industrial processes of sugar processing and molasses into ethanol have environmental implications from the waste management perspective. The discharge of toxic liquid waste, vinasse, and spent wash disrupts the BOD levels in aquatic ecosystems. Such degradation of the biophysical environment translates into various social, economic, and political problems. Although there is mention of the cost implications of GHG emissions in the Integrated Energy and Resource Plan - IRP (2019), both the white paper for renewable energy (2003) and the IRP (2019) have not mentioned the possibilities of waste generation during the production of certain “sustainable” energies such as biofuels. Unfortunately, there is also no mention of any management strategies for all these problems associated with biofuels in both the IRP (2019) and the

White Paper for Renewable Energy (2003). Furthermore, with a considerable literature gap in the South African context, it is also not clear if these impacts have been identified and mitigated by South Africa in their attempt to venture into bioethanol as an alternative to fossil fuel. Therefore, there is a need to consider the environmental perspectives and investigate the sustainability of the total bio-ethanol production system for the impacts of and mitigation to LULCC issues, waste generation, and waste management.

1.2.1 Study Justification

This study has analysed some of the environmental impacts that result from bioethanol production. Land use and land cover change (LULCC), sugarcane agriculture, and the industrial processes for bioethanol production determine the benefit of bioethanol production to the environment and society (Sela et al., 2017).

Competition between forest land space with sugarcane agricultural land space, whereby the land use is changed from coastal forests to farmland (Hess et al., 2016), enhances the atmosphere of such an environment to be vulnerable to an increased level of GHG. For example, deforestation reduces the atmospheric oxygen content and increases the CO_2 content. Furthermore, sugarcane agricultural methods such as monoculture, excessive use of fertilizers and pesticides, burnt harvesting, and the use of diesel operated machinery are unsustainable and consequently contribute to negative environmental impacts (Patterson, 2020), water pollution, and eutrophication (Gunkel et al., 2007), the reduction in water oxygen levels (Edokpayi et al., 2017) and higher than normal BOD and GHG emissions respectively (Leite et al., 2018).

From the sugar-producing, molasses, bagasse, and other wastes are produced as by-products. It was not clear what the sugar-producing plant does with the molasses that are not processed into ethanol, however, if such is dumped it provides bait for the Anopheles mosquito breeding that transmits Plasmodium species that causes malaria (Mweresa et al., 2014). In addition, unused bagasse emits particulate matter to the atmosphere. Ethanol production plants also generate wastes and by-products such as vinasse which, if not managed properly, will contribute to water pollution and cause an increase in aquatic BOD (Christofoletti et al., 2013; Vadivel, 2014; Mikucka & Zielińska, 2020).

Therefore, it was imperative to carry out a study such as this one to recommend and implement better environmental management practices along the bioethanol production chain, which is now globally accepted as one of the best alternatives to fossil fuels.

1.4 CONCEPTUAL AND THEORETICAL FRAMEWORK

The concept adopted in this study was drawn from aspects of life cycle analysis. The bioethanol production chain has various stages with different activities involved. Activities include the sorting of suitable land to be used for sugarcane agriculture, the farming process in the production of the raw material, sugarcane, the production of sugar using sugarcane where molasses is produced as a by-product, and finally, the use of molasses to produce bioethanol. The framework in figure 1.2 outlines the bioethanol production chain as inspired by the life cycle assessment framework of ISO 14040 guideline, which is used as an environmental management tool (Muralikrishna & Manickam (2017).

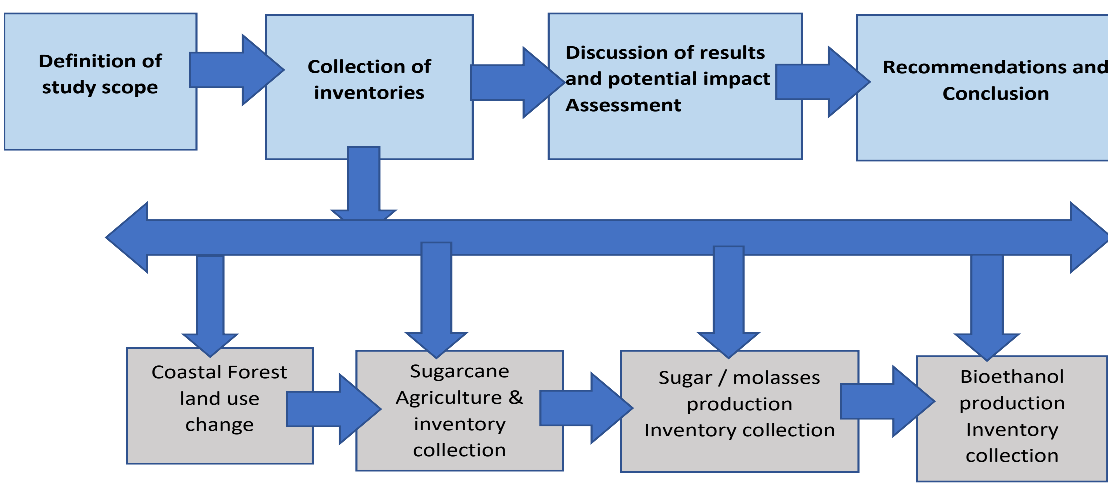

Figure 1.2: Study Framework adapted from life cycle Assessment Concept.

This study has diagnosed the types of waste and their effect on both the biological and physical environment. Multiple writers have advised against the production of biofuels on a large-scale for commercial use if sustainable practices are not employed, because of very high potential environmental risks (McLaughlin and Walsh, 1998; Kim and Dale, 2004; Wright, 2006; Demirbas, 2007; Walter & Machado, 2014 and Jeswani et al. 2020). For instance, biofuel production contributes to 6.5% (about 65,000 ha) of Indonesia's annual deforestation (Obidzinski et al., 2012). The objectives of this study were therefore in line with these considerations.

1.5 RESEARCH QUESTIONS

The study was guided by the following research questions:

- What are the environmental impacts of the bioethanol production chain using sugarcane molasses in KZN South Africa?
- How can the environmental impacts of the bioethanol production on the environment be mitigated?
- What is the extent of land clearing and land use change from natural ecosystems to sugarcane farms in uMlalazi and what is the impact of this?
- How does sugarcane agriculture affect the water catchments of uMlalazi?
- What type of wastes and gaseous emissions are generated from a typical South African sugar and bioethanol plant? How are these wastes managed and what are the environmental impacts of such waste?

1.6 STUDY AIM and OBJECTIVES

1.6.1 The Aim of the study

The aim of the study was to analyse the environmental impacts associated with bioethanol production using sugarcane molasses and suggest mitigation strategies of these impacts.

1.6.2 Study Objectives

- To investigate the extent and impacts of land clearing and land use change from natural ecosystems to sugarcane farming in the uMlalazi area in KZN.

- To evaluate how three different types of sugarcane farming practices contribute to the emission of GHG and to identify GHG emission hot spots from these agricultural practices.
- To assess the environmental impacts of sugarcane production for bioethanol on water catchments of uMlalazi in KZN, South Africa.
- To analyse the wastes, waste management issues, and gaseous emissions and their impacts from case studied sugar and bioethanol factories in KZN, South Africa.

1.7 CHAPTER BREAKDOWN

The study is broken down into eight chapters which include the following:

- **CHAPTER 1**: Introduces the overview and background to this research.
- **CHAPTER 2**: Deals with the related literature that focuses on the topic of land use cover change, sugarcane farming, sugar production, and ethanol/bioethanol production with their impacts on the environment.
- **CHAPTER 3**: Describe the overall study methodology and the design used in the study.
- **CHAPTER 4**: Describes findings of the impacts of land-use change from natural forests and wetlands to sugarcane farmlands on ecosystems services in parts of KZN.
- **CHAPTER 5**: Provides analysis and discussion of greenhouse gas emissions from the different types of sugarcane farms. The farms involved were categorised as small-scale to commercial-scale farms, and these farms were further classified as to whether they use pivotal irrigation systems or not.
- **CHAPTER 6:** Provides the findings and discussions on the effects of sugarcane agriculture on surface water quality in the uMlalazi water catchments.
- **CHAPTER 7**: Assesses waste generation and management issues associated with the studied sugar and bioethanol plants in KZN, South Africa.

- **CHAPTER 8:** This chapter provides the general conclusion and recommendations for waste mitigation in the bioethanol production chain. It also recommends significant ideas for further studies.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Two-thirds of the global energy demands can be supplied by renewable energy (Gielen et al., 2019). Renewable energy is considered to have the potential to reduce the GHG emissions needed between now and 2050 (Gielen et al. 2019; United Nations, 2020). According to Arndt et al. (2019), they have been a steady increase in the net renewable energy capacity from 2007 to 2017, as seen in figure 2.1.

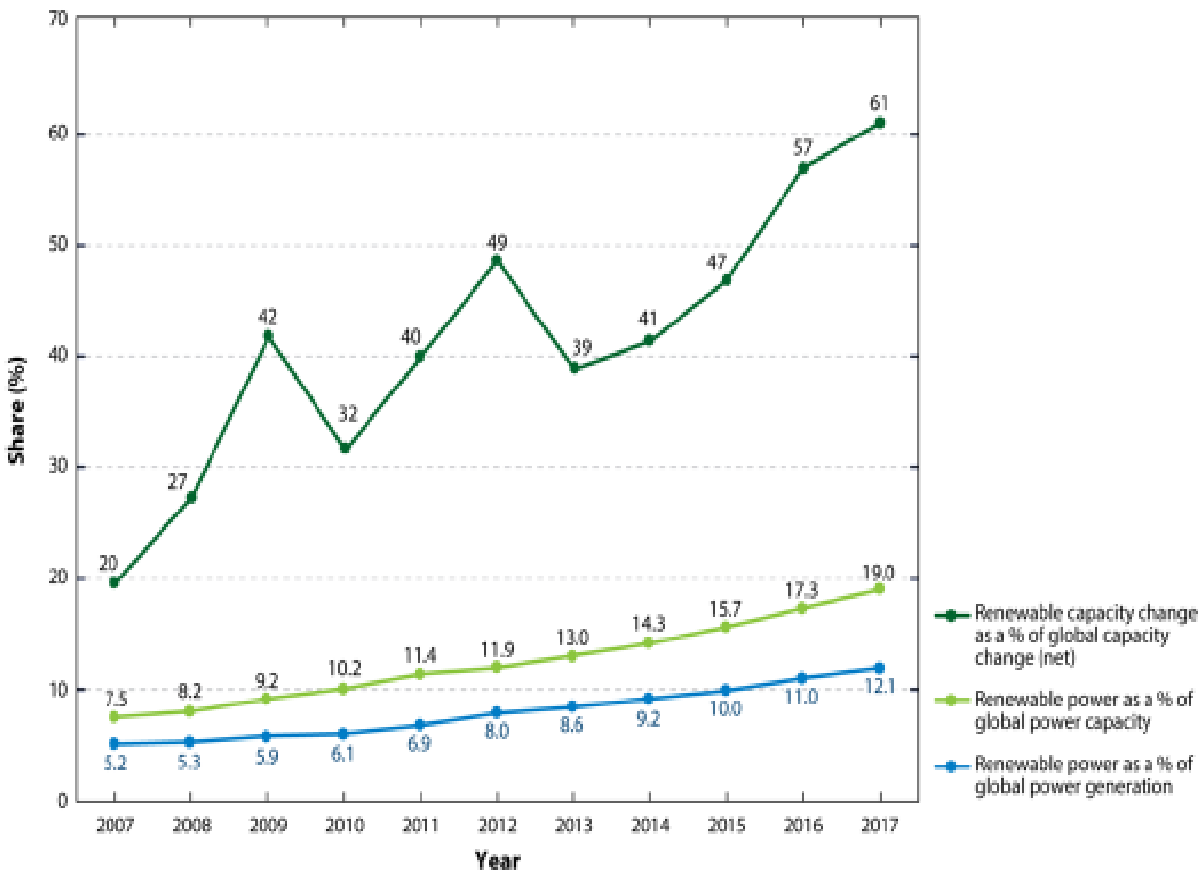

Figure 2.1: Global Renewable energy capacity change from 2007 – 2017 (Arndt et al., 2019).

This net capacity increase comes from the worldwide growing energy demands following the ever-increasing global population. Global population growth has increased by up to 4.2 times over the last century (Zhang and Lis, 2020). Energy matrix linked to better strategies for sustainable economic development have been put forward based on global population growth and recommendations from the Kyoto Protocol targets, Turetta et al. (2017). These energy types for sustainable environments include wind, solar, hydro, bioethanol, and biogas. Historically, humans relied on renewable energy until the onset of technology and the discovery of fossil fuels (Sørensen,1991), and returning to renewable energy has been a gradual process globally.

From the energy transformation roadmap to 2050, climate accord from 2015 seeks to reduce average global temperature rise to “well below 2°C” in this century, compared to pre-industrial times (IRENA, 2018). However, current emission trends are not on track to meet that goal. Accordingly, renewable energy has been the preferred option (IRENA 2018) in reducing this global temperature rise. Biomass energy research has therefore become very popular in countries like Mexico, the USA, China, and Germany (Alemán-Nava et al., 2014). Bioethanol plants in KZN, South Africa are now starting to use biomass in their bioethanol production process leading to more sustainable energy sources. Production of fuel ethanol in the United States has witnessed a significant increase from less than 2 billion gallons to 4 billion gallons and 13 billion gallons respectively in the early 2000s, 2005, and 2010 (Renewable Fuels Association- USA, 2011; Qin et al., 2012). However, there is a continuous but slow increase of up to 17 billion gallons per year in 2019 (EIA, 2019). This is illustrated in figure 2.2.

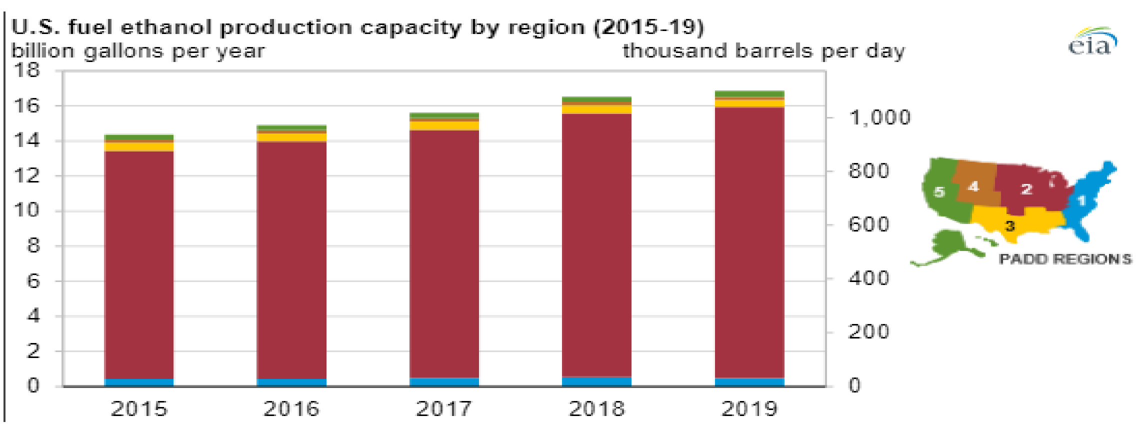

Figure 2.2: Fuel ethanol production in the USA slows down (EIA, 2019).

Despite increases of up to 3.3% in ethanol and biodiesel production in 2018, growth in biofuels for transport remains limited. This limitation is due to the lack of certainties in policy and because renewable markets have not yet developed for the general aviation markets (REN21, 2019).

Southern Africa's regional bioethanol annual production is in the millions of litres, with South Africa leading, although slightly decreasing, as seen in Figure 2.3.

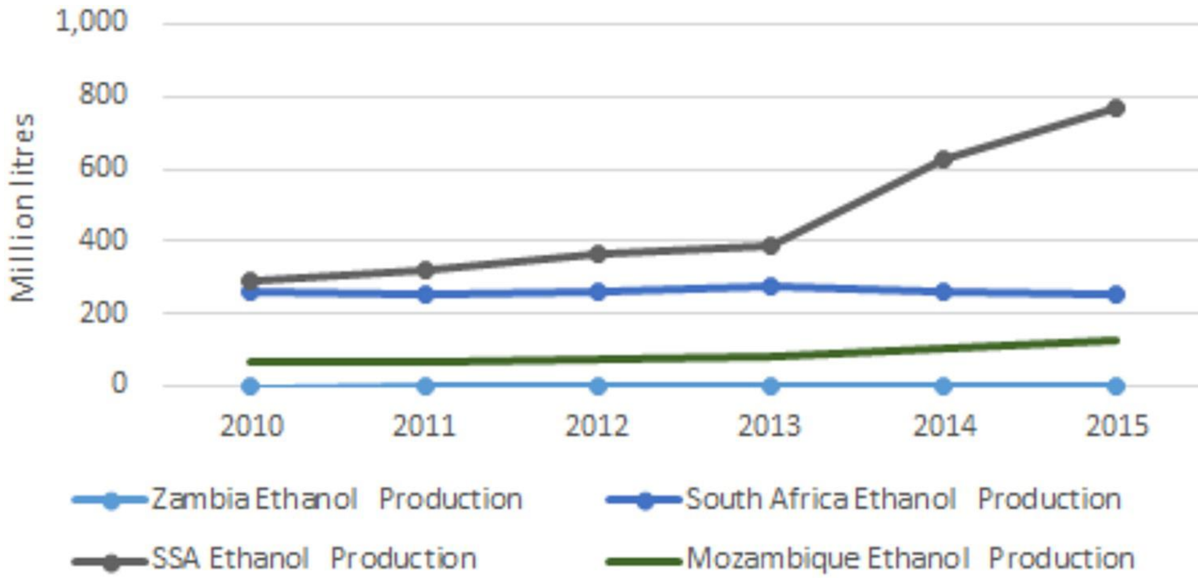

Figure 2.3: Ethanol production and consumption in Southern Africa for 2010–2015 in million litres (Henley & Fundira, 2019).

Many kinds of raw materials can be used in the production of bioethanol. According to Jewitt et al. (2009) and Mistak et al. (2020), these feed stocks include canola, cassava, jatropha, sorghum, soybeans, sugar beet, sugar cane, sunflower, and corn (maize). However, detailed exploration has been made on the feed stock sugarcane for this study's context and scope. Because of its robust agricultural and processing infrastructure, sugarcane is one of the most important commercial crops for the manufacture of bioethanol in the world (Long et al., 2015). In India, sugarcane is one of the essential crops because it is the second largest agro-based industry, although its production is cyclical and poorly organized (Soam et al., 2015). Another quality of sugarcane that makes it one of the most suitably used to produce bioethanol is its photosynthetic rate;

therefore, it grows quicker (Lago et al., 2019). Sugarcane has a comparatively high sugar content, good juice purity, and good ecological adaptability (Lago et al., 2019). Thus, sugarcane can sufficiently supply the carbohydrates required during fermentation for bioethanol production.

Bioethanol seems to be the primary renewable energy source in Argentina. According to Amores et al. (2013), extensive sugarcane agriculture supports bioethanol production in Argentina, with mainly sustainable agriculture. Such sustainability in agricultural practices entails very scare use of fertilizers, pesticides, artificial irrigation, and pre-burning harvesting. According to the South African Department of Agriculture, Forestry and Fishery-DAFF (2014), globally, sugar is produced in 120 countries, which contributes to sugarcane being the crop with an enormous production quantity globally. This exceeds 165 million tons a year with an approximate 80% from sugar cane. Bioethanol production in Southern Africa has also created jobs for the poor rural communities, primarily through sugarcane farming (Henley and Fudira, 2019). However, this research has also raised questions about these rural communities' knowledge and skills in maintaining sustainable agricultural practices.

Sugarcane is planted following the sett planting method, where sugarcane stems are laid in the farrows in a horizontal manner placed at 45° and covered lightly with soil until they sprout (Van Antwerpen & Meyer 1996). Sugarcane is grown through vegetative propagation. It develops a fibrous root system. It grows up to 2 – 4 meters high and about 5 cm thick (DAFF-South Africa, Department of Agriculture, Forestry and Fisheries 2014). The crop cycle for sugarcane falls between 10 and 24 months, and harvesting can be done after 12 to 18 months (DAFF 2014). This short cycle of growth and maturity of sugarcane plants provides researchers an ideal platform to study the farming activities to the end of the farming period. According to the South African Sugarcane Research Institute (SASRI), visitor's guide (2018), the South African sugarcane growing sector comprises about 29130 registered growers who farm predominantly in the KwaZulu Natal province and others in Mpumalanga and the Eastern Cape province. SASRI owns eight research farms, SASRI (2018), with more than 25,000 small-scale growers producing about 10% of the total crop (SA DAFF, 2014). SASRI's farms aim to research new sugarcane varieties, which can prove to be more sustainable.

Sugarcane and its by-products have several other uses besides the production of bioethanol. Sugarcane produces cane sugar, bagasse, cane syrup, molasses, cane trash, filter cake (Gheewala et al. 2017), wax, and rum (Duke, 1983; Nuissiera et al. 2012). Molasses, one of the by-products of sugarcane resulting from sugar production, also have various uses. According to many researchers, molasses is used in sweeteners (Bieze & Nickles, 2017), industrial alcohol, explosives, synthetic rubber, and combustions engines (Duke, 1983), bioethanol production (Arindhani et al. 2016), desulfurisation (Waligorska et al. 2000). While sugarcane bagasse can be used as a raw material in manufacturing paper, cardboard, and fuel, mixing molasses with bagasse produces a mixture used as cattle feed (Bieze & Nickles, 2017). In addition, the dried cane is an excellent mulch, and due to its lightweight, it can easily be baled and shipped internationally (Duke, 1983).

One of the foci in this study was on the use of sugarcane products in producing bioethanol. According to Azhara et al. (2017), bioethanol (ethyl alcohol or C_2H_5OH or EtOH) can be used directly as pure ethanol or mixed with gasoline to produce gasohol which is used as fuel in internal combustion engines (Azhara et al. 2017). This makes bioethanol a more sustainable alternative to fossil fuels. Other uses of bioethanol range from a gasoline improver or octane enhancer to bioethanol-diesel blends, which reduce the emission of exhaust gasses (Venkatesh et al., 2019). Although bioethanol has more advantages than gasoline, such as higher-octane number, broader flammability limits, higher flame speeds, and increased heats of vaporisation, it still produces toxic air-borne pollutants less in contrast to petroleum fuel (Azhara et al., 2017). According to Soam et al. (2015), a significant part of bioethanol produced in India is potable and used for human consumption as liquor and industrial use. The surplus is blended with gasoline.

Fossil fuels are still a part of its production value chain; Goldemberg et al. (2008). Equity issues, environmental, economic, and geographical concerns with far-reaching future implications have rendered fossil fuel unsustainable in the current energy system (Foidl et al., 1996; Kim & Dale, 2004; Demirbas, 2007). The production value chain of bioethanol also has the potential risk of both water and air pollution. From their 2018 studies on the various feedstock for ethanol production, (Foidl et al., 1996; Kim & Dale, 2004; Demirbas, 2007), ethanol produced from sugarcane produces up to 70 g CO_2 eq/km drive while ethanol from woody biomass produced only about 25 g CO_2 eq/km drive, as seen in figure 2.4.

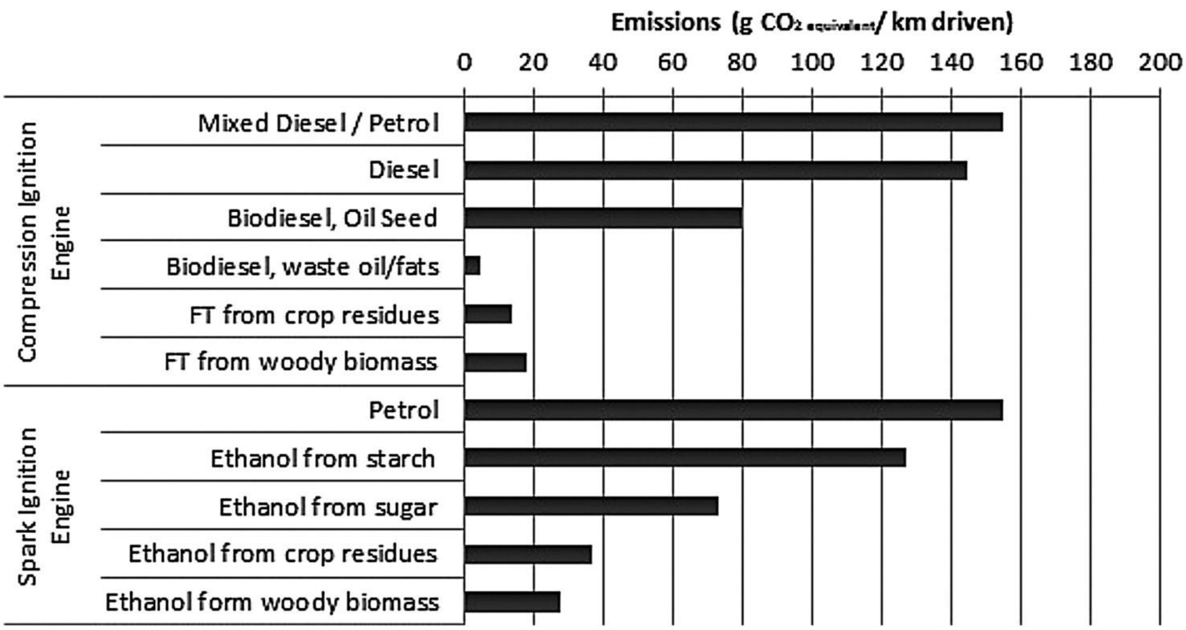

Figure 2.4: Greenhouse gas emissions of biofuels from lignocellulose feed stocks and energy crops, compared to reference fossil fuels; petrol and diesel (Stfford et al., 2018)

From figure 2.4, the use of biofuels from woody biomass on spark ignition engines generates the least GHG compared to when biofuel is used from crop residues, sugar, starch, and petrol, in that order. This means there are better alternatives to sugar/sugarcane from which ethanol could be produced with a lower emission rate. This will reduce the competition between food crops and sugarcane agricultural land. As a result, there will also be less competition between natural forest and sugarcane farmland and eventually more sustainable environments. The history of forest use change to agriculture spans millennia since Homo *sapiens* emerged as a species (Critchley & Bruijinzeel 1996). However, in recent times, this change has experienced accelerated rates.

Land-use conversion is associated chiefly with agriculture and economic development expansion, although the net forests lost in tropical and subtropical countries are also associated with rural population increases (FAO, 2016; Garreth et al., 2019; Fonge et al., 2019). Between 2000 and 2010, about 7 million hectares of global forests have been lost in tropical regions, with a 6 million increase in agricultural land within the same period (FAO, 2016). Large-scale commercial and subsistence agriculture has accounted for 73% of forest loss in tropical countries. South Africa's sugarcane agricultural land expansion has also been a reason for such LUC. In their 2015 study Jewitt et al., (2015), analysed the KZN land coverage types. Table 2.1 shows the aggregate land-cover categories in KZN and a description of the classes. These different land types present different types of ecosystems with unique biodiversity. These ecosystems also provide unique ecosystem services to biodiversity.

Table 2.1: Aggregated land-cover categories in the KZN region of South Africa (Jewitt et al., 2015)

Aggregated land-cover category	Description
Water	Natural open water occurring in pans, rivers, wetlands, mangroves, and estuaries
Plantations	Agro forestry including clear-felled timber and rehabilitated plantation areas
Agriculture	Irrigated and dryland agriculture including permanent orchards, pineapples, sugarcane, subsistence agriculture, annual commercial crops, and old cultivated fields
Mines	Primary surface-based mineral, rock, and sand excavation and dumping sites, including rehabilitated mine areas
Built	All major urban and built-up areas, rural or low-density dwellings, sports fields and racetracks, smallholdings, national, main, and district roads, railways, and airfields
Natural vegetation	Natural vegetation including forests, dense bush, bushland, woodland, bush clumps, grasslands, Alpine heath, and degraded natural vegetation

Sand or rock	They are naturally occurring exposed bare rock and sand, excluding coastal gravel and sand
Erosion	Non-vegetated areas resulting from primarily gully erosion process
Dams	Artificially impounded water
Abandoned	Secondary vegetation areas are arising from abandoned non-natural categories, e.g., left agricultural fields. From a biodiversity conservation perspective, this category is tracked and separated in analyses because once abandoned; biodiversity value is never restored to its original state

2.2 SOME ECOSYSTEM BENEFITS IN THE KZN AREA

An ecosystem is defined as an environment where groups of living organisms (biotic) interacting together and with the non-living components of their environment (abiotic). The KZN ecosystems encompass a wide range of habitat (Jewitt et al., 2015), which link the terrestrial and the aquatic environments (Lubke, 2014). Such environments may include coastal dunes, sandy shores, estuaries, coastal lakes, mangroves, wetlands, rocky beaches, subtidal reefs, and subtidal sediments. In addition, the KZN region is characterised by coastal forests and thicket ecosystems that separate aquatic and terrestrial ecosystems. These ecosystems are home to many plant and animal species (Lubke, 2014). The species complexity increases as the distance from the aquatic into the terrestrial ecosystems increases. For instance, pioneer plants are found in the foredunes very close to the beaches. At the same time, a complex community is in the forest, grassland, or fynbos areas of the ancient land surface. From historical studies (from 5 – 120 years), the uMlalazi area has 8 ecosystem communities with a gradual increase in species complexity as the distance from the shore inland increases. The pathway of change was as follows: pioneer, the enriched pioneer, open dune scrub, closed dune scrub, bush clumps, bush clump/forest margin transition, forest margin, and, finally, forest (Lubke, 2014). There is, therefore, evidence of biodiversity richness in the area about 120 years ago. It was however, not explored what the state of the current biodiversity is with regards to LUC impacts. Many estuaries are also found in the region. From their 2015 discussion paper on the land and ecosystem accounts for KZN, there has been a fluctuation in natural land and sugarcane farmlands (Driver et al., 2015). Figure 2.5 shows these land changes between 2005 and 2011.

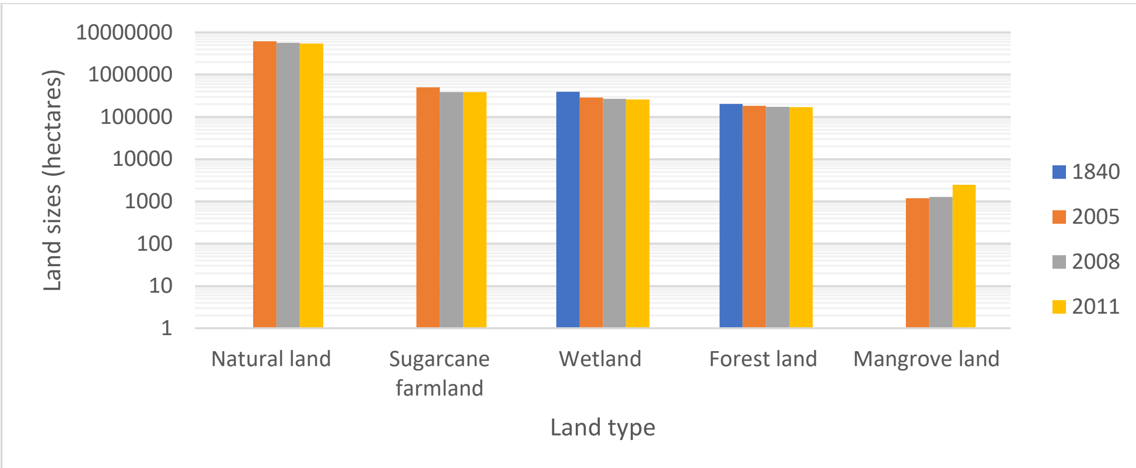

Figure 2.5: Land and ecosystem accounting in KZN from 2005 – 2011 (Driver et al., 2015)

Although sugarcane farmland size in KZN shows a decrease from 1840 to 2011, historically, there had been a general gradual increase in sugarcane farmland size in South Africa, as seen in Figure 2.6. This incremental increase in sugarcane land size has impacted the dimensions of other natural vegetations or wetlands, causing their decrease.

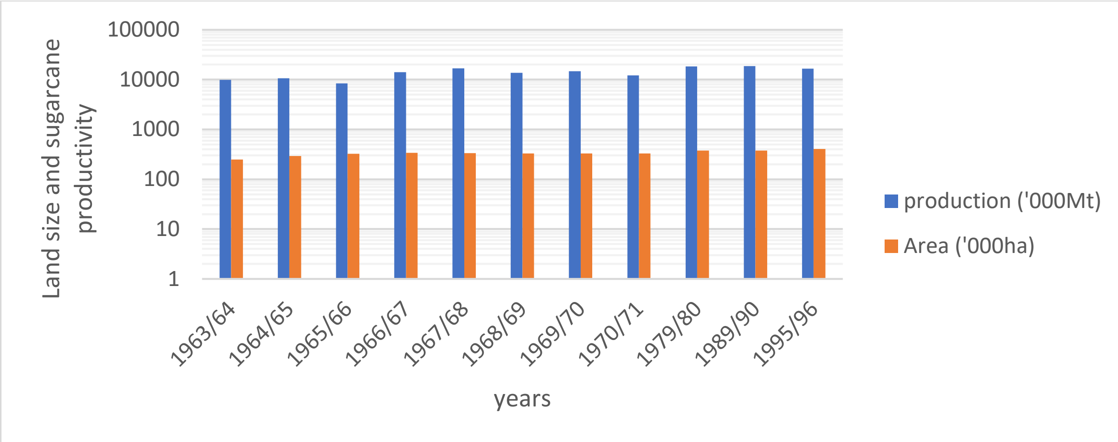

Figure 2.6: Historical data of sugar cane production versus area planted, in the South Africa sugar industry, 1963/64 - 1995/96 (Adapted from Mbowa, 1996)

For this study, in chapter 4, the events in the conservation area in the uMlalazi district in relation to their conversion to sugarcane farmlands are evaluated. Finding about these conservation areas, which include the Mbongolwana wetland, the Ongoye forest, the Dlinza forest, and the Entumeni nature reserve have been presented in chapter 4.

The KZN wetlands

Wetland is formally defined in the South African National Water Act as "land between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which in normal circumstances supports a vegetation typically adapted to life in saturated soil" (GG No. 19182, 1998).

The 1970 International Convention on wetlands saw and formally recognised the high value of wetlands. This intergovernmental convention collaborates with its members in the listing and consequent protection of crucial wetlands. The Convention's mission is "the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution towards achieving sustainable development throughout the world." Established in 1971, RAMSAR (1993).

Today wetlands are acknowledged for their value and role in delivering environmental goods and services. Fortunately, KZN is endowed with some excellent wetlands, and thanks to several past scientists and champions of wetlands, several are well protected and valued. For instance, the Mbongolwane wetland in uMlalazi. Zungu et al. (2016), write that as of 2016, it extends to approximately 400 ha that consists of its central core, standing water with a familiar and invasive reed bed surrounded by *Cyperus latifolius* reed beds and wetland grasses. With such extension this wetland is probably an avenue that provides the locals with many services that may include wetland cropping, livestock, and mainly sugarcane agriculture. Adding to this, Zungu et al. (2016) also found out that there is evidence of LUC around this wetland such as water abstractions for sugarcane agriculture. Such LUC will compromise the ecosystem services of the marsh. Wetlands usually occur in patches of an upland environment, thereby exposing the small and separated wetland populations to extinction (Serran and Creed, 2016; Salaria, 2017).

Wetlands have been considered the third most crucial life support system on earth. They can function as vast sponge-like reservoirs, filtering natural water, thereby moderating both quality and quantity. In addition, they attenuate floods, reduce erosion, trap sediments, recycle nutrients, oxygenate the water, and recharge groundwater (Lubke 2014), and provide climate moderating elements (Orimoloye et al. 2020).

Wetlands provide reeds, grasses, and mangroves for housing; they harbour organisms with medicinal potential and serve as tourism destinations based on their distinctive avifauna, frog and plant species, and other unique wildlife (Lubke, 2014); Orimoloye et al. 2020). Wetlands also contribute to groundwater replenishment and the provision of drinking water (Bassi et al., 2014; Richardson et al., 2016)

While RAMSAR (1993) formally protects these important extensive wetlands, smaller wetlands along the KZN coast play critical ecological roles, although most of them do not get protected. The value of these wetland systems is often forgotten as there are drained for farmlands and filled for development (Lubke; 2014). According to Orimoloye et al. (2020), (2017), and (1987) studies showed a reduction of the Isimangaliso wetland extent from 655.416 Km^2 to 429.489 Km^2 over 30 years between 1987 and 2017. With this significant size reduction, this wetland has probably lost most of its ecological values and significantly impacted biodiversity.

With the use of remote sensing and GIS technique in their studies, amongst the other effects, anthropogenic activities such as agriculture and deforestation have been some of the significant causes of wetlands depletion in KZN Orimoloye et al. (2020).

The KZN coastal forest

According to the 2009 South Africa state of the forest report by the Department of Agriculture, Forestry and Fishery (DAFF), the indigenous coastal forests of KZN cover a land size of 21 089 ha. Although SA biodiversity is under considerable threat, these forests have many uses, ranging from cultural, ecosystem, use-values, and tourism (DAFF, 2011). Threatened species may led to species extinction is care is not given. According to the Red Data Book, threatened species include 3 435 (15%) of South Africa's plant species, 102 (14%) of its bird species, 72 (24%) of its reptile species, 17 (18%) of its amphibian species, 90 (37%) of its mammal species and 142 (22%) of its butterfly species. However, the extent to which biomes are threatened depends upon the fertility of the soil, human population pressures, the economic value it presents, and the extent to which the biome is conserved in protected areas. In chapter 4, studies were done on how conservation areas in uMlalazi are changing with the changes of sugarcane farmland size over the years.

2.3 REASONS AND ISSUES ASSOCIATED WITH LAND-USE CHANGE TO AGRICULTURAL LAND

Assessing land-use changes over time is a step in taking necessary compelling actions towards sustainable environments. The difference in land use destabilises natural ecosystems.

Reasons for land-use change

Globally, according to FAO (2016), thousands of years ago, people began converting forests to other land uses such as the use of wood in making fire, the production of primitive tools, and animal grazing land. Furthermore, with the increase in technology to facilitate hunting and agriculture, humankind has been involved in converting natural forests to agricultural land where the exercise of deforestation aims at creating space for economic development and urbanisation.

According to Fonge et al. (2019), in their study on LUC from forest to agriculture in Cameroon, converting forests to agricultural land impacts water bodies. They also concluded that through deforestation and water pollution, there is a loss of biodiversity.

Environmental impacts of land-use change

The conversion of forests to agricultural land has resulted in the loss of native vegetation in these biomes. In the case of South America, it has led to high carbon emissions, biodiversity loss, and the disruption of local and regional hydrological cycles (Barlow et al., 2016; Baumann et al., 2017; Coe et al., 2013; De Sy et al., 2015; Silvério et al., 2015).

On the one hand, wetland and agriculture are partners for sustainable environments (Ramsar, 2021) and the complete conversion of wetlands to agriculture is partly linked to the expansion of bioenergy production. Still, on the other hand, the total conversion of wetland for agriculture has an environmental degradation effect. The Ramsar Conventions' resolution to the wetland agricultural problems has been considering the impacts on ecosystem services and design policies that restrict these conversions (RAMSAR, 2021). The critical question that arises is if these policies are being implemented and if they are monitored and evaluated. In South Africa, 65% of wetland ecosystem types are threatened, including 48% critically endangered, making wetlands the most endangered of all South Africa's ecosystems (Grain SA, 2014).

2.4 GLOBAL SUGARCANE PRODUCTION

The global top 10 sugarcane-producing countries identified for 2019 include Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Guatemala, Australia, India, and the USA. South Africa came in the 11th position (OECD, 2020), as shown in Figure 2.7.

These top sugarcane-producing countries have been analysed for their productivity over ten years from 2010 to 2019. Averagely Brazil has the highest production while South Africa falls in the 11th position (FAO, 2020). The 2019 sugarcane production from the top sugarcane-producing countries is summarised in Table 2.2. In 2013, as presented by Zhao and Li (2015), the global top 10 sugarcane-producing countries were Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Indonesia, the Philippines, and the USA. Their cane productions (in a million Mg of cane/year) accounted for 34.1, 15.8, 5.8, 4.6, 2.9, 2.8, 1.6, 1.6, 1.5, and 1.3 % (a total of 72 %) of the world total cane production, respectively.

Table 2.2: Top 11 sugarcane producing countries and productivity (million tons/year) for 2019

Top 11 Country	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	Average
Brazil	36400	38350	28620	38600	37800	35950	34650	29500	38870	39150	35789
India	20637	26574	36150	27337	26605	30460	27385	34300	34309	22200	28596
Thailand	6930	9663	10235	10024	11333	10793	9743	14581	14710	10033	10805
China	10777	10336	11246	12822	13452	10200	8200	9440	9150	8250	10387
Pakistan	3400	3900	4500	4980	5600	5140	5240	5500	7200	6800	5226
Mexico	5115	5495	5351	7393	6382	6344	6484	6812	6371	6314	6206
Australia	4700	3700	3683	4250	4380	4700	4900	4725	4480	5100	4462
United States	3074	2878	3254	3543	3327	3414	3511	3507	3412	3680	3360
Guatemala	2340	2048	2499	2778	2862	2975	2832	2719	2865	3049	2697
Columbia	2294	2280	2270	1950	2300	2350	2250	2300	2500	2400	2289
South Africa	2265	1985	1897	2020	2435	2192	1684	1607	2064	2250	2040
Source: Adapted from FAO (2020) Sugar cane production quantity https://knoema.com/atlas/topics/Agriculture/Crops-Production-Quantity-tonnes/Sugar-cane-production											

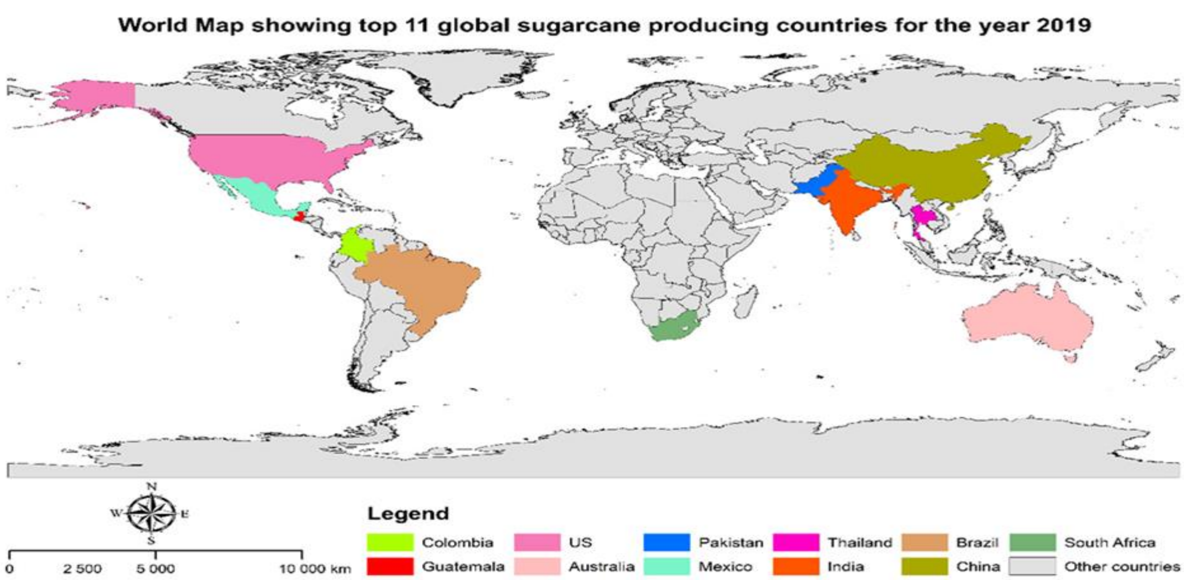

Figure 2.7: Top 11 global sugarcane-producing countries 2019.

Globally, over the recent past years, sugarcane productivity increased with an increase in farm sizes. The years 2016 and 2017, respectively, showed exponential growth in farm sizes (FAO 2020). Farm size increases have resulted from at least a source of LUC. Changing the natural cover of land has negative environmental impacts such as biodiversity loss and reducing or loss of ecosystem services. Globally, from the 2018 statistics above, 26269819 hectares of land size was used in sugarcane agriculture showing a global sugarcane farmland increase of 2580334 ha since 2010. This increase will have a direct impact on both surface and groundwater pollution, and air pollution. There is also an increase in the global production of sugar cane from 10 million ha in 1969 to 26.3 million ha in 2018, showing an average annual growth rate of 2.03 % (Zhao and Li, 2015). In 2013, global sugarcane production amounted to about 1.91 billion tons, with 50% produced by Brazil and India alone (Dotaniya et al., 2016).

According to FAO (2020), the 2019 top 10 sugarcane-producing countries have changed slightly, although, many of the same countries from 2013 still fall in this category. The year 2019 also saw South Africa as the 11th top sugarcane producing country globally. On average, the top 11 sugarcane-producing countries have produced 111856 tons of sugarcane per year from 2010 until 2019.

According to Bento et al. (2018), agriculture is generally considered one of the most significant contributors to atmospheric pollution through the emission of greenhouse gases (GHG). This is felt most especially if the agricultural process combines tillage with fertilizers instead of conventional farming practices. Sugarcane agriculture uses fertilizers to enhance productivity following the growing demands of either sugarcane or its products such as sugar and bioethanol. According to Tsiropoulos et al. (2014), Brazil is the largest sugarcane producer globally. Following the 2009 statistics and 2019 statistics (OECD, 2020), Brazil produced 690 million tons of sugarcane, representing 41 % of global production (OECD, 2011). Brazil in 2019 produced 35789 tons of sugarcane while South Africa produced 2265 tons and 2250 tons in 2010 and 2019, respectively, with a production reduction of 15 million tons. According to more recent studies, Brazil is the second-largest biofuel producer (Forgione et al., 2008; Martinelli and Filoso, 2008, Kim et al., 2009, Filoso et al., 2015, Bento et al., 2018). This has contributed to substantial growth and the escalation of sugarcane farming in Brazil (Forgione et al., 2008; Martinelli and Filoso, 2008, Kim et al., 2009, Filoso et al. 2015, Bento et al., 2018). Responding to market pressures, sugarcane agricultural land has continued to increase in Brazil and other countries.

Figure 2.8 below shows a constant increase in the global sugarcane farmland sizes from 2010 until 2016. This follows an exponential rise in 2017 with yet a drop in 2018. This exponential increase could result from international recommendations to move from fossil fuels to renewable energy, with sugarcane farming for bioethanol in 2017 also increasing. This increase in sugarcane farming is primarily linked to advances in sugarcane agricultural technology (Bordonal et al., 2018). However, this increase directly affects LUC as deforestation, GHG emission, and habitat loss are amongst the resulting impacts causing degradation of the surrounding water or land. The drop in 2018 could also be because of small-scale and new farmers not meeting up with the advancement in farming technology and slagging, thus reducing their farm sizes.

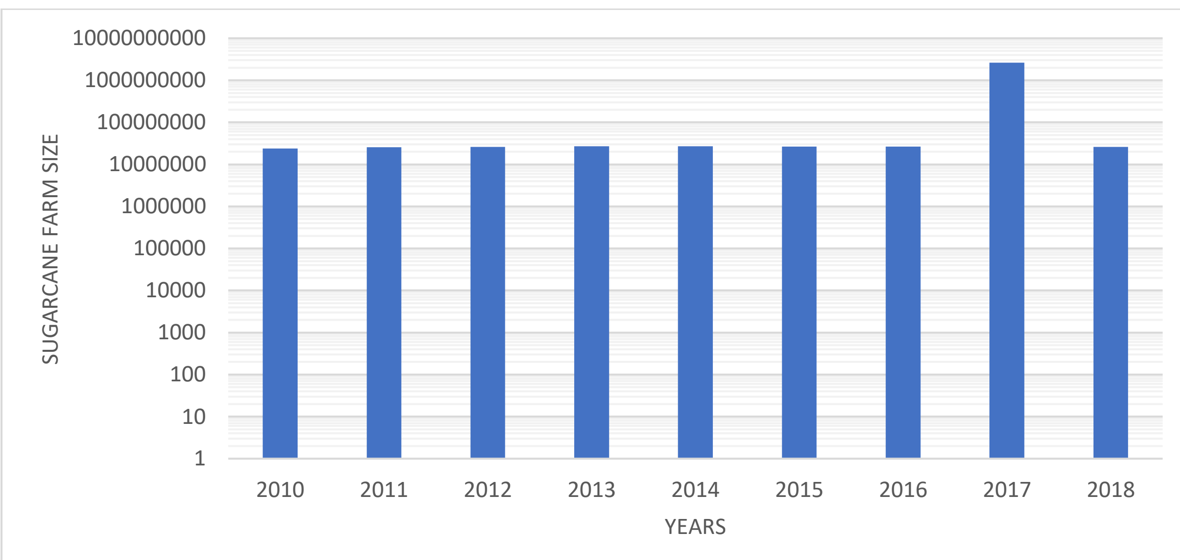

Figure 2.8: Global sugarcane farmland sizes from 2010 to 2018 (Adapted from FAOSTAT, 2020)

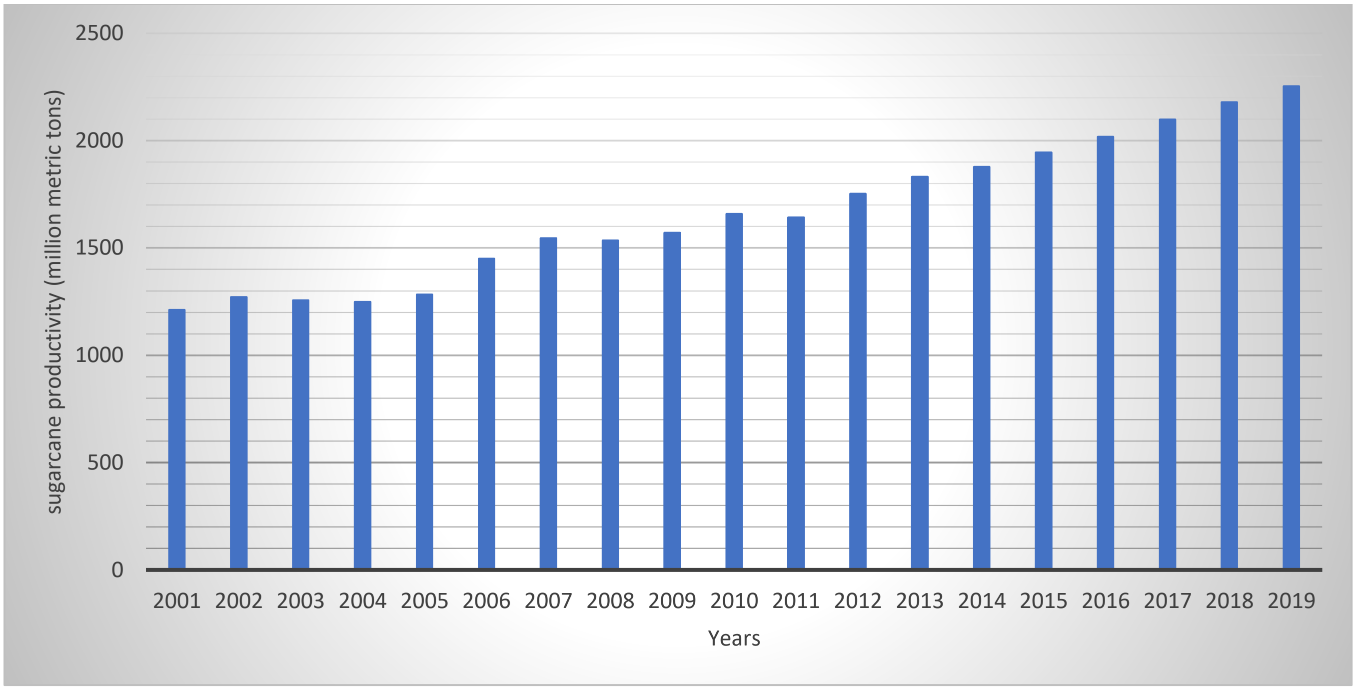

Figure 2.9: Global sugarcane production from 2001- 2019 (Adapted from FAOSTAT, 2020)

Since 2001, sugarcane productivity has experienced a progressive increase globally (Figure 2.9). This productivity has increased from 1211,80 million metrics (mm) tons in 2001 to 1659,12 mm tons in 2010 and again to 2253,70 mm tons in 2019. This steady increase follows the global call to switch to sustainable energy sources in which sugarcane bioethanol is one of them.

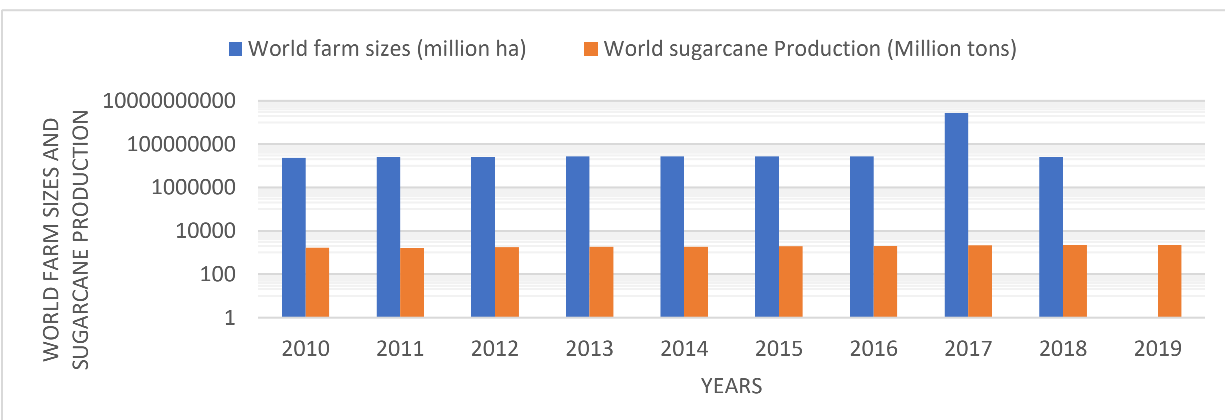

Figure 2.10: Global sugarcane production versus sugarcane farm sizes from 2010-2019 (Adapted from FAOSTAT, 2020)

Following this global trend, sugarcane production has increased progressively and steadily from 2010 to 2019. With a 98.9% increase in sugarcane farmland size from 2016 to 2017 (figure 2.8 & 2.10), an exponential increase, the sugarcane production observes only a 3.79% increase in productivity. This comparatively small increase is because most farmers who contributed to the global sugarcane farmland increase might have been emerging farmers who did not enhance the growth with chemical fertilizers as most commercial farmers do. Overexploitation of farmlands due to LUC might have also caused the infertility of the soil. Drought could have also played a role, thus reducing productivity. According to Zulu et al. (2019), poor re-planting rates and weeds contribute to reduced yields. They also admit that low levels of agricultural education added to poor crop husbandry practices among emerging and small-scale growers (SSG) plays a significant role in their poor sugarcane productivity. In their conclusion, they also report that they perceive weeds to be the top agronomic constraint. In this current study, although not listing it as a leading agricultural constraint, the farmers seem to be using herbicides to reduce the growth of weeds in their sugarcane farms. Therefore, poor agricultural education amongst farmers probably led them to use more than the required amounts of herbicides, which end us in ground waters through leaching.

2.5 SUGARCANE PRODUCTION IN SOUTH AFRICA

The history of sugarcane farming and its distribution in South Africa dates to 1847, with several other trials made with crops such as coffee, cotton, tobacco, indigo, and arrowroot in the process (Lewis 1991). In 1884 the first sugarcane was planted by Edward Morewood in KwaDukuza (http://www.tourismkwadukuza.co.za/discover/history/sugarcane-history-9) in the KZN province.

After these successful trial phases, according to Christopher (1961), sugarcane farming is implemented along the coastlines of KwaZulu-Natal. About 13 years into the primary start-up in 1860, sugarcane farmlands increased to approximately 4953 hectares, and 50 years later, in 1910, most of the sugarcane fields were in the north coastal belts (Lewis,1990). This increase saw sugarcane fields with about 23 658 hectares of land. South Africa has maintained its position in the top 20 global sugarcane-producing countries since 1961 (Knoema, 2020). Its productivity has increased from 1961 with 8,513,000 tonnes of sugarcane to 19 482 246 tonnes of sugarcane in 2019 (Knoema, 2020). This increase also entails an increase in land used for sugarcane agriculture. Increasing this sugarcane farmland also entails converting natural vegetation into sugarcane agricultural farmland. These anthropogenic activities lead to environmental impacts.

Globally, South Africa was the 15th highest sugarcane producer, with 28.13 % of the total contribution of sub-Saharan African sugarcane production (Mohlala et al., 2016). South Africa is now the 11th top sugarcane-producing country (OECD, 2020). Therefore, this research is worth carrying out as sugarcane agriculture in South Africa shows that waste is being generated throughout the process. Following Mohlala et al. (2016), South Africa is Africa's largest producer of sugarcane, followed by Sudan, Kenya, and Swaziland, respectively. Figure 2.11 represents sugarcane harvested area and productivity over 10 years in the South African context.

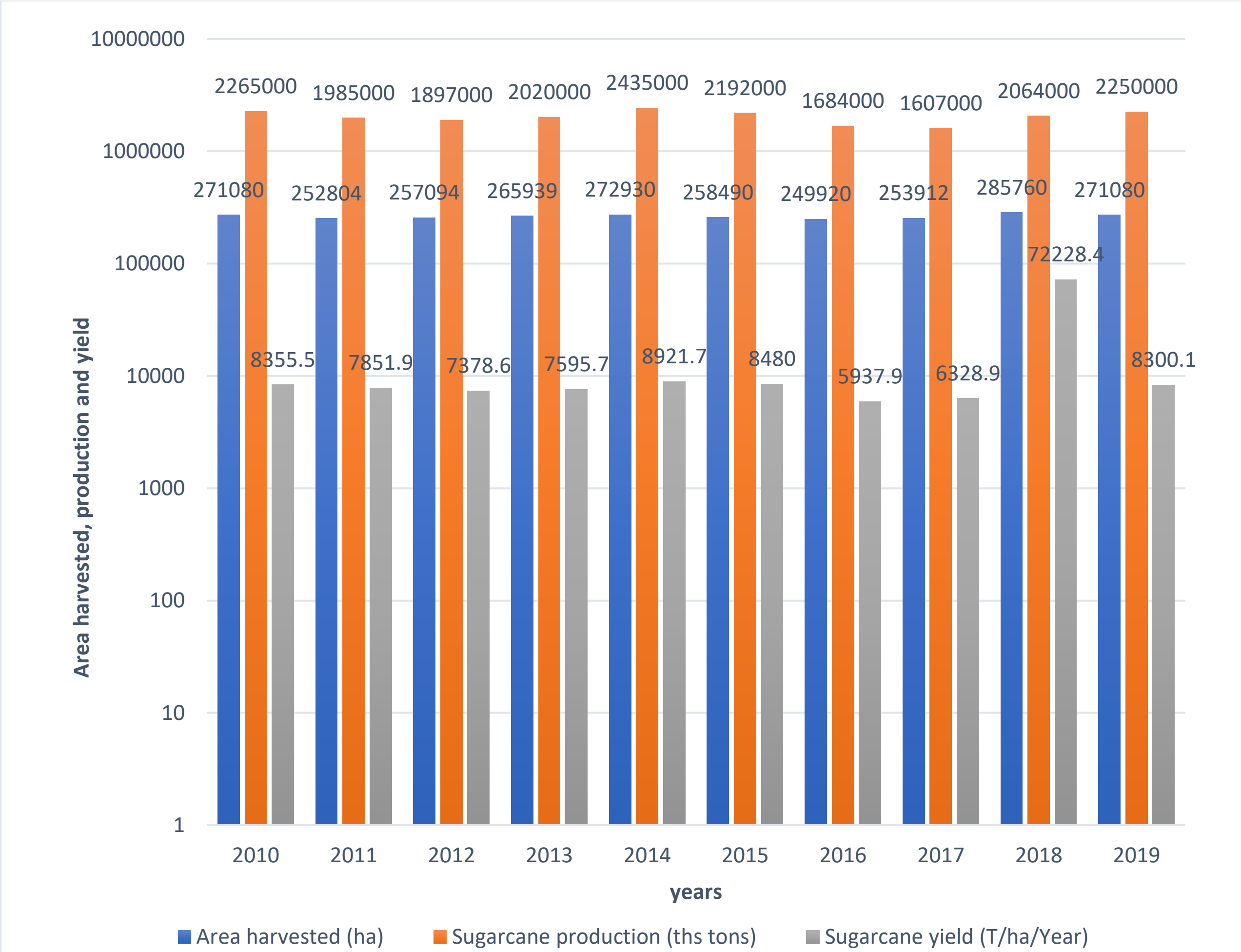

Figure 2.11: Sugarcane production in South Africa (Adapted from Pradhan & Mbowa, 2017 & OECD, 2020)

With a 5.1% net decrease in sugarcane farmland size between 2010 and 2012, South Africa's sugarcane yield demonstrated a gradual decline from 8355 tons/ha/year in 2010 to 7378,6 tons/ha/year at a net loss of 13.2% in 2012. These figures show a net increase of 6.1% and 20.9 %, respectively, for land size and yield between 2012 and 2014. However, between 2015 and 2019, although with a net increase of 4.9% in the farmland size, there was a net yield decrease of 2.1%. South Africa thus experienced an overall decline in the yield between 2010 and 2019 with an approximate 55 t/ha/year, which amounts to a 0.66% decrease. Factors that influence sugarcane productivity rate include but are not limited to the size of the farmland, amount of rainfall, soil fertility, altitude, the use of artificial fertilizers, irrigation, and the use of pesticides. Once these factors become limiting with respect to their threshold supply, productivity will drop.

2.6 SUGARCANE FARMING AND POSSIBLE ENVIRONMENTAL ISSUES

Sugarcane is noted for its soil quality improvement. Sugarcane farming improves the chemical properties of soil, such as increased macronutrient levels and lower soil acidity. This is however, with adverse effects on physical and biological attributes such as increased soil compaction, structural degradation and a decrease in soil organic carbon (SOC), relative abundance and diversity of macrofauna and microbial activity. This study however looked at the GHG emission effects from soil irrigation, fertilizer and pesticide application during sugarcane farming. According to the Brazilian context, as a procedure for soil quality evaluations in sugarcane areas, the recommendation is using a few indicators such as pH, phosphorus levels, potassium levels, visual evaluation of soil structure (VESS) scores, and soil organic carbon (SOC) concentration (Cherubin et al., 2016). It is thus the need to carry out proportional weighting to reflect the soil's chemical, physical, and biological processes. VESS scoring was not evident from the data provided by the farmers during this study.

Even though sugarcane farming goes a long way to promote comparatively more sustainable energy through bioethanol, waste management practices must have adhered. Other agricultural management practices that reduce negative impacts on edaphic and other physical and biological aspects of the environment must be adhered to within agrarian sugarcane lands. This adherence is to prevent unintentional soil, air, and water quality degradation over time.

2.6.1 Environmental issues from routine practices during sugarcane farming.

In sugarcane farming, routine practices describe all the everyday activities farmers perform before, during, and after planting sugarcane. Although these practices aim to ensure better sugarcane growth and eventually better produce during the harvest season, they have come across to impact the environment in one way or the other negatively. Activities that take place during sugarcane farming such as fertilizer application, irrigation, mulching, and harvesting have contributed to the sustainability of sugarcane farming according to this study.

Problems associated with sugarcane farming in this instance of routine practices are multidimensional. Most sugarcane farmers depend on chemical fertilizers to enrich the soil's nutrients (Zulu & Sibanda, 2019). Soils in Brazilian sugarcane farmland studied show consistently low phosphorus (P), despite the application of high rates of P fertilizer (Ghiberto et al., 2009). Soil nutrients are absorbed by the sugarcane plants while some leach. In addition to leaching, soil nutrients are transferred to aquatic ecosystems through soil erosion, prevalent in Brazilian sugarcane agriculture lands (Filoso et al., 2015). Surface runoff transfers nutrients adsorbed onto soil particles to aquatic systems, most often when bare soils are exposed during extreme rain events (Issaka & Ashraf, 2017). With regards to fertilizer application, several countries have recommended rates of N application. For example, in Brazil (60–100 kg N/ha/year) are significantly lower than those in Australia (160–200 kg N/ha/year), India (150–400 kg N/ha/year), and China (100–755 kg N/ha/year) (Robinson et al., 2011), which is an important factor leading to a high energy balance in sugarcane ethanol production (Manochio et al., 2017). Applications over the recommended values will lead to GHG emissions beyond the threshold levels and are considered pollution.

Globally, most sugarcane farms are irrigated. Studies carried out in Brazil indicate that irrigated sugarcane farms release more greenhouse gases (GHG) than rain-fed (Cardoza et al., 2015). GHG such as CO_2 is released because fossil fuel is used to power the irrigation system. In some cases, irrigation in sugarcane farms occurs during the day, making the soil vulnerable to high temperatures leading to increased soil evapotranspiration (Mhlanga-Ndlovu and Nhamo, 2017). Soils are examples of GHG sinks. These GHGs such as, CO_2, N_2O, and CH_4 are emitted to the atmosphere due to soil evapotranspiration if irrigation occurs during the day. Day-time irrigation thus contributes to unsustainable farming practices. About 68% of South Africa's sugarcane is grown within the coast of KwaZulu-Natal, whereas 17% is produced in other areas of KwaZulu-Natal with high rainfall, and 19% of the farms are irrigated (Department of Agriculture, Forestry and Fisheries, 2011). Studies carried out in Brazil indicate that irrigated sugarcane farms release more greenhouse gases (GHG) than rain-fed (Cardoza et al., 2015). This study investigated this claim in the case of South Africa.

Mechanised agricultural practices have an environmental impact on greenhouse gas emissions (Cardoza et al., 2015). This is because of diesel (fossil fuel) that is used to operate the various farm machines and equipment. Examples of farm operations that require devices in a mechanised agricultural system include but are not limited to land systematising, heavy ploughing, fertilizers application, pesticides application, herbicide application, filter cake application, vinasse application, and mechanised planting. The burning of diesel releases GHG such as CO_2 into the atmosphere.

Sugarcane harvesting methods influence the amount of GHG emitted to the atmosphere. Before or after harvest, sugarcane residue burning is the most practiced management strategy during sugarcane production in many countries (Zhao and Li, 2015). According to Farahani and Asoodar (2017), sugarcane trash burning is one of Iran's most significant contributors to all environmental impact categories. Mechanised harvesting of sugar cane is encouraged to avoid social and biophysical problems. However, most countries still practice manual harvesting, where the burning of the sugarcane is done to get rid of the leaves before manually harvesting the cane (Le Blond et al., 2017). Such burning practice comes with many disadvantages, such as dryness of the soil leading to extreme soil erosion, death of workers and animals found in the farms, excessive smoke, and particulate matter in the air (Le Blond et al., 2017).

2.6.2 World production of sugarcane and GHG emission.

According to Behera and Sharma (2007), a farming system comprises complex interactions amongst different inter-dependent parts, whereby a farmer can assign specific quantities and qualities of the significant factors of production to which he has access, such as land, labour, capital, and management. Agricultural products such as maize, barley, oats, rice, sorghum, wheat, and sugarcane, provide biomass to produce bioethanol (Halder et al., 2019). The agricultural phase of bioethanol's value chain leads to the production of sugarcane, biomass from where feedstock is used to produce other energy-generating products. These include heat and steam, producer gas, synthetic fuel oil, biogas, electricity, charcoal, methane, biodiesel, methanol, and bioethanol (Mohlala et al., 2016). Thus, in this study, as we focus on sugarcane as raw material to produce bioethanol, it is noted that sugarcane is a cash crop that has been classified as an exhaustive crop (Paul et al., 2005). Sugarcane agriculture includes activities or variables such as soil preparation, planting, fertilizer application, harvesting, and transportation of sugarcane to the sugar mill. These stages are standard practice in the KZN sugarcane farming practice, as evident in this study.

2.6.3 Top sugarcane producing countries: farms sizes and GHG emissions.

Although comparatively, South Africa has the least sugarcane farmlands amongst the top 11 sugarcane countries studied, with its annual progressive farm sizes, it is evident that GHG such as CO_2, N_2O and CH_4 are produced from South African sugarcane farms (Hess et al., 2016). However, the amount of GHG emission is smaller compared to the rest of the global top 10 sugarcane-producing countries (FAOSTAT, 2020). It is realised that the farmland size, to an extent, determines the amount of GHG for the various countries that were calculated. Some examples of these statistical evidence from FAOSTAT (2020) are presented in Figure 2.12. (a - h).

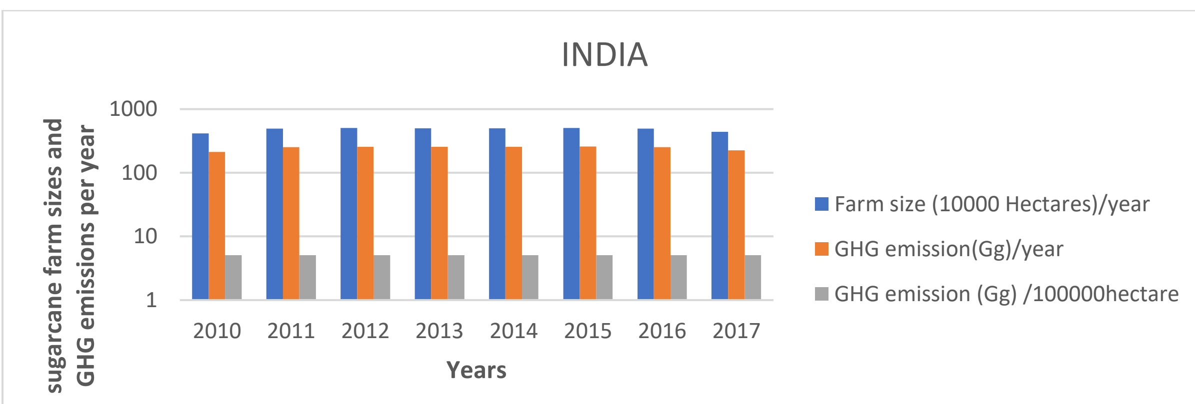

Figure 2.12a: Sugarcane farm sizes against GHG emission in India between 2010 and 2017 (FAOSTAT, 2020)

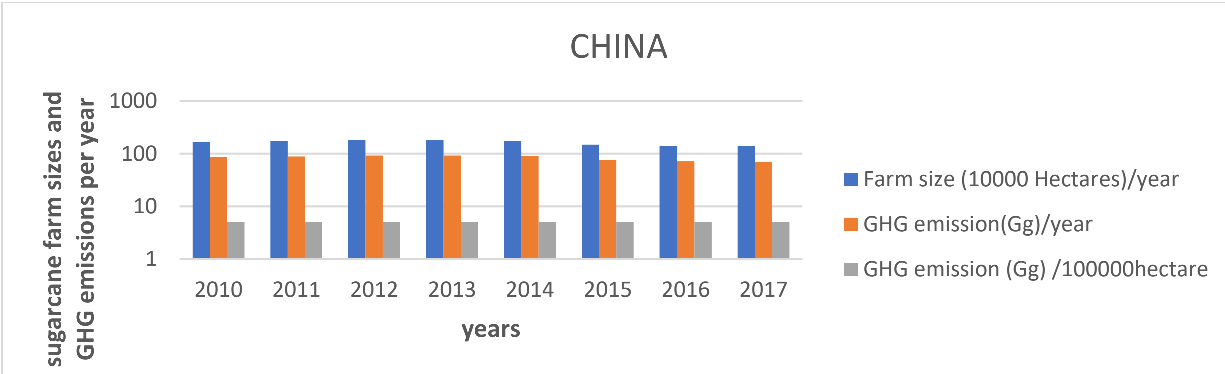

Figure 2.12 b: Sugarcane farm sizes against GHG emission in China between 2010 and 2017 (FAOSTAT, 2020)

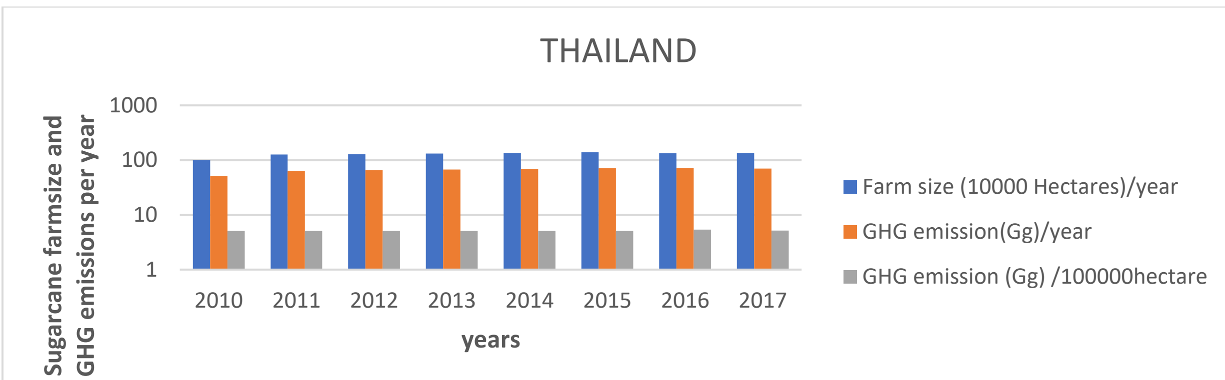

Figure 2.12 c: Sugarcane farm sizes against GHG emission in Thailand between 2010 and 2017 (FAOSTAT, 2020)

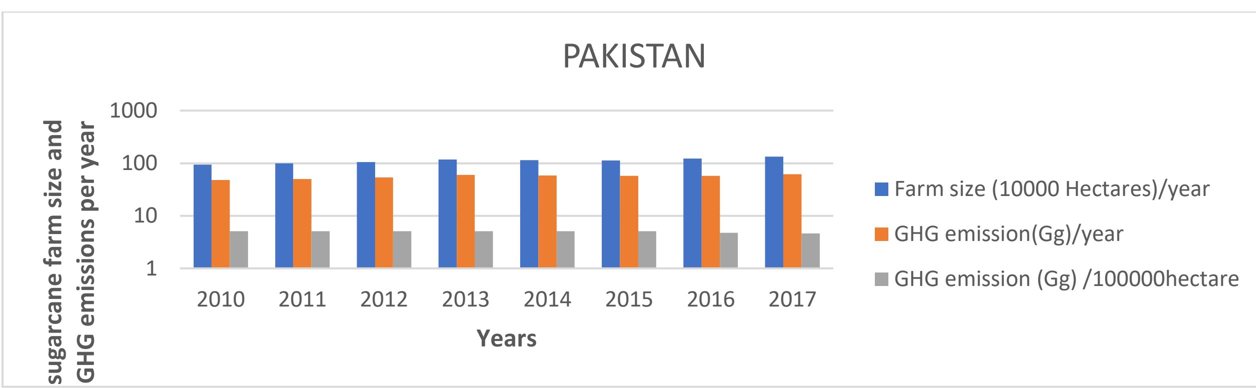

Figure 2.12 d: Sugarcane farm sizes against GHG emission in Pakistan between 2010 and 2017 (FAOSTAT, 2020)

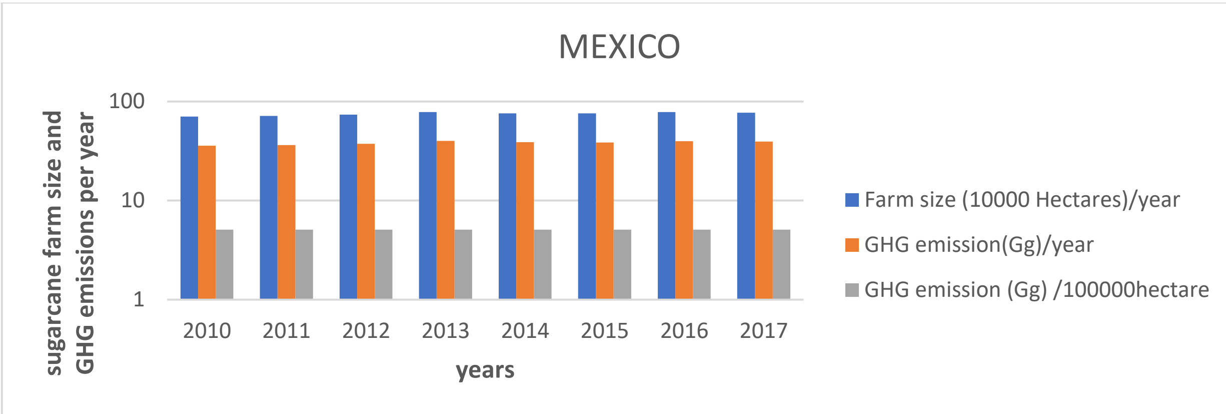

Figure 2.12 e: Sugarcane farm sizes against GHG emission in Mexico between 2010 and 2017 (FAOSTAT, 2020)

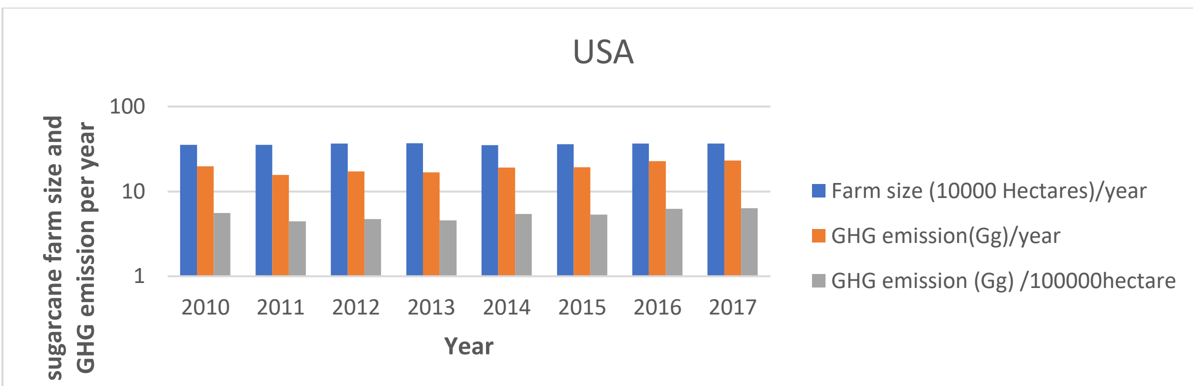

Figure 2.12f: Sugarcane farm sizes against GHG emission in the USA between 2010 and 2017 (FAOSTAT, 2020)

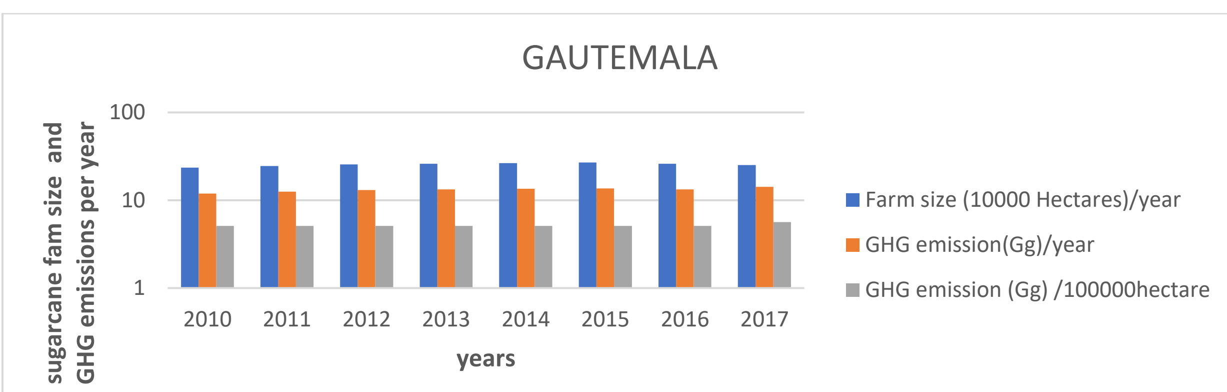

Figure 2.12g: Sugarcane farm sizes against GHG emission in Guatemala between 2010 and 2017 (FAOSTAT, 2020)

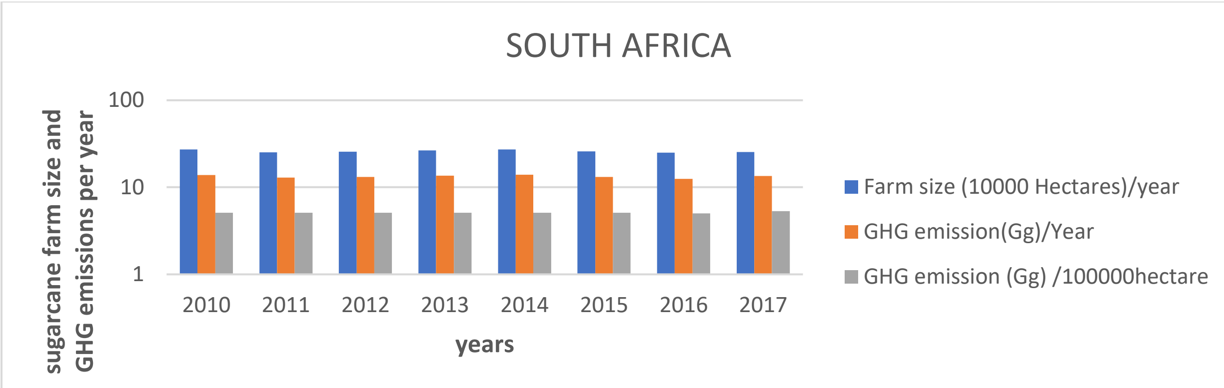

Figure 2.12h: Sugarcane farm size versus GHG emission in South Africa from 2010 – 2017. (FAOSTAT, 2020)

From Figure 2.12(a-h), the bigger the sugarcane farmland size, the higher the GHG emission. This could be an indication that globally most countries still practice similar unsustainable farming activities. In India, both 2010 and 2017 show comparatively smaller farm sizes compared to the rest of the years, and correspondingly, the amounts of GHG emitted in these years are also less comparatively. According to Walter et al. (2011), in the Brazilian context, increases in sugarcane farmlands have mostly occurred at the detriment of grassland used as grazing land and other temporary crops. This signifies a competition between farmland use and pastureland use; what takes preference? Land use change (LUC) follows negative environmental impacts in this case. In this current study, sugarcane farms expansion in South Africa is at the detriment of the sizes of wetlands, mangroves, and coastal forests. Ecosystem services on these specific ecosystems are thus negatively impacted.

Akoth (2016) also reports that the Northeast "Zona da Malta" - the forest of Brazil, has been cleared continuously since the 16th century to make space for sugarcane agriculture. This massive deforestation affects the amount of CO_2 emitted into the atmosphere, negatively impacting global warming and climate change. From the economic dimension, studies carried out in Kenya show that the sugarcane industry has provided jobs to over 500,000 citizens (Akoth, 2016), thus improving their economic status. Conversely, the sugarcane industry can also negatively affect the economy as means need to be devised and executed in order to solve the various environmental pollution and related social issues such as food crop and cash crop competition that emerged due to sugarcane agriculture.

Globally most sugarcane farmers use artificial fertilizers and burnt harvesting systems, just like in South Africa, as seen in this study. Most countries such as Brazil, Australia, India, and China have prescribed recommended fertilizer application rates based on their soil quality (Robinson et al., 2011). However, it is noted that because of the appetite to increase productivity, most farmers go beyond these recommended thresholds, leading to GHG emissions beyond the acceptable points. From this study, the SA sugarcane farmers also use diesel in the tractors used in ploughing and trucks transporting sugarcane from the farms to the sugar plants. These all contribute to the emission of GHG.

As one of the outcomes of COP21 the IPCC and the Paris agreement aimed at reducing GHG emissions to ensure a reduction to the rate at which global temperature increases, thereby limiting this increase to at most 1.5ºC (Jonathan and Werani, 2016). Both sugarcane harvesting methods (green and burnt) influence the soil temperature and atmospheric pollution (Terezinha et al., 2018). Pre-burnt harvesting occurs to increase harvesting efficiency and reduce transportation costs to the sugar mill (Meyer et al., 2005). However, it is noted by Ball-Coelho et al., (1993) and Bordonal et al. (2018) that in Brazil, green cane harvesting contributes to increases in sugarcane yield. Although many farmers practice burnt harvesting methods, green harvesting methods are also practiced in most of Queensland's (Australia's) sugarcane farms (Soam et al., 2015). Sugarcane crop production, with burnt harvesting, therefore, increases the amount of greenhouse gas (GHG) emission. With the use of farm machineries and tools that are powered by fossil fuels, these farms also contribute to the emissions of GHG indirectly. The most common examples of GHG emitted in these instances are CO_2, N_2O, and CH_4.

Soam et al. (2015) further explained that in India, the sugarcane farming phase contributes approximately 85% of the total GHG emission throughout the value chain of bioethanol. Such emission rates thus trigger the researcher to focus on measures to reduce this GHG emission during sugarcane crop production. Other disadvantages associated with sugarcane burnt harvest include dryness of the soil leading to extreme soil erosion, death of workers and animals found in the farms, excessive smoke, and particulate matter in the air (Le Blond et al., 2017). These are prevalent practices in Sao Paulo (Martinelli and Filoso, 2007).

The use of machinery and technology during sugarcane agriculture is gradually taking over the agricultural sugarcane industry. However, mechanised agricultural practices also lead to higher GHG emissions than manual agricultural practices in sugarcane farms (Bordonal et al., 2018). This is because fossil fuels such as diesel are the primary energy source used to operate the various farm machines and equipment. Examples of farm operations that require the use of devices in a mechanised agricultural system include but are not limited to land systematising, heavy ploughing, fertilizers application, pesticides application, herbicide application, filter cake application, vinasse application, planting, and mechanised harvesting (Cardoza et al., 2015; Terezinha et al., 2018). Being amongst the top ten global sugarcane producers in 2012, Indonesia produced 29 million tons of sugarcane on 0.41 million hectares (Mha) of land in 2012 (Khatiwanda et al., 2016). Offering a focus from the Indonesian perspective, manual labour is used for most agricultural activities, including planting, harvesting, and fertilizer application, with a total estimate of 117 Man-day per hectare of sugarcane farmland (Zulu et al., 2019). Burnt harvesting is practiced in 50% of the total sugarcane farmland in Indonesia Khatiwanda et al. (2016) which poses severe respiratory health hazards as the farmers get directly exposed to GHG.

Another example is seen in some cases in Brazil, as stipulated by Rosendo & Matos (2012); due to economic reasons and job creation, manual harvesting is the most used method of harvesting sugarcane in Brazil. Manual harvesting has created employment for about 500,000 workers throughout the country (Barbosa et al., 2012). Since sugarcane harvesting only takes place during certain seasons of the year, harvesters are forced to work daily for at least six days a week as their salaries are measured according to the number of tons they have harvested. Therefore, this is a high-risk activity as harvesting sugarcane tends to be tedious as it is done under high temperatures in the fields, resulting from the climate and the heat from burning sugarcane. Burnt sugarcane harvesting would also be harmful for neighbouring farms if the land size is massive. According to their studies, particulate matter sizes less than 10 microns (PM10) are highest in the atmosphere during the pre-harvest burning process compared to sugarcane cutting after burning and sugarcane processing in the factory (Le Blond et al., 2017). The following figures represent particulate matter (PM), from their findings; 1807 μm/m³, 123 μm/m³, and 175 μm/m³ for PM10 during pre-harvest burning, sugarcane cutting after burning, and sugarcane processing in the factory, respectively (Le Blond et al., 2017). A brief comparative analysis of burnt and green harvest is shown in Table 2.4.

Table 2.4: Advantages and disadvantages of different cane harvesting methods. Adapted from Ma et al. (2014)

Harvesting Practice	Advantages	Disadvantages
Pre-burnt cane harvesting	Less amount of trash will reduce the handling cost	Sugar deteriorates
	Pests are killed when burnt	Increased greenhouse gas emissions
Green cane harvesting	Water and soil conservation	The negative effect of harvesting efficiency
	Weed control	The increased cost of harvesting.
	Reduction of pollutant emission	More significant loss of stalk in the field
	Reduced damage by lesser stalk borer	Soil temperatures decrease by the trash layer, which may potentially slow down early plant growth
		Air temperature near the plant canopy may also be reduced due to the trash layer, exposing young plants to damage by frost.

Some cities with the most sugarcane production in some global top sugarcane producing countries use artificial fertilizers in their farms. According to Janke et al. (2015), some organic waste is recycled, and the nutrients are re-absorbed by the growing cane. Such waste could result from the sugarcane factory during sugar production, for instance, vinasse and filter cake. Other parts of the sugar factory residues are used as fuel in low-efficiency energy systems such as bagasse. Some residues, such as straws, decay in the fields because of limited technical and financial resources to produce bioenergy from them. However, non-controlled biodegradation of such waste on the fields may contribute to the emission of GHG like methane. This release of methane is detrimental as it contributes to climate change. Janke et al. (2015), stipulate that sugarcane farming practices contribute to about 64% of energy consumption due to fertilizers and irrigation systems. This energy is mainly fossil fuel.

2.7 CLIMATE CHANGE DRIVERS ASSOCIATED WITH SUGARCANE AGRICULTURE

Environmental modifications such as climate change and global warming due to increased anthropogenic activities on sugarcane fields have been observed. Climate change negatively affects water supply in some parts of the world, such as the Mediterranean, Sub-Saharan Africa, and north-eastern Brazil (the United States Environmental Protection Agency, (USEAP), 2017).

GHG emissions resulting from the on-site burning of crop residues contain methane (CH_4) and nitrous oxide (N_2O) gases. Such emissions are estimated by FAOSTAT via computerisation at Tier 1 following the IPCC (2006) Guidelines for National GHG Inventories (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html). GHG emission records are provided at national, regional, and special groups, with global coverage, relative to the period 1961-present (with annual updates) and with projections for 2030 and 2050, expressed both as Gg CH_4, Gg N_2O, Gg CO_2eq, and CO_2eq from CH_4 and N_2O where implied emission factors for N_2O and CH_4 as well activity data (biomass burned) are also provided. When estimating the mass of fuel available for burning, the parts are taken out for animal feeding, use in other sectors, and even when it decays in the field, before burning should be considered. This includes but is not limited to biofuel, domestic livestock feed, building materials. In the 2019 statistics, together, both China and the United States have contributed 40 percent of today's global CO_2 emissions (http://www.fao.org/faostat/en/#data/GB - 10 June 2019).

In the 1980s, the USA's CO_2 per capita emissions levelled up at five metric tons per person while China's readings were relatively low at 1.4 metric tons per person. Such per capita discrepancies are standard between developed and developing countries and are central to the global call to ensure climate-friendly economic growth and development.

From the South African perspective, Tongwane et al. (2016) explained that it is evident that cereal production emits the highest amount of GHG, which accounts for 68% of production. However, in their classification of "other field crops," sugarcane produced the highest amount of greenhouse gases with an average of 64% of the total emission from five different field crops. These are some drivers towards the bioethanol life cycle assessment in South Africa. According to FAO, South Africa has shown the following amounts of GHG emission over the years from sugarcane farms (Figure 2 .13).

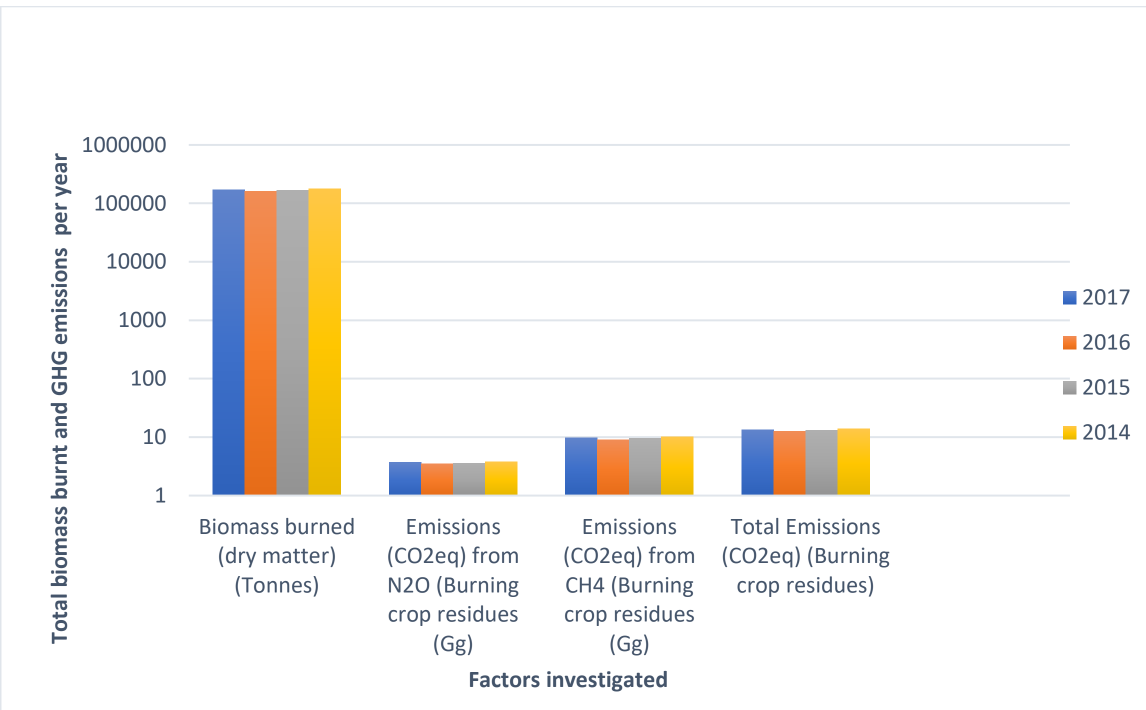

Figure 2.13: South African sugarcane farms and GHG emission due to the burning of crop residues (Source: www.fao.org/faostat/en/#data/GB Accessed on 10th June 2020).

Due to biomass burning, total GHG emissions for South Africa sugarcane farms have gradually decreased between 2014 and 2016 due to many more small-scale farmers embarking into green harvesting methods. However, there is a 7.2% increase in 2017, in probability due to the rise in demand for sugarcane for bioenergy (Hess et al., 2016). With this sugarcane demand, small-scale farmers are thus forced to practice burnt harvesting to meet with sugarcane harvesting and sugar processing time.

2.8 IMPACTS OF SUGARCANE AGRICULTURE ON WATER QUALITY

It is estimated that demands for water in South Africa are currently 15 billion cubic meters and will reach 17.7 billion cubic meters in 2030, where 7.9 billion cubic meters are assigned to irrigation (FarmBiz, 2020). Basing their study on previous scientific research, Hess et al. (2016) wrote that the South Africa sugarcane farmers base their practice on both rain-fed and irrigated methods. These irrigation methods are compared to the results obtained during this current study. Irrigation of sugarcane farms is also based on the geographical location and the hydrological conditions of the area. Although South Africa is a semi-arid region, its water catchment areas around sugarcane farms are still potentially impacted negatively due to chemical run-off into the catchments (Davis et al., 2011) and farm irrigation. Such impact is also still evident in the current study. The W13B11 and W13B13 catchments both have pH values of 8.19, with Water Quality Indices of 279.35 and 211.43, indicating inferior water quality according to the WQI classes (Kawo and Karuppannan, 2018). These 2 catchments also showed an Electrical conductivity (EC) of 5027.00 and 3804.49 mS/m, respectively. These different water quality impacts on overall quality. Therefore, it is concluded that pollutants increasingly threaten aquatic systems within and or near sugarcane agricultural activities from agronomic inputs and processing wastes.

On the one hand, the extraction of and the transmission of water from rivers, groundwater, or constructed reservoirs can affect flow patterns or rivers and aquifers. India is a classic case in illustration where irrigated sugarcane has contributed to severe scarcity of surface and groundwater at various spatial scales in several river basins (Rodell et al., 2009). Nevertherless, an increase in rain-fed sugarcane areas might change the quality of water resources whereby chemicals from the farm are washed downstream (Hess et al., 2016), as was also the case in the current study.

2.8.1 Impacts of sugarcane agriculture on groundwater quality

Using a systematic review of relevant literature, El Chami et al. (2020) reviewed that the increase in sugarcane agricultural land over multiple years' harms ecosystems, negatively impacting the services offered by the affected ecosystems. Groundwater is one of such ecosystems. For example, in the East Africa study by Thornton et al. (2009), changes in irrigation requirements with this increase in sugarcane agricultural land with time have contributed to the over-abstraction of groundwater for irrigation (Thornton et al., 2009), thus stressing both the quality and the quantity of groundwater. Groundwater abstraction is severe in South Africa, a water-scarce country with its water withdrawal capacity for sugarcane agriculture at 9.8% (El Chami et al., 2020).

El Chami et al. (2020) have described the impact of sugarcane agriculture on groundwater as both quantitative (in terms of water abstraction for irrigation) and qualitative (in terms of leaching of nutrients and chemicals from farmland into the groundwaters). Brazil sugarcane farms are mostly rain-fed, while in South Africa, there is a combination of irrigation and rain-fed farms, as observed in this current study. Impacts of sugarcane production on water resources thus vary with the variation of the local agro-meteorological conditions. According to Olivier and Singels (2012), the South African irrigation requirements fluctuate between 731 and 1062 mm a year.

Shih and Gascho (1980) estimated their irrigation requirements to be between 1055 mm and 1360 mm per year from the USA perspective. In Australia, they were estimated to be between 855 mm and 1642 mm a year (Thorburn et al., 2011). Simulating irrigation requirements on two different soil types, using climate data for 1968–2003 in South Africa found that irrigation water requirements could vary between 835 mm and 1496 mm in South Africa (Singels and Smith, 2006). In their study, El Chami et al., (2020) compared the sugarcane crop evapotranspiration (ETc) of the previous researched works with the estimates of ETc for South Africa in 2020. They found that the former is much lower than the latter. This, is an indication that the groundwater level of recent years is lower than the groundwater level of previous years, thus portraying that because of gradual increases in sugarcane farm sizes over the years, there is equally an increase in the rate of water abstraction for irrigation as the years pass.

Regarding qualitative impact, chemical fertilizers, pesticides, and herbicides on sugarcane farms contribute to leaching such chemicals into the groundwater space. From the South African context, in this study, more than 80% of the farmers that took part in this study use chemical fertilizers on their farms. Studies by Camenzuli et al. (2012), Shaw et al. (2012), Rasiah et al. (2013), and Alves et al. (2014), all confirm the deteriorating nature of groundwater quality by agrochemicals used during sugarcane agriculture. The results of their Brazillian and Australian contexts showed that groundwaters in sugarcane areas contained varying concentrations of “Ametrin,” “Diuron,” “Triazine,” and “Hexazinone which are molecules making up pesticides and herbicides which are highly used in sugarcane growing regions (Camenzuli et al., 2012, Shaw et al., 2012, Rasiah et al.2013, and Alves et al., 2014).

2.8.2 Impacts of sugarcane agriculture on surface water quality

Water run-off from sugarcane farms, either after irrigation or heavy rains, carry along with chemical substances to nearby surface water bodies (Davis et al., 2011). These chemical losses from irrigated farms change the chemical compositions that cause water pollution. Eutrophication is the most commonly physically visible impact of surface water that is near sugarcane farmlands. For example, eutrophication is evident in Australia’s Great Barrier Reef and Lake Victoria due to being located within sugarcane plantation catchments, affected by a range of pollutants such as nutrients and pesticides (Omwoma et al., 2014).

Although published articles on sugarcane agriculture impacts on water quality in Africa are limited, it is noted that sub-Saharan Africa’s sugarcane farms, except for Cameroon, Liberia, Congo, and the Central Africa Republic, are reliant on irrigation (Hess et al., 2016).

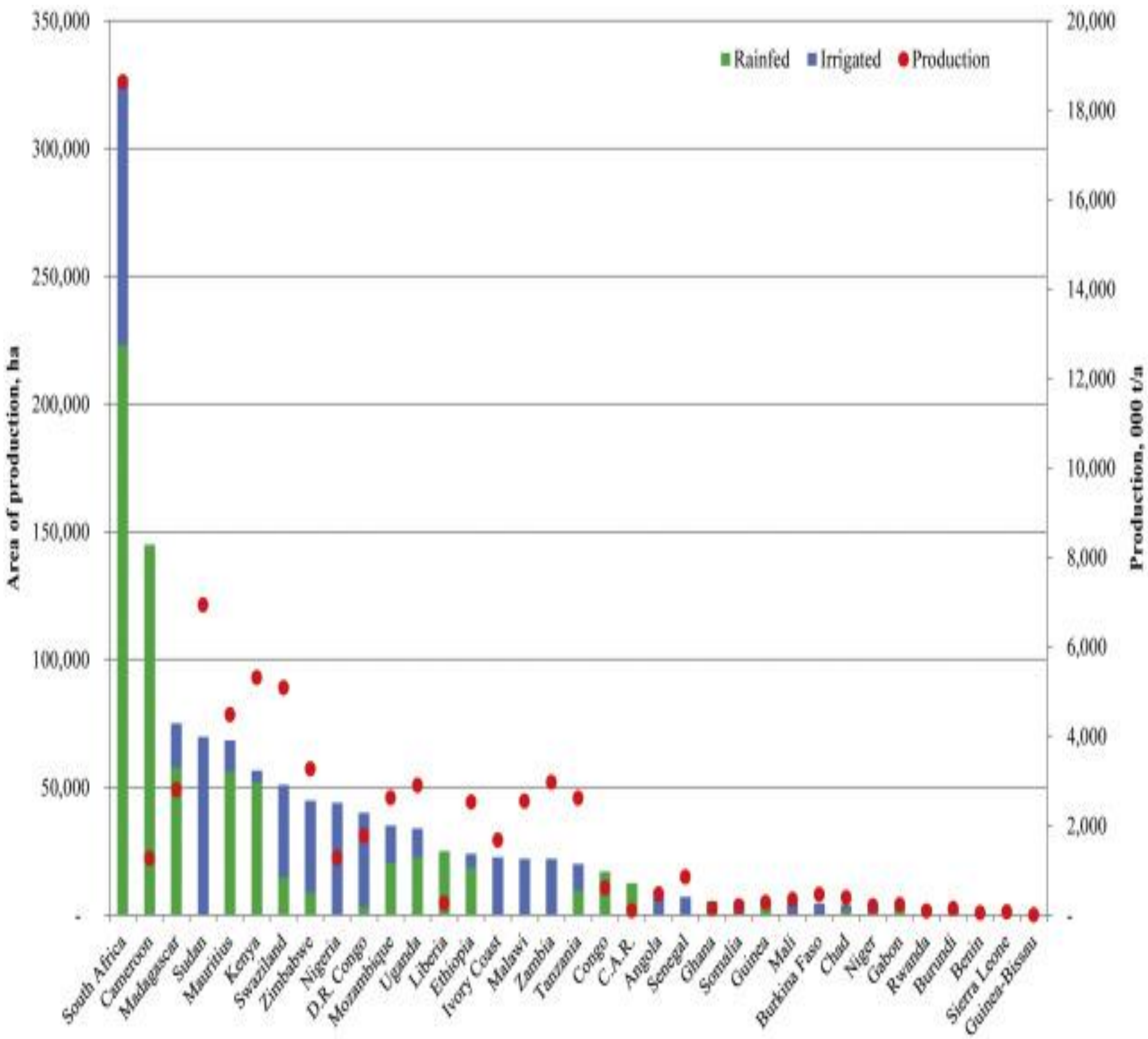

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Figure 2.14: Sugarcane harvested area (ha) and average production (×000 t) and irrigation water source, by country in SSA (Hess et al., 2016).

On the one hand, from figure 2.14, irrigated sugarcane farms will cause a modification to water balances as they will be a scarcity of surface water, thus leading to competition amongst shared users. On the other hand, rain-fed sugarcane farms also contribute to changes in available water resources since sugarcane farms replace another previous land use. In the case of South Africa, according to Hess et al. (2016), competition for surface water resources in specific catchments has forced the sugarcane industry to justify its farm irrigation on the provision of economic returns. In this situation, the triple bottom line and sustainable development become a debate.

2.8.3 South Africa’s Contribution towards Sustainable Sugarcane Agriculture

2.8.3.1 Sustainable Sugarcane Farm Management System (SUSFARMS): An analysis of their conceptual framework (SASA, 2019)

SASRI has developed the SUSFARM framework to encourage sustainable sugarcane agriculture (SASRI, 2019). This framework integrates three principles which include economic, social, and environmental regulations. The framework indicates complete integration of these principles such that the implementation of one principle should not neglect the following principle. For instance, if farmers tend to increase profitability, this should not be detrimental to the natural environment. According to this framework, the measures are fair to both small-scale and large-scale farmers. These measures are according to legal requirements and better management practices that are not necessarily bound by the law.

This conceptual framework requests a Land Use Plan (LUP) on land-use change, a legal requirement drawn according to the South African legal standards (SASA, 2019). In addition, slopes greater than 4%, and LUP must contain details and specifications regarding:

- Conservation terraces
- Waterways
- Roads and cane extraction system
- Types of road drainage systems
- Natural wetlands and watercourses
- Dams
- Quarries and rubbish dumps

Farmers are also expected to present any legal document showing ownership of the land intended to be cultivated (SASA, 2019).

This framework, SUSFARMS, also covers the annual production plan with measures of annual variables that can impact production. Both direct and indirect energy use is also planned for. This may include the type of energy, the required amount to be used, the agricultural stage where this energy will be used, and the machinery used at that time. However, this current study makes it questionable if a sustainable monitoring strategy is presented with such a framework. There was no evidence of such monitoring with the farmers who took part in this study.

2.9 SUGAR AND MOLASSES PRODUCTION AND THEIR ENVIRONMENTAL EFFECTS

According to 2009 statistics, globally, sugar is produced in 121 countries, and 70% of the sugar is obtained from sugar cane plants, grown mainly in tropical countries (Contreras et al., 2009). The sugar industry generates effluents that pollute water the most (Rao et al., 2011). Sugar production has shown a fluctuation between surplus and deficit over the years. For instance, with almost 4 million tons deficit of sugar production in 2009, there has been a persistent surplus from 2010 – 2014, with 2013 having the most significant excess of close to 9million tons. The years 2015, 2016, 2019, and 2020 also indicate deficits. With the highest deficits of more than 5 million tons seen in 2015. 2017 had a considerable surplus of almost 10 million tons (Orive, 2020). India, one of the world's largest sugar producer and consumer, also realized more than 7 million tons surplus in 2019. With current increases in ethanol production rates, this surplus sugar observed in India will potentially be reduced. Ethanol production from cane priced at more than USD40/tonne is not an economically viable option considering abundant molasses supply (Orive, 2020).

Thailand has produced more sugar than it can consume from 2011 until 2018 with the most significant surplus of about 11.7 million tons was observed in 2017. Over these years, the consumption has been constant at an average of 3 million tons consumed a year (Orive, 2020).

With such sugar production, molasses is also produced as a by-product. Molasses is used either in the production of bioethanol or sweeteners and alcoholic beverages. The 2020 statistics show India exported the highest molasses while South Africa exported the least with 737.12 million kg and 42.73 million kg, respectively (Shahbandeh, 2021).

In South Africa, most factories that produce sugar are situated in the coastal regions of KZN, where the sugarcane farms are also mostly found. There is also no doubt but to assume that such waste from the sugar factories also causes either groundwater or surface water pollution. This assumption is made per the LCA of the sugar industries in South Africa, as studied by Mashoko, Mbohwa, and Thomas (2010).

Sugarcane production, consumption, and ethanol production experienced a slight fluctuation over the years. Surplus sugarcane, which is not processed into cane sugar and subsequently molasses, produces bioethanol (Pradhan & Mbohwa, 2017). The following table, Table 2.5, represents the quantities of sugar production in South Africa over five years.

Table 2.5: Sugar and bioethanol production in South Africa (Pradhan & Mbohwa, 2017)

SUGAR PRODUCTION, CONSUMPTION, AND SURPLUSES					
Season	**2010/ 2011**	**2011/2012**	**2012/2013**	**2013/2014**	**2014/2015**
Sugar production (Million ton)	1.92	1.83	1.96	2.35	2.12
Sugar consumption (Million ton)	1.55	1.69	1.61	1.55	1.69
Surplus sugar (Million ton)	0.37	0.14	0.35	0.80	0.43
Tons cane to 1-ton sugar	8.35	9.17	8.81	8.51	8.38
Surplus sugarcane (Million ton)	3.09	1.31	3.09	6.83	3.62
Ethanol from surplus sugarcane (Million liters)	227.5	96.7	227.8	504.4	267.3

According to the South African Sugarcane Research Institute (SASRI), visitor's guide (2018), South Africa's sugar industries produce one of the world's leading cost-competitive and high-quality sugar. In this study the researcher analysed sugarcane farming inventory and impact assessment results which, according to Mashoko et al. (2010), shows that non-renewable energy consumption is 5350 MJ per ton of raw sugar produced.

The sugar production industry is a hectic industry both in terms of its production and waste generation. Some of the waste or by-products such as molasses from sugar production are used to manufacture bioethanol. Waste, such as bagasse, is used mainly in the supply of processed heat for the boilers in the sugar factory. According to Tongaat Hulett Ltd. (2009), every 100 tons of sugarcane harvested and milled produces 11.8 tons of sugar and 28–30 tons of bagasse. The remaining material from the 100 tons of sugarcane inputted is commonly disposed of as waste. In the Nigerian context, their first sugarcane bio-refinery is located Zaria and was created in 2015, established to optimise sugar and ethanol production (Mohlala et al., 2016). In South Africa, 14 companies mill sugarcane, 12 of which are found in the KZN province and 2 in Mpumalanga. In terms of their sugarcane milling operations, Illovo Sugar Limited and Tongaat Hulett Ltd. are the largest, with each company operating four sugar mills, followed by TSB sugar with three mills (Mohlala et al., 2016). This is concerning as it is not certain how waste and gaseous losses are managed along the sugarcane value chain. In addition, Gledhow, Umfolozi, and UCL sugar companies own a mill each. Waste generated from sugar mills such as bagasse and molasses are used to generate electricity, the industrial production of ethanol, paper manufacturing, and used to produce animal feed. Bagasse is fibrous biomass, and it is the material that remains once the juice has been extracted from the sugarcane stalks (Canilha, 2012).

One by-product, molasses, contains sucrose, glucose, fructose, ash, moisture, potassium, and calcium, including other non-sugar compounds (Dotaniya et al., 2016). According to Bušić et al. (2018), the fermentable sugar in molasses is fermented into alcohol, leaving behind the non-fermentable content in the spent wash. Kumar and Thankamani (2016) further explain that such raw spent wash generated is acidic and has a dark brown colour with an unpleasant odour, and with high chemical-oxygen demand (COD), and a biological-oxygen demand (BOD) of 100,000 and 45,000 mg/l, respectively.

2.9.1 Cane preparation, milling, and diffusion versus waste generation.

Cane preparation begins with the washing of the cane. (Rao et al., 2011), followed by "preparation," whereby the cane is finely shredded for the juice to be extracted. Rao et al. (2011) and Nara (2014) have given a similar description of how waste is generated during sugar production and the dynamics of the process. Firstly, the preparation of the cane is done by crushing and squeezing the juice out of the cane. Sugarcane is prepared by passing it through one or two sets of cane knives and again through a shredder (Nara, 2014). It is usually preferable to crush finely shredded cane to ensure higher quality juice is extracted. Crushing finely shredded cane as opposed to cane stalks produce optimal extraction of sucrose. According to this study crushing is done either by milling or diffusion. Bagasse and molasses are made during this phase.

2.9.1.1 Cane Milling

Generally, cane mills contain three grooved rollers. Squeezing of the prepared cane takes place between the rollers, where the juice is forced out of the fibre (Nara, 2014). Thus, the mill separates the juice from the fibre (Nara, 2014). Imbibition is a type of diffusion through which water is absorbed by solids-colloids (Colonna et al., 2016). This process causes a considerable increase in volume to be applied at this stage, where water is added to the prepared cane before milling. Water is added to ensure no juice is retained in the fibres (Nara, 2014). Because a single milling unit would produce shallow extraction, six mills are usually set in tandem for the cane to be passed through many mills to ensure maximum juice extraction (Filoso et al., 2015). Residues commonly known as process residues produced during this phase include bagasse (the chaffs/fibres) of sugarcane left over after all the juice has been squeezed out (Nara, 2014; Colonna et al., 2016; Mohlala et al., 2016). Process residues can be treated in 2 ways; they are either left to dry on the farm, burnt off, or found littering the streets next to the mills. Neither of these practices is sustainable, as in both cases, there is environmental pollution (Mohlala et al., 2016).

2.9.1.2 Diffusion

A diffuser is an enclosed carrier where a bed of prepared cane is slowly passed through. During this process, large amounts of water and juice percolate through the bed to wash out the juice with sucrose (Nara, 2014). As a result, the waste or by-product leaving the diffuser has absorbed much liquid. Such waste is drained of water in a mill before being sent to the boilers or by-product processors.

2.9.1.3 Purification of juice

Cane juice that falls out between the mill's rollers contains large amounts of cane fibre (Nara, 2014). This fibre is removed by pouring the liquid over a wire mesh. The fluid will pass through the mesh while the wire mesh will trap the thread due to the screening effect of the cane bed. The juice is heated at about 70°C for the first time, and after that, the juice can react with lime and sulphur dioxide (Rao et al., 2011) to neutralize the juice's natural acidity. The neutralised juice is again heated at 105°C and then placed in a large clarifier which helps to settle the juice. After clarification, a clear juice is produced, free of suspended matter—muddy juice filters in this process. According to Rao et al. (2011), the filtered liquid is again taken back into the clarifier to extract the filter cake. In this process, flocculent is added to increase the precipitation (Filoso et al., 2015).

The settled residue, mud, once pumped out of the clarifier, is sent to the filtration station, where the remaining juice will be extracted. If a diffuser is used, the juice is sent to the diffuser and filtered through the bed of bagasse (Filoso et al., 2015).

2.10 BIOETHANOL PRODUCTION

At the level of the bioethanol production plant, the availability of feedstock is a problem during the production of bioethanol. Figure 2.14 shows examples of feedstock used as raw material for bioethanol production and their bioethanol production potential. Again, rice and maize show the highest potential, while sugarcane and sweet sorghum have the lowest prospects, respectively.

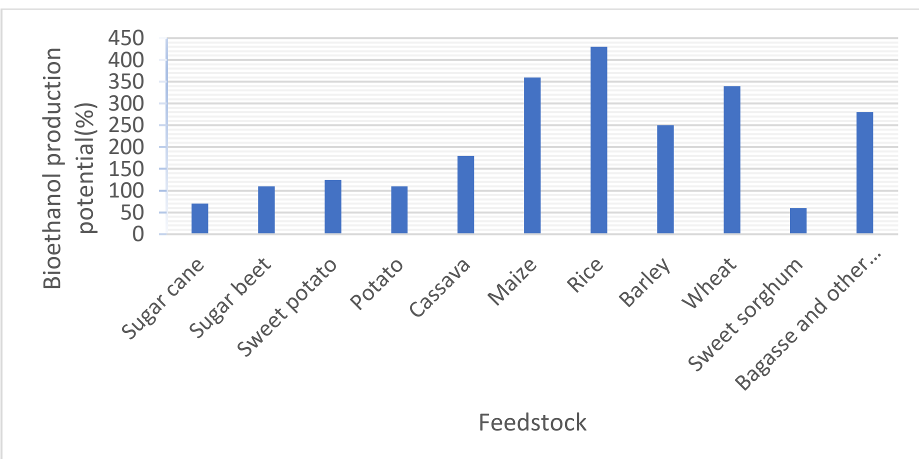


Figure 2.15: Comparing bioethanol production potential (L/ton) from various Feedstock (Hamat, 2012)

Although sugarcane shows a lower bioethanol production potential than other feedstock, it has been adopted in South Africa as the primary feedstock instead of other grain cereals (Figure 2.14). Sugarcane is preferred due to its reduced competition with other food crops and more minor economic and social concerns (Prahan and Mbohwa, 2014). Three significant steps are involved in producing bioethanol: getting fermentable sugar solution ready, fermenting the sugars to obtain alcohol, and finally separating and purifying the alcohol (Demirbas, 2007; Bušić et al., 2018).

Although with a potential higher production cost than fossil fuels, according to Liboni (2012), bioethanol, compared to oil and its derivatives, is less toxic and readily biodegrades if spilled accidentally. This preference of sugarcane as a feedstock implies that ethanol's environmental impacts are significantly lower in accidents. The environmental recovery is faster than when there is spillage of fossil fuel (Liboni, 2012).

Molasses used in the production of bioethanol need to be transported. The distilleries make up for the energy (fuel) used in this transport with bagasse and biogas (Prakash et al. 2005). After dilution and fermentation of molasses, the resulting broth contains 6–8% (v/v) ethanol. For distillation to about 40% ethanol, this broth is sent into an analyser column. According to Filoso et al. (2015), the ethanol vapours are passed through a rectification column where hydrous ethanol of approximately 95% (v/v) concentration (rectified spirit) is produced. The 95% ethanol undergoes a dehydration step for fuel-grade ethanol, resulting in 99.5 % (v/v). Stillage exits the analyser column as liquid effluent. Stillage has a very high chemical and biological oxygen demand (BOD) which requires the need to be treated appropriately to avoid ground and surface water contamination after its disposal, Feuss and Garcia (2014).

In a case study in Brazil, Filoso et al. (2015) analysed and concluded that vinasse production is about 20 litres per litre of ethanol upon producing second-generation ethanol from sugarcane trash. Vinasse shows chemical characteristics such as high labile organic carbon content, high biological oxygen demand, and a high concentration of potassium and nitrogen (Zani et al., 2018). Vinasse, therefore, has a high potential of causing water eutrophication if not properly managed from the ethanol mill. With the eutrophication tendency of vinasse, the Brazilian government has tried to reduce the amount of vinasse being poured into water bodies. Instead, it should be used as a form of fertilizer in the sugarcane fields. This process is called fertirrigation (Filoso et al., 2015).

Fertirrigation has a positive effect on aquatic ecosystems. However, there are still some increasing concerns about fertirrigation using vinasse on soils. Vasconcelos et al. (2022) analysed that the application of vinasse in soils that have been treated with synthetic N fertilizer can contribute to increasing N_2O emissions, thus, increasing the disadvantages of using sugarcane ethanol to reduce GHG emissions from fossil fuels. Thus, the repeated application of vinasse and chemical fertilizers becomes problematic as this contributes to potassium accumulation in the soil. This accumulated soil potassium will leach to groundwater causing groundwater contamination and eventually leading to surface water eutrophication. On another note, there is a high demand for water during the industrial phase of bioethanol production. However, approximately 36% of the water used in ethanol mills is from washing sugarcane stalks to remove soil particles and small debris before the fermentation phase (Filoso et al., 2015).; this is in the case where sugarcane is used directly to produce bioethanol. According to Mangwanda et al. (2021), the fermentation and distillation phase accounts for 27% of the water use. Reusing and recycling water during sugarcane washing will thus contribute to the overall water use reduction in the mill.

Quantities of bioethanol produced from 1 ton of molasses (Table 2.6) may vary depending on many factors. For example, India has an average of 235 litres of ethanol produced from 1 ton of molasses (Mohan, 2015), while in Pakistan, 1 ton of molasses produces 181.4 litres of ethanol (Parkash, 2015). This difference could result from the sugar content of the sugarcane resulting from variables such as climatic conditions, soil nutrient content, quantity and composition of fertilizers used, and whether the farms are irrigated.

Table 2.6: The total possible ethanol production versus molasses used in Kanpur, India (Mohan, 2015)

Sugar Season	Total Molasses Production (Lakh tonnes)	Molasses available for alcohol production (Lakh tonnes)	Estimated Alcohol Production Potential (Crore litres)
2011-12	118.24	112.33	263.98
2012 - 13	117.44	111.57	262.19
2013 - 14	108.50	103.08	242.24
2014 - 15	124.82	118.60	278.70

In a nutshell, this study looks at general waste production, most especially wastes that contribute to the overall rise in water pollution and the level of greenhouse gases that contribute to global warming, their management strategies, and mitigation strategies.

2.11 SOME OF SOUTH AFRICA'S ENVIRONMENTAL LEGISLATION CAN BE LINKED TO THE PRODUCTION CHAIN OF BIOETHANOL.

With the umbrella Act being the National Environmental Management Act (NEMA) No 107 of 1998, several Specific Environmental Management Acts (SEMAs), norms, standards, and municipal by-laws have been developed to ensure the implementation of activities that will lead to and maintain sustainable environments.

2.11.1 National Environmental Management Act (NEMA) No. 107 of 1998.

NEMA stipulates the implementation of principles that will encourage sustainable environments. Some of these principles are discussed below:

Chapter 1, S_3 states that; "Development must be socially, environmentally and economically sustainable" while chapter 1, S $_{(4)\ (a)}$ states that Sustainable development requires the consideration of all relevant factors including the holistic nature of the environment. Sugar industry is thought to be based mostly on the generation of income while disturbing the natural ecosystems through sugarcane farming practices, discharge of untreated waste from both the sugar and bioethanol industries on the natural environments. This study is thus important as it has looked at these various sources of environmental degradation along the value chain of bioethanol.

NEMA is designed to protect wetlands from anthropogenic activities. NEMA forbids constructions of any type close to water sources and stipulates that such actions must be performed at least 32 meters away from the water sources and riparian zones (NEMA, 107 of 1998). According to this study, some of the sugarcane farms in KZN are on wetlands, depriving the environment of the wetland ecosystem services. In addition, sugarcane farms pollute the waters of the marsh due to contaminants from the fertilizers and pesticides used on the farms, as all farmers make use of chemical fertilizers, according to evidence gathered in this study. Furthermore, before carrying out any activity around the wetlands, that activity must be subject to an environmental impact assessment (Glazewski, 2011). However, through the interactions during this study, there is no historical and documented evidence of an impact assessment before the sugarcane plantations were developed.

2.11.2 Integrated Coastal Management Act 24 of 2008

As a Specific Environmental Management Act (SEMA), the Integrated Coastal management Act regulates the conservation of wetlands as an international priority commitment. This wetland conservation is done through an integrated approach to the sustainable management of natural resources in coastal wetlands. Laws are enforced that protect and control wetlands from anthropogenic activities (Kuntonen van Riet, 2007). It is evident from this study that most sugarcane plantations in South Africa are occupying land that was previously wetlands. This may be assumed that they have not followed the directives of the integrated coastal management Act of 2008. Therefore, the environment will not be able to get rid of its wastes naturally through the services of the wetlands, which act as natural filters due to them being destructed by the presence of sugarcane farms.

Chapter 7 of this Act deals with protecting coastal environments through various notices and the requirements for environmental authorisation. Section 28 of NEMA that deals with the “duty of care,” covers the prevention of significant harm to the coastal environment. Notices laid in this Act are for access to and use the coastal environment, repair, remove or demolish any structure constructed illegally within a coastal environment. According to these notices, it is not clear if developing a sugarcane farm without any notice to access the land is considered a criminal offense whereby notice is issued, or administrative action is requested from the farmer.

2.11.3 National Water Act 36 of 1998

Section 2 of this Act states the purpose of this Act, amongst which are the following:

- That the nation’s water is protected, used, developed, conserved, managed, and controlled. And that this is done in ways that consider factors meeting the basic human needs of present and future generations and promote equitable access to water.

Thus, authorisation is required when one’s activities temper with natural water resources. This authorisation is granted in four different categories, which include

- Schedule 1 Water Use
- Existing lawful Water Use
- General authorisation of Water Use
- Licensed Water Use

Regarding the sugarcane farming practice, water from natural water resources is used for irrigation. Therefore, the effect of fertilizers leaching into groundwater and running off into surface water is a significant concern that requires a water use license. This legislation is enforced by officials from the Department of Water Affairs and Sanitation.

Section 19 directive of this Act deals with the prevention of pollution. This section affects all 3 levels/phases of bioethanol production: sugarcane farming, molasses production, and bioethanol production.

2.11.4 National Environmental Management: Biodiversity Act, no 10 of 2004

The National Environmental Management: Biodiversity Act (NEM: BA) protects certain animal and plant species that need protection measures. The aims of the Act, amongst others, include the following:

- The management and conservation of biological diversity within the Republic and of the components of such biological diversity
- To provide for co-operative governance in biodiversity management and conservation

Section 3 of the Act states that section 24 of the National Constitution must be fulfilled through the organs of state that implement the legislation applicable to biodiversity. This implies the management and conservation of biodiversity sustainably. However, it is not sure how this Act has been implemented in sugarcane agriculture, and there is evidence of LUC that affects biodiversity.

The National biodiversity frameworks and Bioregional plans facilitate biodiversity planning and monitoring, which should have been used before converting original land use to sugarcane farms. Before 1994 where these legislations were not yet enacted, the Biodiversity Act of 2004 would not have been applicable. However, with the recent farm size expansion observed in this study, it is not clear if this Act was applied to every single farm's extension before the extension was effected ten years ago. In this case, although they do not create offenses, the National Norms and Standards for Biodiversity Management Plans for Ecosystem should have been applied to manage the sugarcane farmers' activities.

For the sugar and bioethanol plants' activities, it is evident that they generate effluents. However, it is not clear how these effluents are managed or disposed of. Moreover, in the case of toxic effluence being discharged into water bodies, aquatic organisms which constitute part of the earth's biodiversity are negatively impacted.

In proper monitoring, compliance notices could be issued to the sugarcane farmers, sugar plant, and ethanol plant operators to minimise or prevent harm to biodiversity, where the failure to comply will be considered a criminal offense.

2.11.5 National Forests Act No. 84 of 1998

The National Forest Act (NFA) protects certain tree species only. No natural forest, indigenous tree in that forest, or any trees considered a protected tree in terms of the National Forests Act 84 of 1998 and identified in the Government Gazette may be cut, damaged, or destroyed except through a license. Sugarcane farms have made use of land previously covered by forests. From the Land and land cover change from forests to sugarcane farms, it is sure that some of the trees in the studied forests were protected since these forests are areas under conservation.

2.11.6 National Environmental Management: Air Quality Act No 39 of 2004

Air pollutants emitted during sugarcane agriculture, from the sugar industry, and the bioethanol plants are all aspects that require an air emission license before their commencement. According to the National Environmental Management: Air Quality Act (NEM: AQA) of 1998 in section 24G, recommends that activities that emit air pollutants need the authorisation to commence. However, these activities need to be analysed in terms of the emission quantities and listed activity. The Cool Farm Tool model used in chapter 5 of this study pays particular attention to the atmospheric emission of greenhouse gasses during sugarcane agriculture. With these, individual farmers can measure their emissions. Estimating emission rates will lead to better and more efficient air emission management practices. With the approach of burnt sugarcane harvesting, ambient air is immediately polluted. Section 24 of NEM: AQA guards against such activity without authorisation.

2.11.7 Carbon Tax Act No 15 of 2019.

The President of the Republic of South Africa signed the Carbon Tax Act No 15 of 2019, which came into effect on 1 June 2019. The carbon tax aims to mitigate climate change by putting a price on GHG emissions. The immediate objective is to encourage cleaner air practices. Amongst many sources of emissions, combustion attracts the carbon tax if such emission is above the acceptable thresholds. In addition, farmers will now measure their emission rates using the Cool Farm Tool model. However, using the recommended "emission factors" established by the Intergovernmental Panel on Climate Change may seem challenging and complicated to use by local farmers (The Carbon Tax Act, No.15, 2019).

Although they have no thresholds, fugitive emissions still attack the carbon tax irrespective of GHG emitted. Therefore, fugitive emissions should be monitored in both the sugar and bioethanol plants.

The legislation is built on the “polluter pays” principle, where those responsible for harming the environment must bear the cost of environmental damage. Therefore, the Carbon Tax Act applies to industries that conduct activities above a given threshold, as stipulated in Schedule 2 of the Act, where these activities release significant quantities of greenhouse gases. For example, suppose sugarcane farmers, sugar plants, and bioethanol plants could be guided on applying and getting an air emission license. In that case, it will regulate and manage the amounts of pollutant air being emitted from their activities (The Carbon Tax Act No 15 of 2019).

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

3.1 INTRODUCTION

This chapter provides the philosophical assumptions underpinning the research and the choices on the research design, the research methods, and the data gathering tools for the study area. Research limitations and ethical considerations for the study have also been identified for this study. The primary purpose of this study was to evaluate the sustainability of bioethanol production. This evaluation builds up from the analysis of the impact of LULCC from natural ecosystems into sugarcane agriculture within the study area and by investigating the environmental impacts of bioethanol production on the surface water resources and its effects on air resources (GHG emission) across the whole value chain. The chapter begins with an outline of the research design. It is followed by a thorough description and explanation of the rationale of the research methods and data-gathering instruments employed for the study. Evaluation of sustainability-related bioethanol production requires considering the product's entire life cycle (Davies et al., 2009; Manik et al., 2013). However, this study only achieved some aspects of such life cycle research through the analysis of waste generation concerning potential environmental issues in some significant stages of the value chain of bioethanol.

3.2 RESEARCH DESIGN

A research design can be described as how the implementation plan of the study is conducted (Creswell, 2014; Sileyew, 2019). A research design, through the method, portrays how different parts of the study play a role in answering the defined research questions. The main objective of this study was to evaluate the sustainability of bioethanol production by investigating the environmental impacts of the various process in its value chain. The processes involved in bioethanol production include sugarcane farming, sugar production, and bioethanol production, as highlighted in Figure 3.1. Environmental issues for each of the significant bioethanol production phases are also represented in Fig 3.1.

The mixed-method research was chosen for this study due to the nature of the survey, which required an analysis of both qualitative and quantitative data to achieve its objectives (Creswell, 2014 and Sileyew, 2019). Therefore, both quantitative and qualitative data were collected through primary and secondary data collection tools.

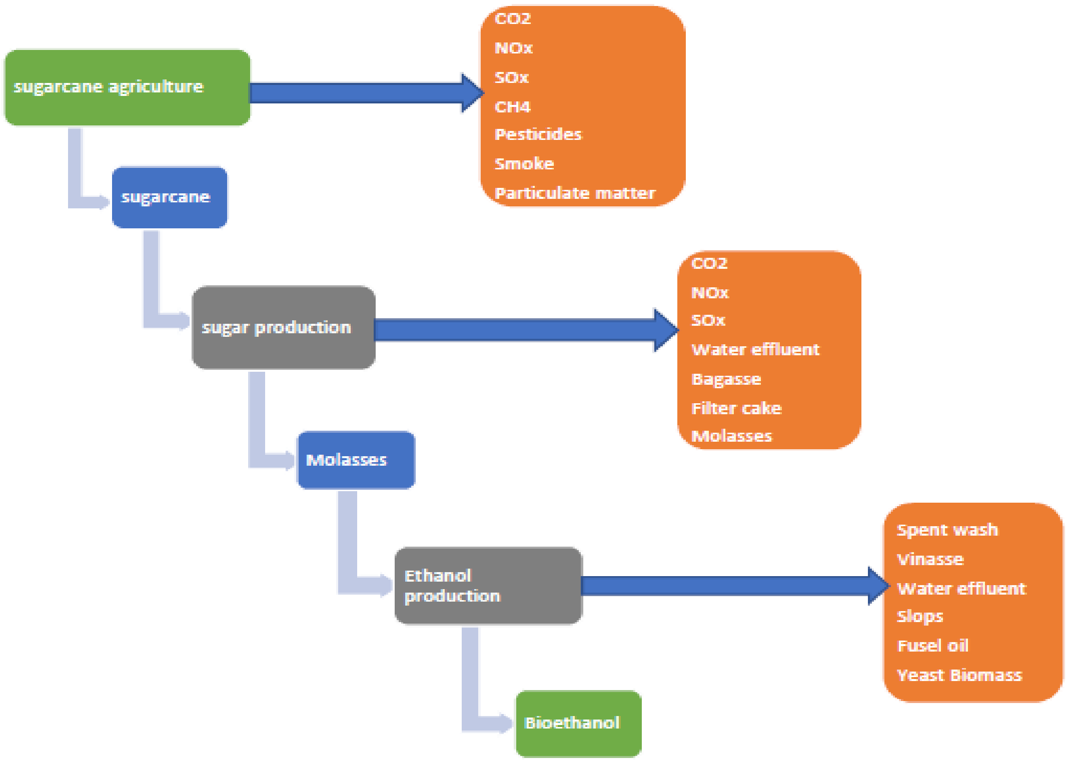


Figure 3.1: Process system boundary and waste generation of environmental concern.

Satellite maps using GIS imagery studies were obtained to analyse the extent of sugarcane agricultural land changes compared to the conservation areas land cover size over 35 years. This study was conducted with data obtained for years between 1985 and 2020. This was done to analyse the impact of LULCC from the conserved land to sugarcane farmland.

Following that, structured questionnaires targeting the sugarcane farmers in KwaZulu-Natal province were used to collect data on the farming systems used by the several farmers, farm sizes, inputs used in sugarcane farming, location, harvesting methods used, and other related data. In addition, semi-structured interviews with factory managers and site observation were used to collect data regarding waste management practices by the sugar milling plants and bioethanol plants. Secondary data included historical water quality data for the uMlalazi catchment area, composed and recorded by the Department of Water Affairs and Sanitation (DWS), waste management data by the sugar mill, and the bioethanol plant. The historical water quality data was used to assess spatial and temporal variation of surface water quality of the uMlalazi catchment area.

Additionally, a case study approach was employed in this study to answer the research questions appropriately and adequately. Selected sugar milling and bioethanol production plants were used to examine the various research objectives of this study by collecting data from actual cases. A case study approach was used because this type of research method allows an up-close, in-depth, and detailed examination of the case in the process of investigating a problem (Hallinberg, 2018). Scientists use case studies to test theories, develop several topics, or produce background material to discuss a concrete situation (Gustaffson, 2017). This study used an exploratory type of case study approach to understand better whether bioethanol production has had negative impacts on the ground and surface water resources in KZN. In this region, commercial farming is dominated by sugarcane farming.

3.3 SITE SELECTION

The study was focused on KwaZulu-Natal, a province located along the eastern region of South Africa and is popularly known for sugarcane agriculture. While sugarcane farmers are registered in Mpumalanga and the KwaZulu-Natal provinces, KwaZulu-Natal presents the most sugarcane farms in South Africa (SASA, 2020). The province also harbours the bulk of the sugar milling plants in the country, producing molasses, an important raw material for bioethanol production (Kohler, 2016). South Africa produces most of its bioethanol through the fermentation of molasses, a by-product of its sugar industry, and therefore has plants located in KwaZulu-Natal. KZN is found at 28.5306° S, 30.8958° E, and present temperate (Chimonyo et al., 2016 and sub-tropical (https://www.gov.za/about-sa/geography-and-climate) climatic conditions. At the same time, Port Shepstone has a high altitude of 32.5 m (https://www.worldweatheronline.com/port-shepstone-weather-averages/kwazulu-natal/za.aspx), other areas present altitudes in the range of 21–23 m (Chimonyo et al., 2016). The soil in KZN is generally sandy (Chimonyo et al., 2016). The study collected primary and secondary data from sugarcane farms, a sugar mill, and an ethanol plant in KwaZulu Natal. The sugar mill studied is in Tongaat (-29º 34' 0.0048" S 31º 7' 0.0012" E), located 40 km North of Durban. The ethanol plant is in Durban (29º 52' 59.9988" S, 31º 2' 59.9964 E). All the farmers that took part in the study have their farms located in Richards Bay (-28° 46' 58.84" S 32° 02' 15.65" E), KwaDukuza (-29° 19' 41.38" S, 31° 17' 22.34" E,) uMlalazi (-28.956 S, 31.757 E), Pietermaritzburg (-29° 37' 0.44" S 30° 23' 34.01" E) and Port Shepstone (-30° 44' 28.93" S 30° 27' 17.96" E). The visited sugarcane farm, sugar milling plant, and bioethanol plant are shown in Fig 3.2 below.

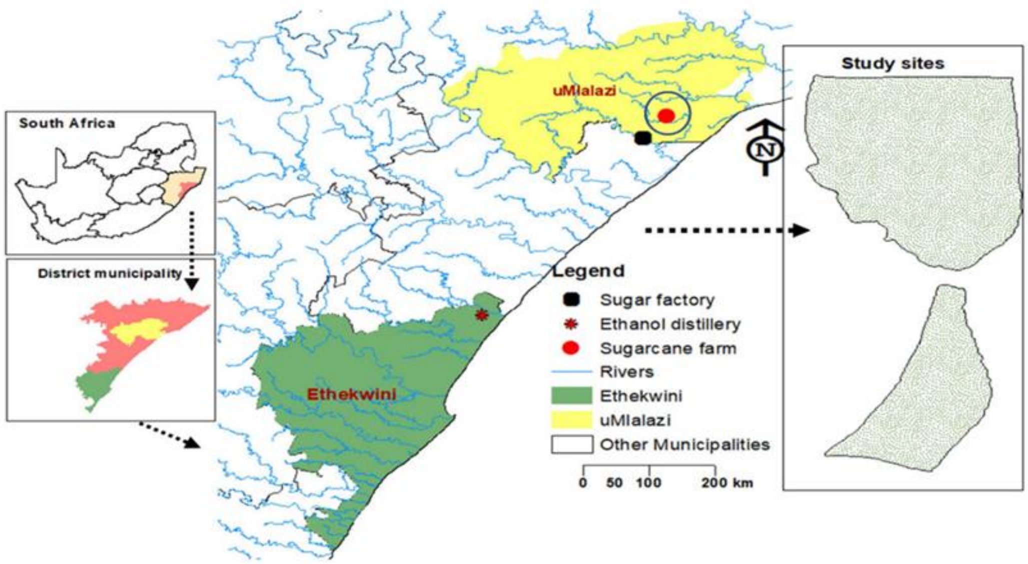


Figure 3.2 Figure showing the study area for this research.

3.4 STUDY PARTICIPANTS

The study participants were limited to 37 farmers, a sugar milling plant, and an ethanol distillery. While the national data from the 2019/2020 register showed that 21,926 sugarcane farmers were registered with the South African Cane Growers Association (SACGA) and the South African Farmers Development Association (SAFDA) (SASA, 2020), a limited number of farmers participated in this study because of consent issues. Although the researcher requested permission from various sub-associations to collect data from the farmers through questionnaires, only one community farmers' association consented to this call. All the farmers that took part in this study supply cane within their local sugar mills. The farmers' meeting represented KwaDukuza, Pietermaritzburg, Mosel Bay, and Port Shepstone, who attended the interactive discussion. The researcher observed and presented at this sugarcane growers' association meeting at the mill on 9th March 2018. Out of the 55 registered sugarcane farmers present at the meeting, only 37 from the different regions consented to participate in the study. The meeting and study participants included both more experienced commercial (referred to in this study as commercial farmers) and emerging farmers. The farmers were categorised into three groups for further analysis based on the irrigation used as follows: commercial farmers with pivotal irrigation, commercial farmers without pivotal irrigation, and emerging farmers without pivotal irrigation.

3.5 RESEARCH METHODS AND FIELD DATA COLLECTION

To address the key research objectives of this study, the researcher used a combination of qualitative and quantitative data collection methods, relying on both primary and secondary data sources. However, before embarking on the field work, knowledge was sourced about a general background knowledge about the bioethanol industry in South Africa through an interaction with key role players in the industry. This was considered a pilot study through questionnaires from a sugar technologist and the Secretary General for bioethanol for Southern Africa (Annexure, section 3). Below are the descriptions of the data collection methods and processes during the field study.

3.5.1 Evaluation of the Environmental Impact of Land Use Land Cover Change

Land cover maps are used for climate change modelling, environmental impact assessments, spatial development planning, land use policy development, greenhouse gas inventories, initiatives to reduce emissions from deforestation and forest degradation, mapping ecosystem services, and biodiversity conservation planning, amongst other things (Wessels et al., 2016). This study used satellite images of the land cover of uMlalazi to analyse the changes in coverage sizes of the various forests conserved today and the wetlands in the area compared to sugarcane farms from 1985 to 2020. In addition, satellite maps were compared to produce a transition matrix (Romero-Ruiz et al., 2012).

Transition matrices are the foundation for various metrics that analyse temporal change among categories (Yang et al., 2019) and provide a general understanding of spatiotemporal patterns of land dynamics (Huang et al., 2018). These satellite maps enabled the evaluation of environmental impacts and the ecosystem services lost due to the gradual conversion of these natural ecosystems and their land coverages to sugarcane agricultural land over the years.

3.5.2 Evaluation of the GHG emission from individual sugarcane farms.

Both qualitative and quantitative data using a combination of primary and secondary sources were collected. The samples were limited by the number of farmers who consented to participate in the study. However, primary data were collected using questionnaires collecting information on various farming systems and practices, quantities of inputs, farm sizes and location, and other related data needed to evaluate GHG emission (see annexure B).

There are many models that are available to calculate GHG emissions such as DairyWise, FarmAC, HolosNor, SFAMMOD and the IPCC (2006) model. While the rest are mainly used for dairy farming, (Hutchings et al., 2018), IPCC (2006) provides a less holistic and less informative approach than the CFT model (Hillier, 2013). The CFT model was also provided to the researcher at no cost by the model owners during the pilot phase of this study. CFT model is also seen to be easily used by the local sugarcane farmers if provided with the platform. Thus, CFT was the preferred model for this study.

The completed questionnaires were segregated according to the various farming system; commercial farmers with pivotal irrigation, commercial farmers without pivotal irrigation, and emerging farmers without pivotal irrigation highlighted above. The collected inventories were compiled following the definition of sustainability indicators informed by the Cool Farm Tool (CFT) model (Hillier et al., 2011). The CFT model analyses and quantifies GHG emissions from various agricultural practices (Hillier, 2013). The collected data was modelled using the CFT model to calculate the GHGs gasses emitted by each farm and presented as averages for each farming system under investigation (https://coolfarmtool.org/coolfarmtool/greenhouse-gases/).

Secondary data for GHG emissions from the top 11 sugarcane-producing countries was collected from the Food and Agricultural Organisation Cooperate Statistical Database website (FAOSTAT, 2019), providing free food and agricultural data worldwide. The secondary data included the GHG emission profiles for the top sugarcane producing countries and the total GHGs emitted by each country due to sugarcane growing. The data was compiled and compared with data from the study.

3.5.3 Assessing the environmental impact of sugarcane farming on surface water by determining the water quality in the catchments within the uMlalazi sugarcane farming communities.

To evaluate the surface water quality, secondary surface, water data for the uMlalazi catchment in KZN, consisting of quaternary catchments W11C, W12E, W13A, and W13B, were collected from the Department of Water and Sanitation (DWS). The study combined two approaches, first analysing the historical water quality records to distinguish sub-catchment water quality trends and investigating the links with land use activities by mapping water quality drivers within the sub-catchments. Although with some data gaps, the DWS has extensive records of historical and current water quality data (weekly, to bi-weekly to monthly) for major ions (CO_3^{2-}, Cl^-, Na^+, SO_4^{2-}), and in-situ field measurements (pH, total dissolved solids, electrical conductivity, and total hardness). The missing data which could have added more value to the obtained results include ions such as Ca^{2+}, K^+, Mg^{2+} and nutrients such as NO_3^-, NH_4^+, and PO_4^{3-}. Although many different anthropogenic activities could have caused the discharge of these chemical ions into the studied catchments, it is possible that their presence is caused by the activities of the sugarcane industry as uMlalazi is an area where sugarcane farming is the main anthropogenic and economic activity.

The DWS has approximately 40 active sampling points in the uMlalazi catchment area, located at strategic locations for monitoring surface water, with both rivers and wetlands being monitored by the DWS. The monitoring sites include both surface and groundwater sampling sites. The Department of Water Affairs routine monitoring sites of these quaternary catchments were delineated using the Geographical Information Systems (GIS). However, groundwater data from the borehole was limited between 1994 and

1995, with all the reported monitoring stations no longer active. As a result, only surface water data for 2014 and 2018 were considered in this study. A comparative analysis was aimed at verifying if over the years they had been an improvement of the surface water quality following sugarcane agriculture in the catchment area. Spatial analysis was conducted by developing thematic map layers of water quality parameters from the analytical results using the inverse distance weighted (IDW) interpolation technique available in ArcGIS 10.3 software. Spatial analysis was beneficial in visually interpreting the water quality status of each sub-catchment concerning the location and the land use activities within the catchment. This was done to compare the 2014 and 2018 scenarios of water quality parameters. In addition, the various parameters were compared to the standard concentration levels prescribed by WHO (2011) using tables and graphs. In the first group analysis, univariate analyses were conducted to describe the patterns of the yearly average of water quality parameters and the WQI from the monitoring stations in the uMlalazi catchment area. After that, the mean, standard deviation, and the spline regression technique were applied to depict variations of the different water quality parameters and the WQI with time for each sub-catchment for the 2 years studied. Different monitoring stations recorded different sets of parameters, with some limited to only a few of the parameters of interest for this research.

3.5.4 Evaluation of the waste generation and possible environmental impacts of sugar mills and ethanol plants.

Primary data was collected through semi-structured interviews with the plant managers and observation collecting information on waste management practices by the plants. The discussions and observation focused on collecting qualitative data about the processes involved in running the plants and the waste generated in producing the products. The list of questions on the interview schedule is attached in annexure B.

Secondary quantitative data was collected through document analysis. The observations were carried out together with the interview schedule. The sugar milling plant provided data records concerning the waste generation by the plants every month and the plant's waste management practices. The interviews and secondary data from the plants were assessed to analyse the type of waste generated and the potential environmental impacts of the generated wastes from the plants. The use of observation in conjunction with interviews and secondary data analysis provided multiple sources of evidence and ensures the reliability of the results (Creswell, 2014; Faryadi, 2019). The obtained data from the sugar industry was analysed for its waste types, quantities, and the potential to cause environmental pollution. This was done simply by using Microsoft Excel and a narrative analysis.

3.6 DATA PROCESSING AND ANALYSIS

Data analysis is a process of examining data to come up with vital information to use. This research contains mainly qualitative data.

Descriptive statistics such as percentages, frequencies, means, deviations, and inferential statistics were used to analyse the quantitative data through Microsoft Excel. Descriptive statistics describe the distribution and range of responses to each variable and examine skewness data (Creswell, 2014; Bhatia, 2018). Descriptive statistics helps to summarise the data and find patterns in the data. Inferential statistics are used to interpret and draw conclusions from the data that cannot be derived from descriptive statistical analysis (Bhatia, 2018). Where applicable, multiple regression analyses were applied to predict relationships between variables. The surface water quality state was not only associated to sugarcane farming but also to other point source pollution.

Qualitative data analysis in this study involved triangulation of data. Qualitative data was collected through interviews, observational studies by the researcher, and document review. The collected documents consisted of Microsoft Excel workbooks containing qualitative and quantitative data about the wastes generated by the plants, the amounts, and various mechanisms and approaches for waste minimisation by the plants. Content analysis was used to interpret the information contained in the provided documents and records from observational reports by the researcher. The data analysis procedure involved organising the content, appraising, and synthesising the information from documents regarding the waste generated by the sugar and bioethanol plants. The obtained data were corroborated with data from the interviews. Analysis of interview data was performed using framework analysis. Framework analysis incorporates the use of the summarisation technique to organise and manage data. Data summarisation contributes to the interpretation of data by looking at the theme and cases within the data. Accurately collected and recorded data were summarised. Site visit observations and informal discussions made during the site visits were also translated according to themes or patterns.

3.7 VALIDITY OF RESULTS

The results obtained from this study were validated using different validation methods. The paragraphs below represent the validation methods that was considered for the results presented in chapter 4 -7.

In Chapter 4, the validity of the results was ensured by collecting samples (GIS images) over many years – (35 years), the sizes of conservation areas in uMlalazi were compared over these years and these sizes were again compared to the size of the sugarcane farms over the same period. At the end, an average comparison was made which gave the overall results of the increase or decrease of these conserved areas compared to the sugarcane plantation.

The results presented in chapter 5 demonstrate views from farmers from different areas within KZN practicing similar farming methods. These different farms presented similar results with respect to their GHG emission footprint.

In chapter 6, many different water samples from the same catchment were tested for the presence and concentration of the different water quality parameters. The averages from the different water quality parameters were used in calculating the water quality index for each catchment which gave an indication of the water quality.

Data collection methods presented in chapter 7 was validated since face-to-face interviews and observation of the sugar mill and bioethanol production plant were made.

3.8 SCOPE AND LIMITATIONS OF THE STUDY

The broad objective of this study was to investigate the environmental impacts of the various processes in the value chain of bioethanol production. The value chain includes all steps in bioethanol production, starting with sugarcane farming practice through to ethanol production. While the environmental impacts of bioethanol production vary, including the effects on the biosphere, the surface and groundwater resources, the atmosphere, and the soil at every stage in the value chain, this scope is limited to selected areas of interest. The study did not include any analysis of the impacts of bioethanol production on soil and ground water resources. Additionally, the effects on air resources did not consider other critical aspects of air pollution. The focus of the study was limited to the assessment of GHG emissions and the assessment quality of surface water around KwaZulu-Natal to evaluate the impacts of bioethanol production. The effects of toxic gases on global warming were evaluated by converting them to CO_2 eq. The effect of particulate matter from sugarcane's burning practice during harvesting is not included in the analysis of bioethanol production.

While the national database has over 21000 sugarcane farmers, with most of these in KwaZulu-Natal, only a tiny portion of the farmers (37) was involved in the study. In addition, challenges were encountered with securing qualified participants for this study. Approaches to various sugarcane growers' associations to request permission for their participation in the survey were unsuccessful. This resulted in only 1 group (association) consenting to their members to participate in the study.

A stakeholder screening was considered, and only stakeholders from groups directly linked to the product under investigation were included in the system boundary. For instance, sugarcane farmers, sugar factory workers, bioethanol plant workers, and other stakeholders affiliated with these mentioned areas from a social and intellectual point of view.

3.9 RESEARCH ETHICS

Research ethics may be described as a code of conduct that governs the standards of conduct for researchers. According to Carling (2019), ethics is associated with moral standards, which can further be attributed to what is right and wrong and conforming to the standard code of conduct of a given profession or group. This is academic research and committing to ethical responsibility, and the required ethical guidelines and principles were adhered to and were a primary concern of this study. Before the commencement of this study, a request for ethical clearance was lodged with the University of South Africa's Research Committee and was granted (annexure A1). Permission was also obtained from the KZN Department of Environmental Affairs before questionnaires could be distributed to the sugarcane farmers during their quarterly meeting (annexure A2). Participants volunteer to take part in the study and free to withdraw at any time. Participants were also free to leave out certain questions unanswered if they were not comfortable answering the question. Permission was also sought from the single farmer whose farm was used as the main case studied farm as observation was made throughout the year on all the farming stages. Research ethics implore that all researchers must follow certain moral principles, and participants must be treated with respect by the researcher. To ensure these ethical measures, the following were considered in this research

3.9.1 Privacy and confidentiality

To ensure privacy and confidentiality, only intentionally selected persons could have access to the identity of the participants (Carling, 2019). These included people responsible for collecting and analysing the data, such as the researcher, the research supervisors, and the specialist data analyst. In this study, although a questionnaire was used as an instrument for data collection, participants were not obliged to write their identification details. In cases where respondents volunteered to reveal their names, such information was treated with strict confidentiality; furthermore, since the research was tentative, the confidentiality of the information and the participants' privacy was guaranteed. For example, individual participants' names are not mentioned in this study and have not been shared with any other parties. The names of the companies from where interviews were held, and data collected for the study were also removed and are not mentioned anywhere in this document.

3.9.2 Informed consent

Obtaining informed consent from participants is very important. It offers the participants the right to participate voluntarily and to withdraw from the study at any time, thus preventing potential undue influence and coercion (Carling, 2019). To implement the ethical principles while seeking informed consent, written information about the study was provided to the prospective participants by the researcher. The written information included the purpose of the study, details of subject confidentiality, information on risks and benefits, and who to contact for further information (Carling, 2019). Participants could ask additional questions for clarity before they could consent to engage in the studies. The Informed Consent Form (annexure A3) was given to the respondents to sign before data collection. The form highlighted that it was voluntary to participate, and they were at liberty to withdraw at any time during the process. The respondents for the interviews were also given their informed consent forms to go through and sign before the discussions and requesting permission to use the tape recorder before the interviews commenced.

CHAPTER 4 THE ENVIRONMENTAL IMPACTS OF LAND USE AND LAND COVER CHANGE TO IMPLEMENT SUGARCANE FARMING IN THE UMLALAZI AREA IN KZN

4.1 INTRODUCTION

In a 2008 study, it is estimated that six million hectares of land were used for sugarcane production in only six African countries (Watson et al., 2008). It is critical to find out what was the natural states of these pieces of land before they were converted to sugarcane farms. It is also critical to find out if ecosystems have been disturbed due to these land use changes. Africa perceives the abundance of land for agriculture in its continent. As a result, large tracks of previously uncultivated land have been converted into sugarcane agricultural land. Is this also the case in KZN, South Africa? Generally, sugarcane agriculture in sub-Saharan Africa is increasing, fuelled partly by the promise of increased demand for bioethanol (Watson, 2011).

According to Jewitt et al. (2015), the KZN province is experiencing a loss of its natural vegetation because of land use and land cover changes (LULCC). In their study Jewitt, Thompson, and Moyo (2017), highlighted the various land use and land cover types in the KwaZulu Natal province, as seen in Figure 4.1. Amongst them are forests, wetlands, and sugarcane farms, which will be focused on in this chapter.

According to Zungu et al. (2018), vegetation maps that were compiled in the past were based on dominant species and vegetation structure classes as indicated by Todd (1994) and Weisser (1978b). However, as of 2018, no detailed plant community descriptions based on total floristic composition have been conducted for the uMlalazi municipality (Zungu et al., 2018). Thus, this makes it challenging to estimate the extent to which land use and land cover changes have occurred, making it difficult to efficiently analyse the environmental impact of such changes.

In this chapter analysis has been made to the environmental impacts of such land use and land cover change (LULCC). Reviewing literature and studying the area’s vegetation using satellite maps, the changes in land use and land cover in the uMlalazi area of KZN from 1985 to 2020 have been analysed. These have been compared to the changes in land covered with sugarcane agriculture in the same area. In conclusion, the possible environmental impacts of these changes have been analysed.

Although there are some arguments that sugarcane expansion has not directly replaced natural biomes, it has had an indirect environmental impact when the agricultural activities following sugarcane farm expansion move towards or into these natural or protected biomes (Bordornal et al., 2018).

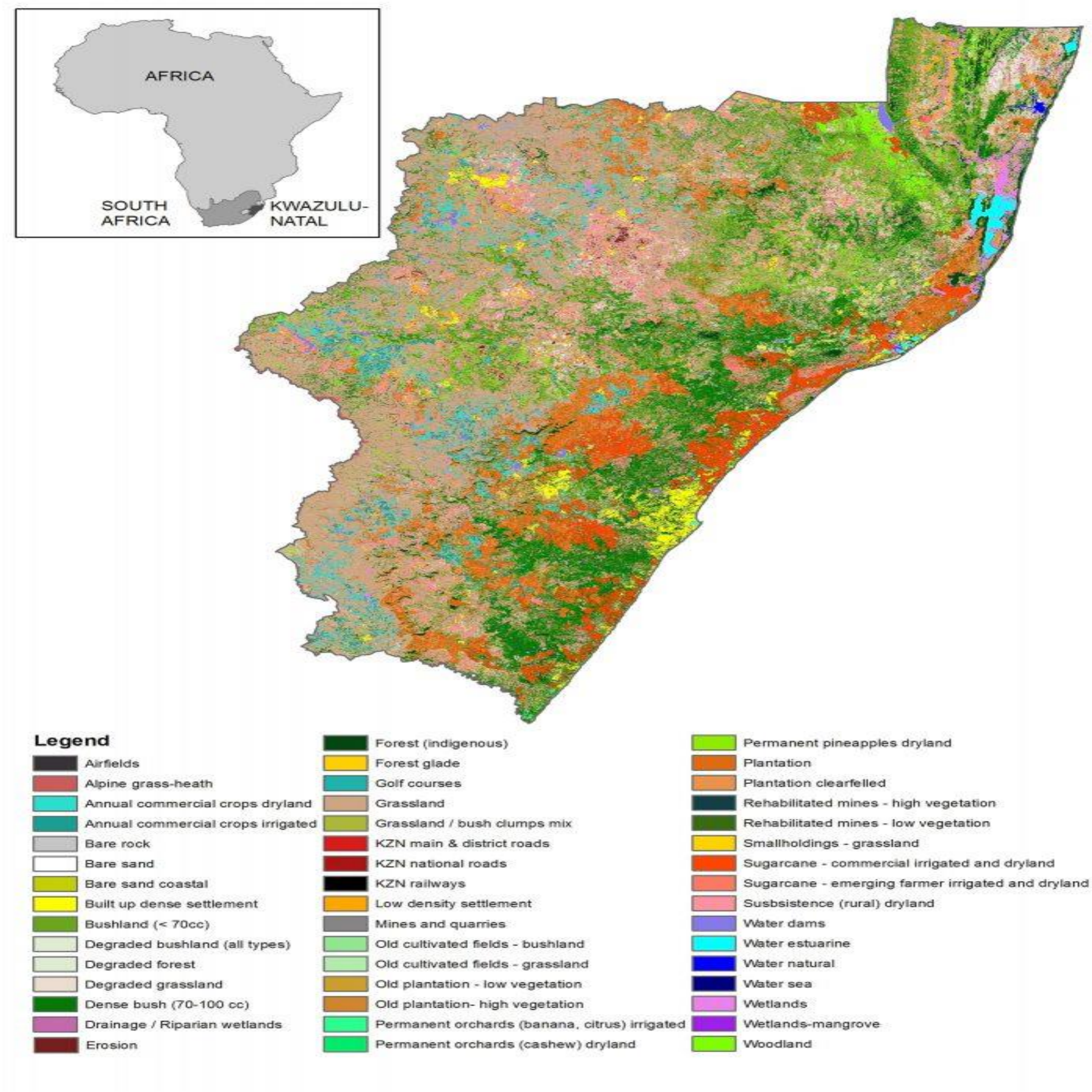


Figure 4.1: Land cover map for KZN – 2017 (Jewitt, Thompson & Moyo, 2017)

According to Zuurbier & van de Vooren (2008), indirect land use and cover change are more challenging to evaluate. The case of uMlalazi is a combination of both direct land use and land cover change. There is evidence of sugarcane farms extending into these natural ecosystems, which have been classified as "important conservation areas" according to the Insingo Projects (Pty) Ltd (2018) report to the uMlalazi municipality. The depreciation of ecosystem services has a significant impact on biodiversity and stands like a driver to climate change in one way or the other. In this chapter, therefore, the following questions have been answered:

- To what extent have the uMlalazi conservation areas changed over time since 1985?
- Has sugarcane agricultural land cover increased or decreased within the same period?
- What are the environmental impacts of such LULCC?

4.2 STUDY AREA AND SCOPE

The KwaZulu-Natal (KZN) province with 92,100 km^2 land size has various land cover types. These range from savannas and natural grasslands to exotic forestry and sugarcane plantations irrigated and dryland cultivation, amongst others (Wessels et al., 2016). In the KZN province, this chapter focused on LULCC in uMlalazi (-28.956S, 31.757E). It is situated on the north-eastern coast of KZN. The municipal area covers a land space of 2217 km^2 and has experienced a general population increase between 2001 and 2016 of 221078 to 223140 respectively (uMlalazi Integrated Development Plan, 2020/2021). The mean annual average rainfall of uMlalazi is approximately 980 mm, with most occurring between September and March (Wigley et al., 2009). The uMlalazi Nature Reserve represents numerous ecosystems disappearing from a rapidly transforming landscape outside of formally protected areas in Zululand (Zungu et al., 2018).

Figure 4.1 shows the land use map of uMlalazi (Bulangi, 2019). uMlalazi is specifically covered with sugarcane plantation as its primary agricultural activity, and the main economic activity for the people of Mabhokweni is sugarcane farming. Although at a smaller scale compared to sugarcane farming, other farming practices in uMlalazi include timber plantation and citrus farming (Insingo Projects (Pty) Ltd, 2018).

Important conservation areas in uMlalazi include the Ongoye forest, the Entumeni nature reserve, the Mbongolwana wetland, the Dlinza forest. The scope for this chapter was limited to identifying the LULCC extent in uMlalazi areas concerning the identified conservation areas within the municipality. This defined scope focused on verifying the importance of and analysis of the environmental impact of such changes if the conservation areas were being changed from their natural land cover to sugarcane plantations. Therefore, the focus in this chapter has been on the featured conservation areas, including the Ongoye forest, the Entumeni nature reserve, the Mbongolwana wetland, and the Dlinza forest.

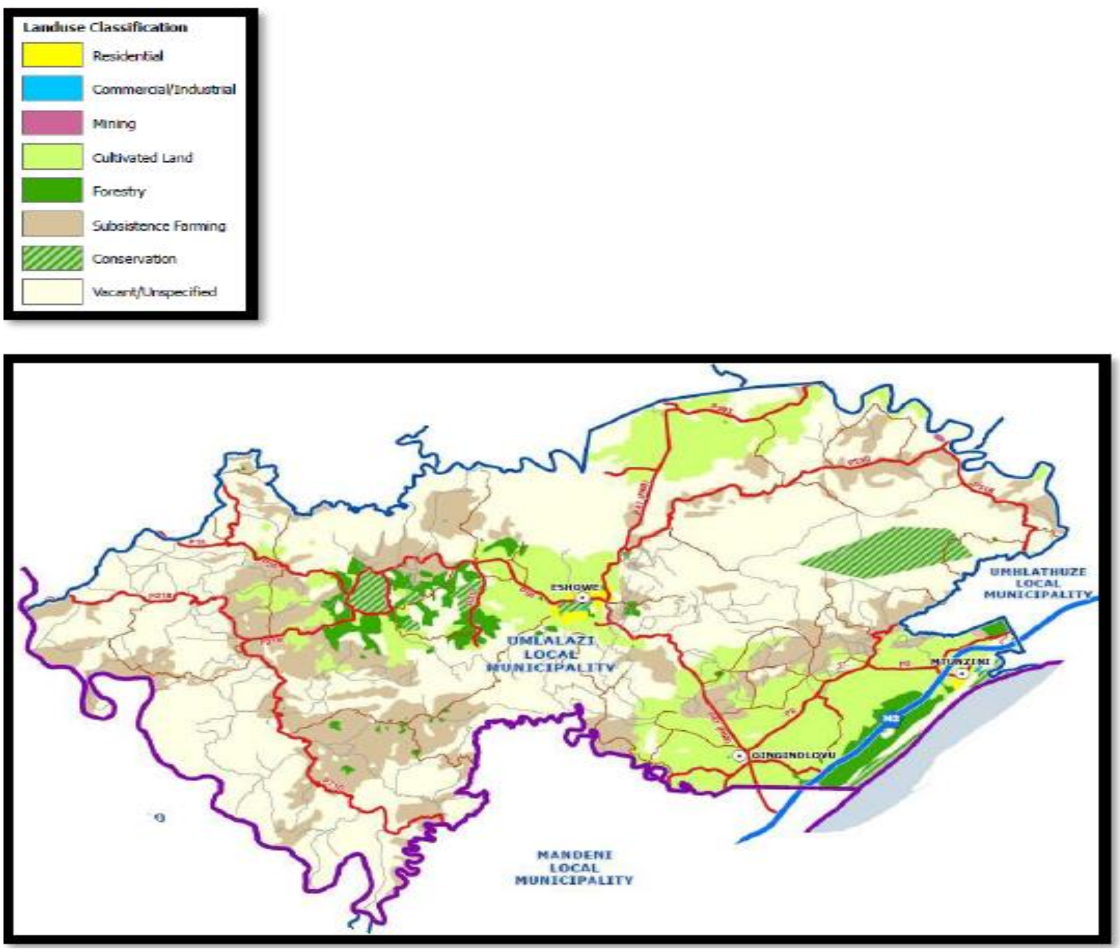


Figure 4.2: Map of uMlalazi showing its land-use classification. Source: Bulagi (2019)

4.3 METHODOLOGY

4.3.1 Data Collection

Land cover Maps of uMlalazi – KZN

The land cover change differences were studied by using images taken with the use of remote sensing. In addition, with a focus on biodiversity conservation, ecosystem services provision, and environmental impact mitigation, satellite maps were taken for previous and current years (1985 – 2020) to analyse the extent of LULCC in the uMlalazi area KZN. The following steps describe the data collection methods.

Image classification

An example of image classification is a computer-based process that classifies an image according to its visual content (Vocaturo, 2020) or involves organizing an image into various categories based on pixel similarities (Jain & Tomar, 2013; Dhaware & Wanjale, 2016). The central idea of image classification is to assign specific image pixels to a landcover class (Gašparović, 2020). The images on the satellite maps obtained in this chapter were thus assigned pixels to each landcover class studied to identify their differences easily.

Satellite Data collection

The satellite images were downloaded from the United States Geology Survey's Earth Explorer (USGS Earth explorer: https://earthexplorer.usgs.gov/). The search criteria were restricted to specific dates (1985-01-01 to 2020-12-31), and only images with less than 20% cloud cover were downloaded. The image acquisition months ranged from February to May due to optimal vegetation growth in this period resulting from the region's optimum summer rains and early winter rains (Zungu et al., 2018). Due to criteria requirements and unavailability of data for some satellites at a certain period, images collected for this study were from different satellites, as indicated in Table 4.1.

Table 4.1: Image and associated satellite

Image Acquisition Date	Associated Satellite
1985-03-23	LANDSAT 5 TM
1990-05-24	LANDSAT 5 TM
1995-03-19	LANDSAT 5 TM
2000-03-24	LANDSAT 7 ETM
2005-05-17	LANDSAT 5 TM
2010-04-03	LANDSAT 5 TM
2015-04-11	LANDSAT 8
2020-02-04	LANDSAT 8

Image processing and classification

A supervised classification technique was used. This technique allows the analyst to assign pixels to classes or land uses (Nath et al., 2014). The main advantage of this technique surrounds the easy detection of errors that will warrant corrections (Nath et al., 2014). Thus, land coverage captured using this technique corresponds precisely to the samples collected. There are three main steps that this technique followed, which include:

- Defining data collection sites and collection of the training samples
- Extracting signatures and
- Image classification (Krohn, 2011; Rwanga & Ndambuki, 2017).

Data collection site and collection of training samples

Training samples were generated in which every class was assigned to specific pixel values. That is training a computer to read distinct pixels as a defined landcover (Krohn, 2011). The selection of classes was made regarding generated natural colour images and google earth satellite images (Krohn, 2011; Rwanga & Ndambuki, 2017) in conjunction with colour infrared in bands specified by the United States Geological Services -USGS for 2015 as shown in Table 4.2.

Table 4.1: Satellite Image and band combinations

Satellite	Natural image bands	Colour infrared bands
Landsat 5 TM & 7 ETM	R=3, G=2, B=1	R=4, G=3, B=2
Landsat 8	R=4, G=3, B=2	R=5, G=4, B=3

Source: (USGS, n.d.; USGS - United States Geological Service, 2015)

Extracting signatures

The signatures generated from the training samples were exported in both shapefiles and signature files. The idea behind developing a signature shapefile is to allow the analyst to identify and correct mistakes after classifying an image (Nath et al., 2014).

Image classification

Images were classified using the Maximum likelihood classification method. In this method, both classes mean vectors and covariance matrices constitute the signatures (Krohn, 2011); hence the results are more reliable with an accuracy level of 90%. There were 6 classes with 105 training samples. All image pixels are then assigned to the defined class that has the highest probability of similarity (Ahmad et al., 2018).

4.3.2 Data Analysis method

The chapter identified the areas of landscape transformations in uMlalazi. Therefore, it is essential to analyse such LULCC to determine the potential environmental impacts and effectively plan for biodiversity conservation (Jewitt et al., 2015). Although this chapter focuses only on specific areas of uMlalazi, it will set a precedence for further research in other regions of South Africa.

Area calculation of the satellite map images

Raster images produced from the image classification process were converted into polygon shapefiles. The areas of the polygons were calculated using the 'Calculate Geometry' function in the Attributes Table. All area values were calculated in hectares (ha). Only Sugarcane plantation, Mbongolwane wetland, Ongoye forest, Entumeni nature reserve, and Dliza forest area sizes were recorded.

In analysing the impact of LULCC in uMlalazi, according to (Jewitt et al., 2015), the change in the quantitative extent of LULCC was used in addressing possible environmental impacts concerning ecosystem service depreciation or appreciation and the consequences.

4.4 RESULTS

4.4.1 Introduction

The results of the LULCC of the uMlalazi catchment show that sugarcane has played a considerable role over the years in terms of land use and land cover changes, dominating other activities in the area by a large margin. Over the years, the total land use coverage related to sugarcane farming has decreased in the uMlalazi catchment (currently occupying about 47% of its size in 1985). The other land use and land cover activities, however, have remained steady. The forestry areas have all increased in size, while the wetland area has experienced minimal changes. Below is a detailed discussion on the available results.

4.4.2 The uMlalazi Ecosystems

The uMlalazi catchment is home to natural forests, the Ongoya Forests, Dlinza Forests, and Entumenu Forests. The Mbolongwane wetland is also a major ecosystem under conservation in the area. Together with the sugarcane plantations studied within the uMlalazi catchments, these conservation areas have shown marked changes in land coverage in hectares between 1985 and 2020. However, the land coverage of the natural forests has been increasing over the years, as shown in Table 4.3. These wild forests are significant as they are habitats to some of the world's rare animals and birds, including some endangered species. The resulting satellite maps showing these ecosystems are recorded in Figures 4.3 – 4.18. On the contrary, the land coverage for sugarcane plantations has been dropping since 1985. Table 4.3 shows the change in the sugarcane agricultural land size changes from 1985 to 2020.

The change in agricultural land size is significant over the years. This change shows a decrease of at least 53% from 1985 to 2020. The results showed an expected growth in sugarcane farming, especially after the century, as more black farmers entered the trade after the apartheid to satisfy the growing demand for sugarcane products. However, overall, sugarcane agriculture in KZN has never gone back to the levels seen in the 1980s. Several different factors could have driven this. One of these could be associated with the period of droughts (Dubb, 2013), which heavily impacted small-scale and emerging farmers who could not afford irrigation systems to either reduce their farm sizes or quit sugarcane farming. The other challenge was related to the human resources to work in the fields. During these years, the wages offered to labourers were minor compared to what was received by labourers in the mines (Dubb, 2013). Thus, most sugarcane farm labourers would choose the better-paid options. Another reason for this decline in sugarcane farm sizes between 1985 – 2000 can be linked to farmers' ages. According to studies carried out by Ntshangase (2016), farmers are mainly of an aging population and are left with little physical strength to pursue farming on a large-scale basis. The youths are also seen to be reluctant to embark in such farming practices but will prefer to migrate into cities in search of "better" jobs.

The area again experienced an increase in sugarcane farmland size from 2005 to 2010. This increase can also be associated with improving sugarcane agriculture knowledge coupled with the use of machinery and other technology. It is also noted that the restrictions on growers' registration were removed (Dubb, 2013). This would probably lead to many more farmers having the opportunity to farm. Thus 2010 – 2015 experienced an increase in sugarcane farmland size within the local municipal area.

The Ongoya forest has shown a gradual but continuous increase in land size over these years (Table 4.3 and figure 4.19). This indicates that the conservation intentions of this forest have been bearing fruits over the years. Forest ecosystem services such as CO_2 sinks and the provision of Oxygen, habitat for other species leading to biodiversity conservation are thus improved within this forest. Furthermore, both the Dlinza and the Entumenu forest have shown general increases between 1985 and 2020. Furthermore, the wetland has also shown a general increase with about 9 ha between 1985 and 2020. This increase secures an overall rise in ecosystem services. However, with this slow growth rate, ecosystem services will still be expected to serve the area's biodiversity.

The maps in figures 4.3, 4.5, 4.7, 4.9, 4.11, 4.13, 4.15, and 4.17 are representatives of LULCC of uMlalazi from 1985 to 2020.

In 1985, sugarcane plantations covered 33824 ha of land, 29557 ha greater than the total land size covered by all the different studied ecosystems with only 4267ha land coverage size as seen in Table 4.3.

Table 4.3: Studied ecosystems and their land coverage sizes (ha) from 1985 to 2020

Featured ecosystems and Sizes in hectares in uMlalazi KZN					
Years	**Ongoya forest**	**Dlinza forest**	**Entumenu forest**	**Mbolongwane wetland**	**Sugarcane plantation**
1985	2 659,95	360,71	758,85	488,04	33 824,61
1990	3 054,95	441,64	1 305,10	481,13	33 619,75
1995	3 028,84	491,76	1 618,79	452,65	29 338,77
2000	3 050,82	482,04	2 015,35	478,63	22 177,30
2005	3 120,68	394,47	1 894,56	498,45	28 823,55
2010	3 156,81	306,46	967,85	478,48	24 161,75
2015	3 221,96	462,86	1 596,82	499,04	24 858,00
2020	3 639,57	422,96	1 736,45	497,421	15 819,68

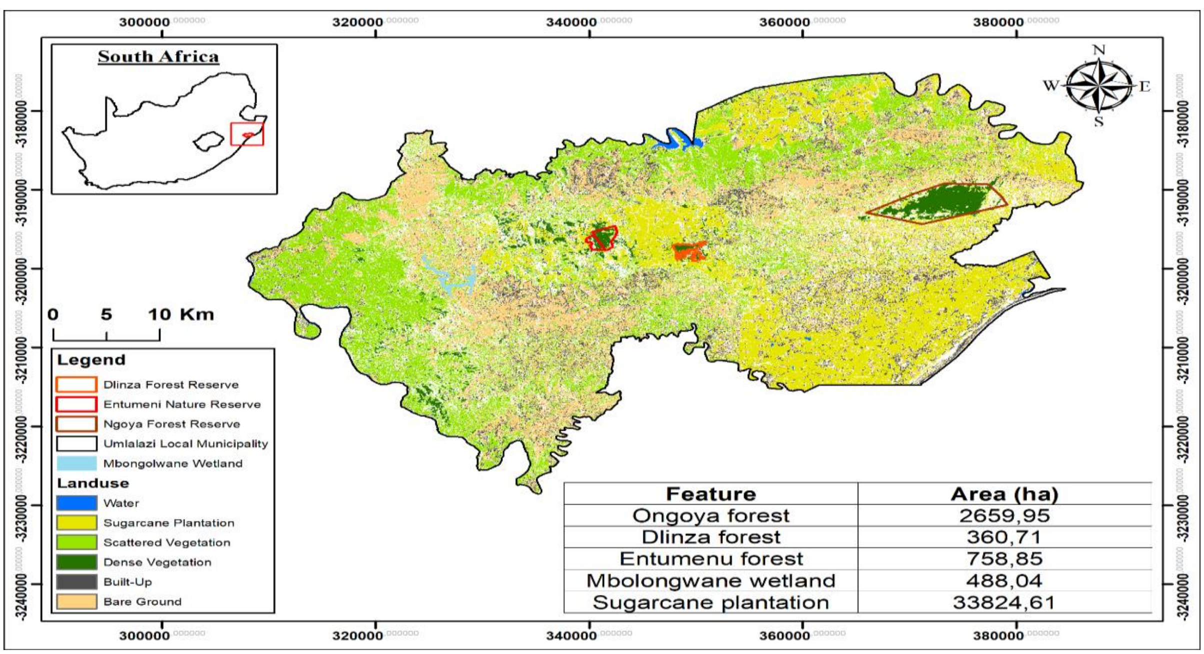


Figure 4.3: Sizes of uMlalazi conservation areas versus the size of sugarcane farms in 1985 (Ha)

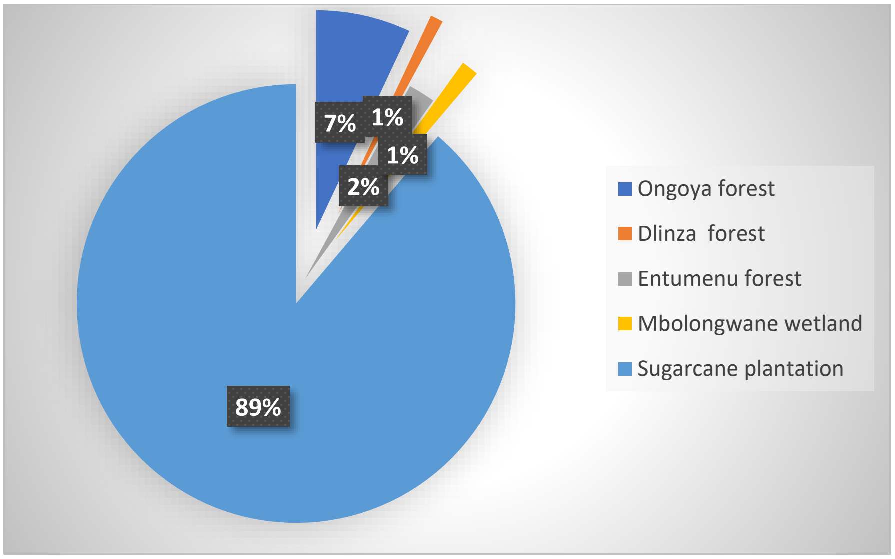


Figure 4.4: Percentage land coverage of the different studied ecosystems in 1985

Figure 4.4 shows the total land coverage of the studied ecosystems in uMlalazi. The land coverage of each in 1985 was 89%, 7%, 2%, 1%, and 1% respectively for sugarcane plantations, the Ongoya forest, the Entumenu forest, the Dlinza forest, and the Mbolongwane wetland.

From this study averagely, sugarcane farms in uMlalazi nature reserve have shown a decrease in size of up to 204.86 ha. This is seen between the years1985 and 1990. In 1990, the sugarcane total land cover size is 28336 ha bigger than the full land coverage size of all the studied ecosystems with 5282 ha, as shown in figure 4.5.

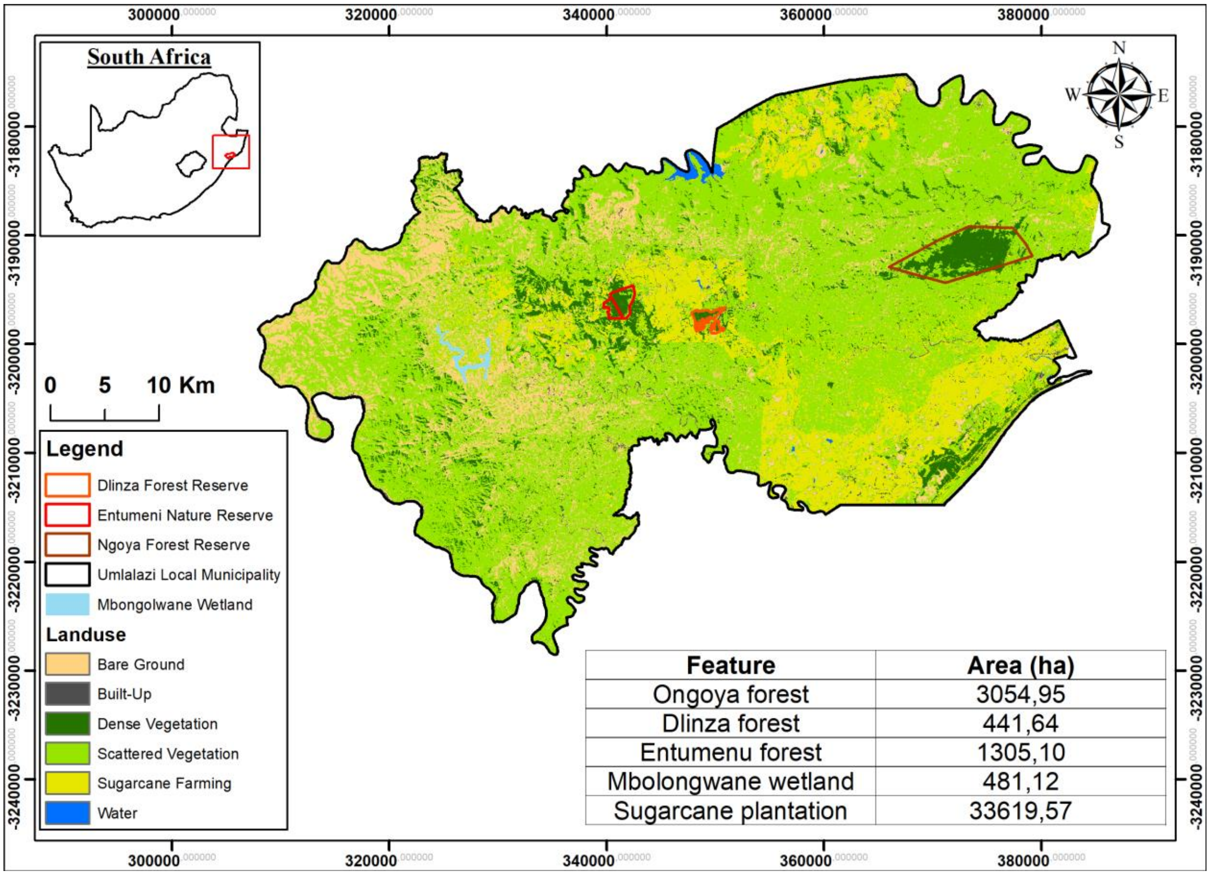


Figure 4.5: Sizes of uMlalazi conservation areas versus the size of sugarcane farms in 1990

From the perspective of changes in the land sizes, figure 4.6 indicates a decrease in the sugarcane land sizes for 1990 from 1885.

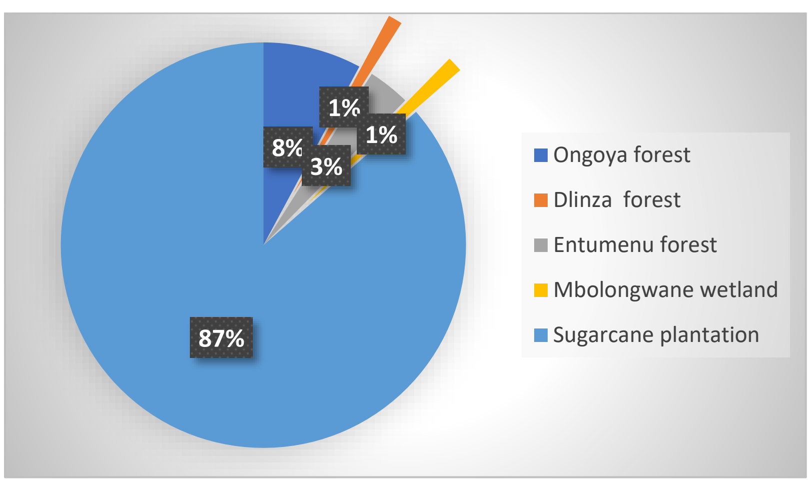


Figure 4.6: Percentage land coverage of the different studied ecosystems in 1990

Figure 4.6 shows the total land coverage of the studied ecosystems in uMlalazi. The land coverage of each in 1990 was 87%, 8%, 3%, 1%, and 1% respectively for sugarcane plantations, the Ongoya forest, the Entumenu forest, the Dlinza forest, and the Mbolongwane wetland.

The complete coverage of all the studied ecosystems for 1995 is 5592,04 ha, Figure 4.7. Thus, in 1995, sugarcane plantations covered 29338,77 ha of land, 23746.7 ha greater than the total land size covered by all the different studied ecosystems, Figure 4.7.

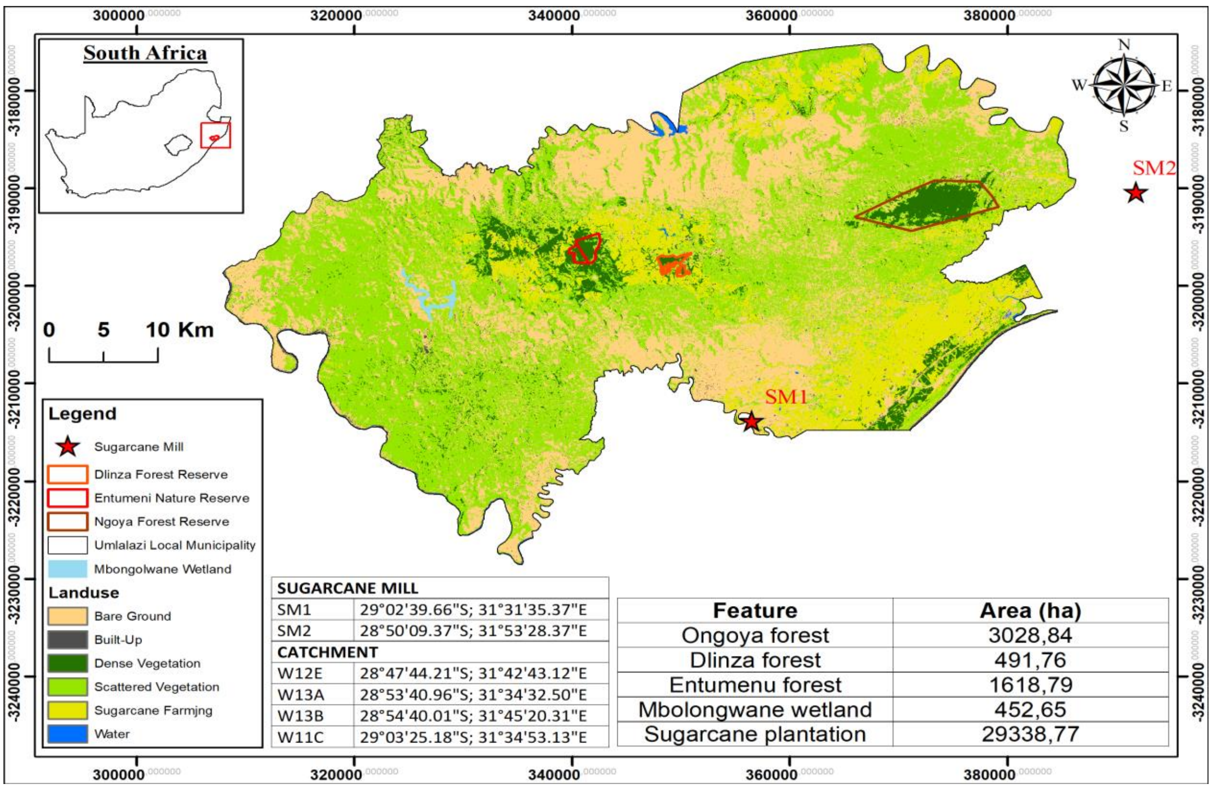


Figure 4.7: Sizes of uMlalazi conservation areas versus the size of sugarcane farms in 1995

Figure 4.8 shows the total land coverage of the studied ecosystems in uMlalazi. The land coverage of each in 1995 was 84%, 9%, 5%, 1%, and 1% respectively for sugarcane plantations, the Ongoya forest, the Entumenu forest, the Dlinza forest, and the Mbolongwane wetland.

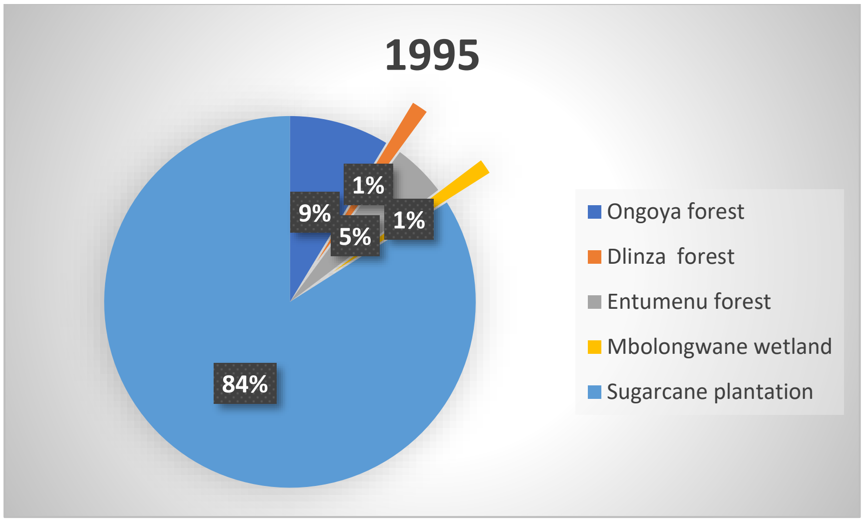


Figure 4.8: Percentage land coverage of the different studied ecosystems in 1995

The year 2000 saw a decline in the sugarcane plantations as it covered 22177.3 ha of land, making it 16150.46 ha greater than the total land cover of the conserved ecosystems occupying only 60626.84 ha of land (Figure 4.9).

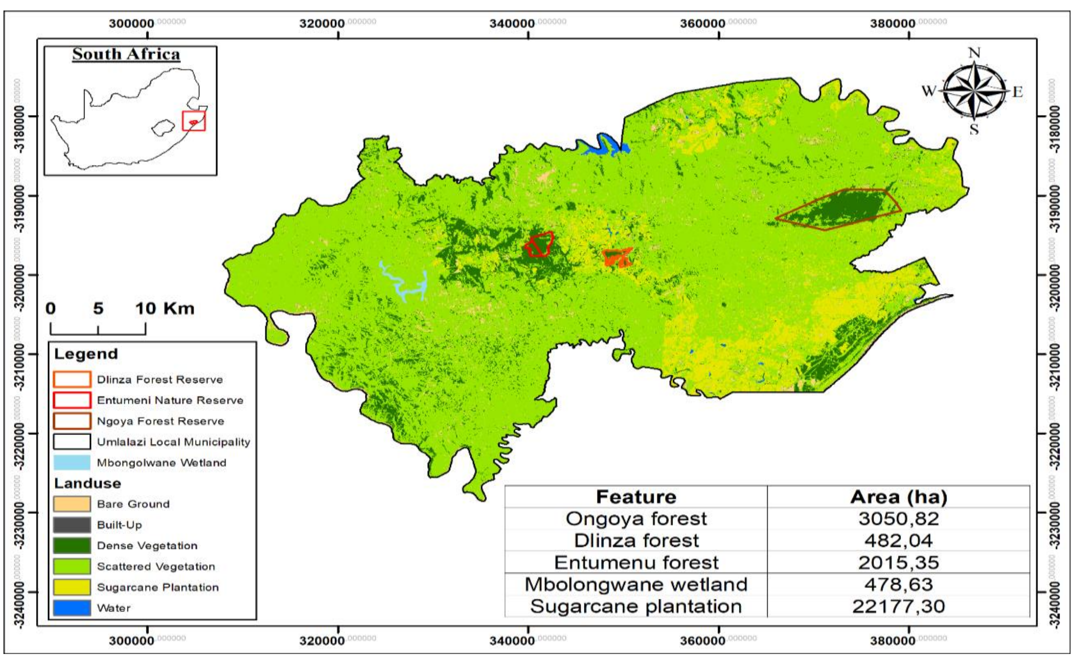


Figure 4.9: Sizes of uMlalazi conservation areas versus the size of sugarcane farms in 2000

Figure 4.10 shows the total land coverage of the studied ecosystems in uMlalazi. The land coverage of each in 2000 was 78%, 11%, 7%, 2%, and 2% respectively for sugarcane plantations, the Ongoya forest, the Entumenu forest, the Dlinza forest, and the Mbolongwane wetland.

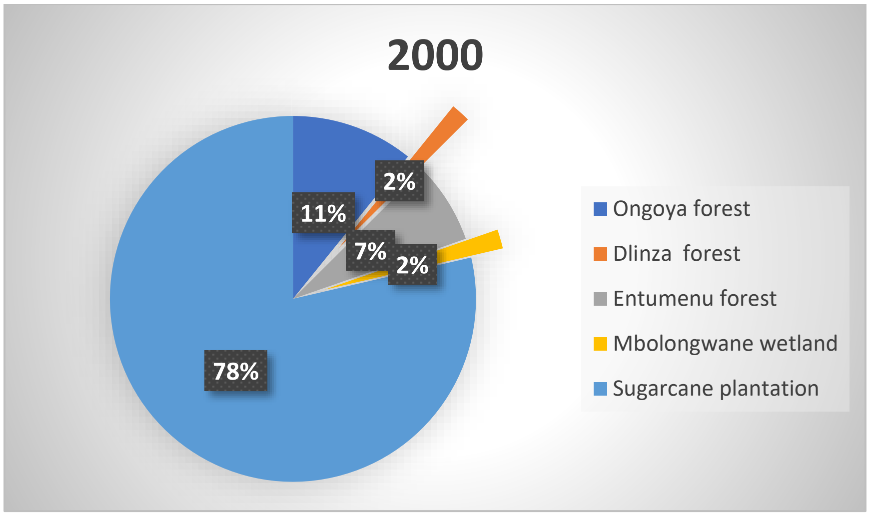


Figure 4.10: Percentage land coverage of the different studied ecosystems in 2000

In 2005, sugarcane fields saw an increase in land cover for up to 28823.55 ha while the total land cover of the studied conserved ecosystems declined and occupied 5908.16 ha of land, Figure 4.11. Thus, 2005 shows a difference of -22915 ha, as seen in Figure 4.11.

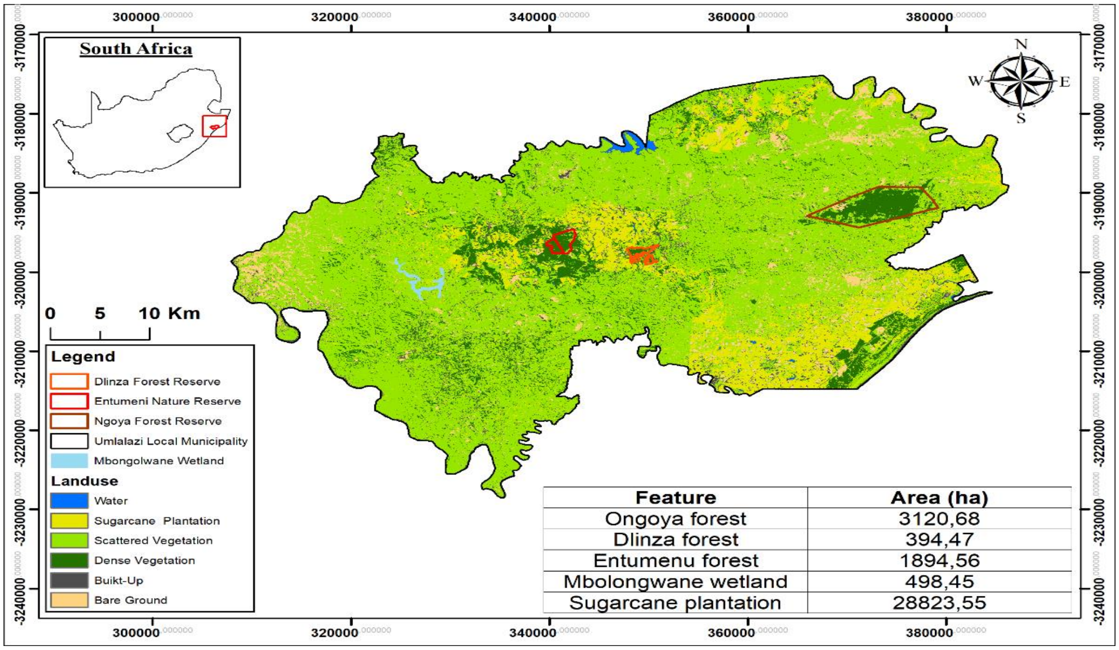


Figure 4.11: Sizes of uMlalazi conservation areas versus the size of sugarcane farms in 2005

Figure 4.12 shows the total land coverage of the studied ecosystems in uMlalazi. The land coverage of each in 2005 was 83%, 9%, 6%, 1%, and 1% respectively for sugarcane plantations, the Ongoya forest, the Entumenu forest, the Dlinza forest, and the Mbolongwane wetland.

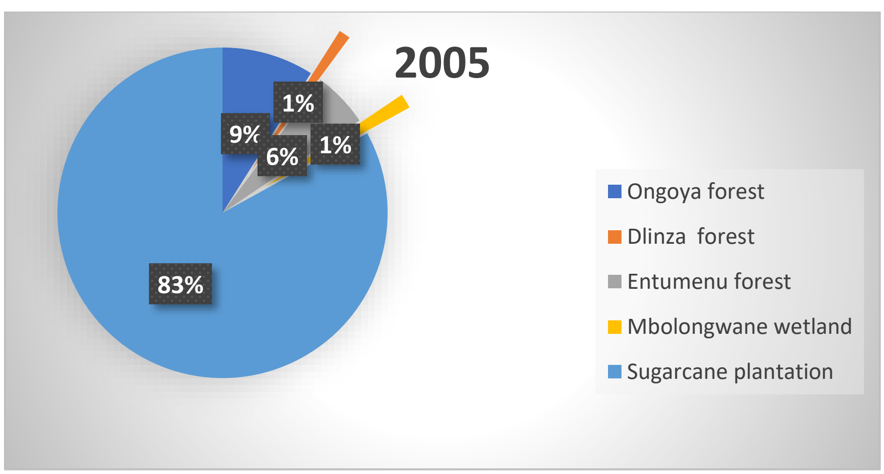


Figure 4.12: Percentage land coverage of the different studied ecosystems in 2005

2010 shows a drop in the sugarcane land cover size with 24161.75 ha of land. The conserved ecosystem occupied a total land size of 4909.6 ha making a difference of 19252.15 ha, as shown in Figure 4.13.

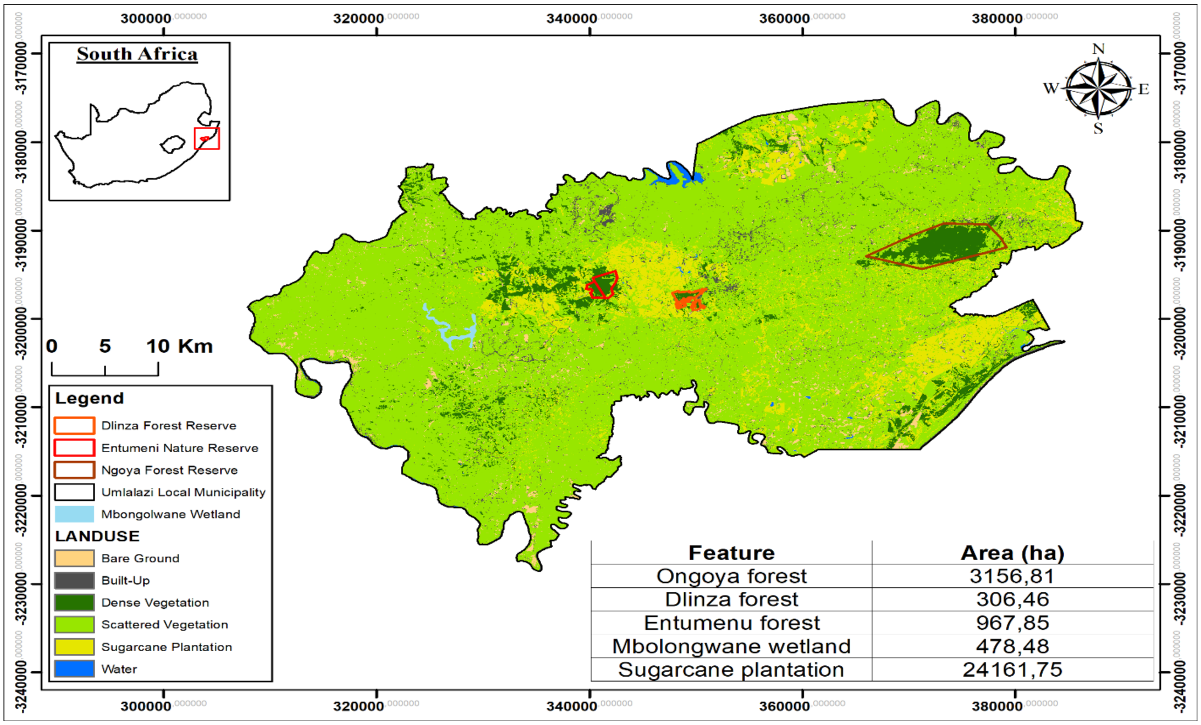


Figure 4.13: Sizes of uMlalazi conservation areas versus the size of sugarcane farms in 2010

In figure 4.14, the total land coverage of the studied ecosystems in uMlalazi. The land coverage of each in 2010 was 83%, 11%, 3%, 1%, and 2% respectively for sugarcane plantations, the Ongoya forest, the Entumenu forest, the Dlinza forest, and the Mbolongwane wetland.

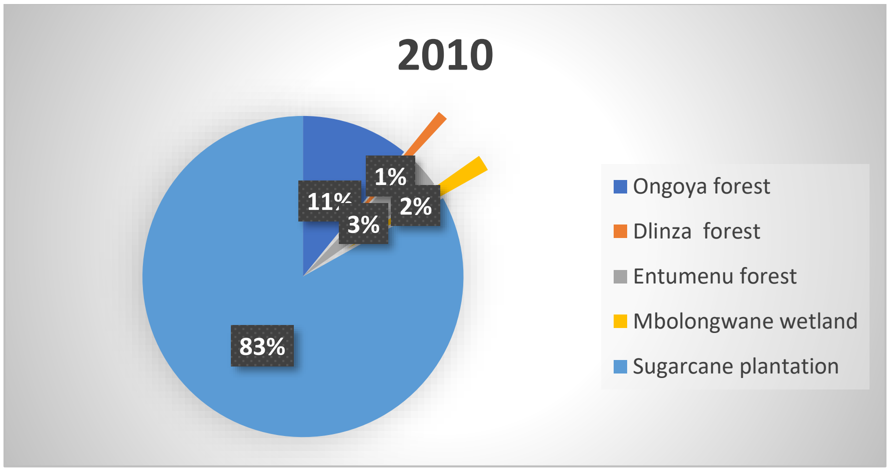


Figure 4.14: Percentage land coverage of the different studied ecosystems in 2010

2015 saw a slight increase in sugarcane plantation farmland sizes of 24858 ha while the total land size occupied by the conserved ecosystems is 5780,68 ha showing a difference of -20077.32 ha (Figure 4.15).

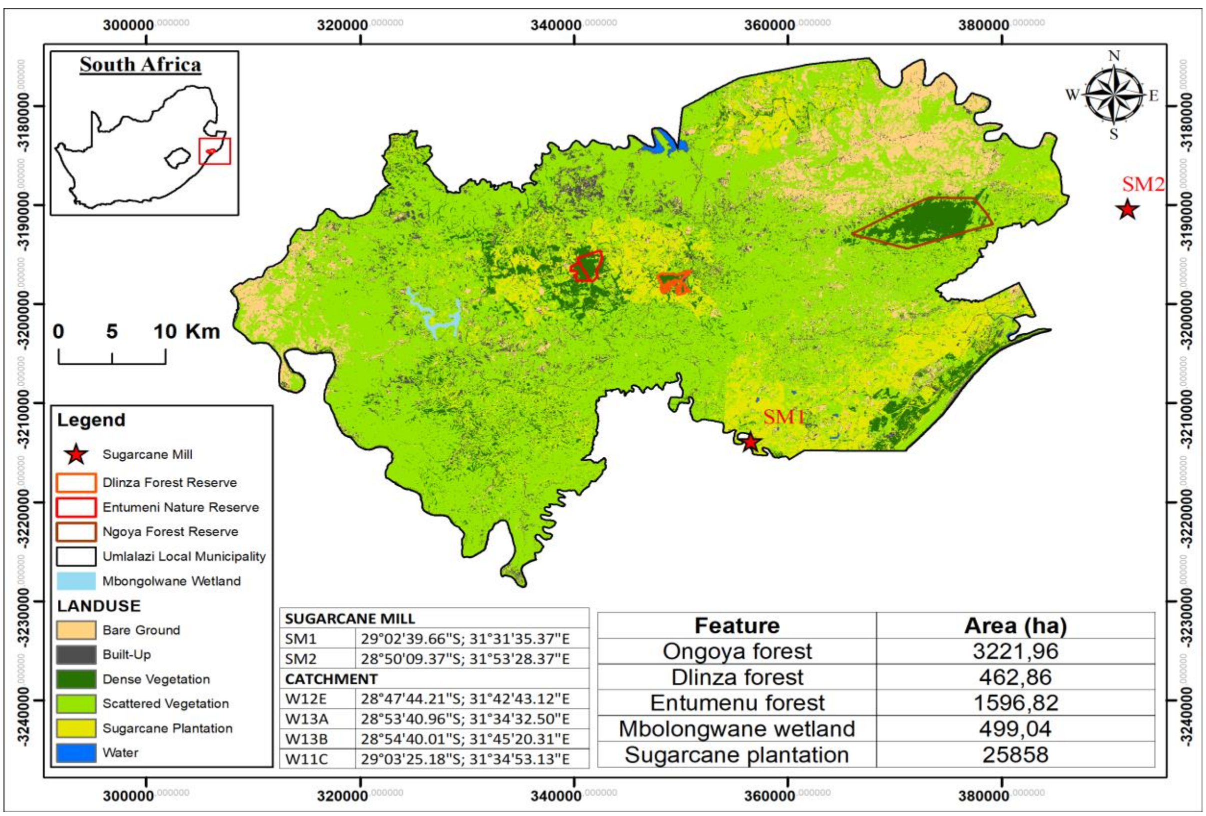


Figure 4.15: Sizes of uMlalazi conservation areas versus the size of sugarcane farms in 2015

In figure 4.16, the total land coverage of the studied ecosystems in uMlalazi is shown. The land coverage of each site in 2015 was 81%, 11%, 5%, 1%, and 2% respectively for sugarcane plantations, the Ongoya forest, the Entumenu forest, the Dlinza forest, and the Mbolongwane wetland.

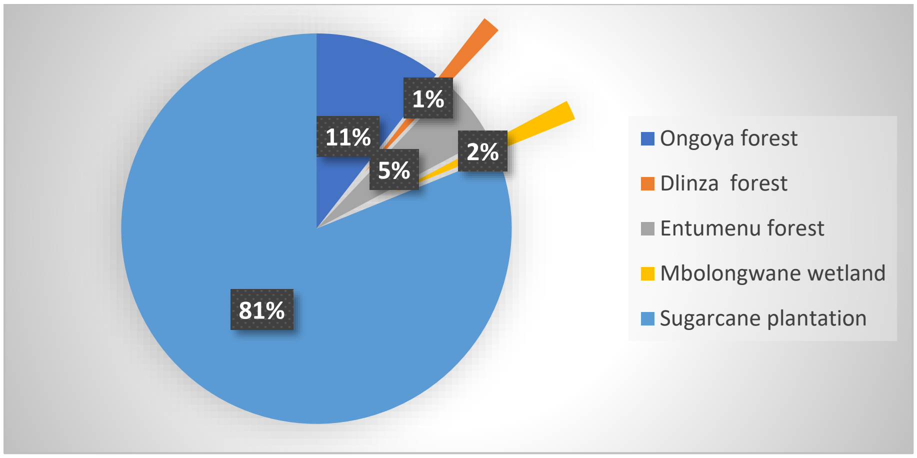


Figure 4.16: Percentage land coverage of the different studied ecosystems in 2015

In 2020, sugarcane farming dropped in uMlalazi as the farmland size indicates a decrease from 25858 ha in 2015 to 15819 ha in 2020 while the total land size of the conserved ecosystems is 6296.4 ha showing a difference of -9523.28 ha (Figure 4.17).

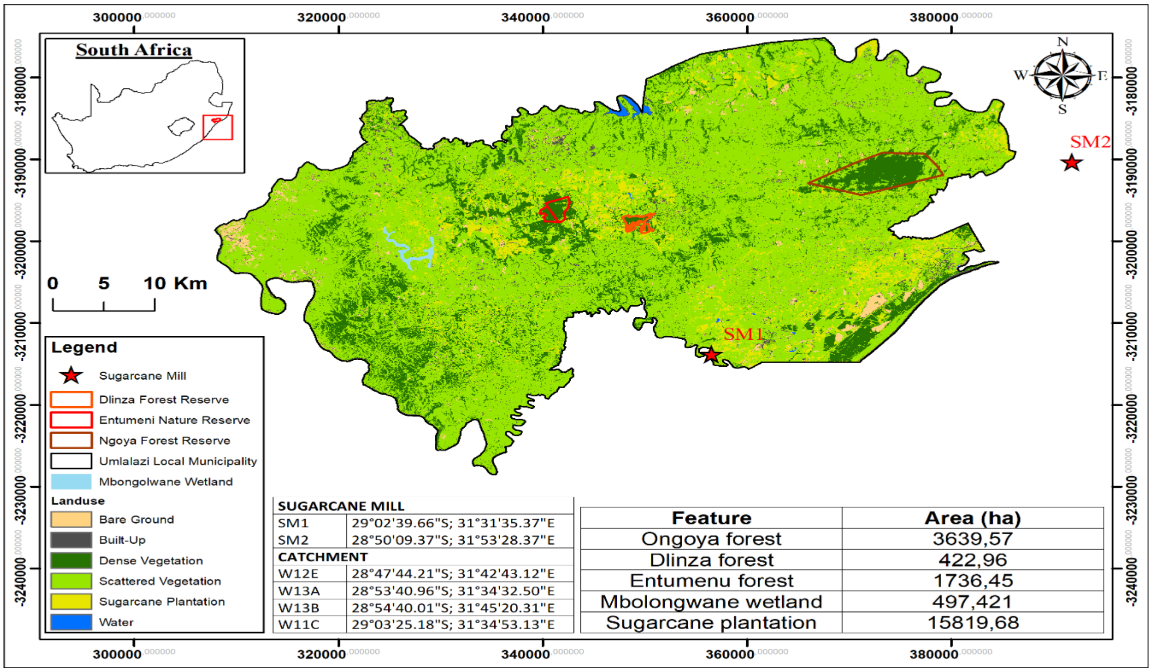


Figure 4.17: Sizes of uMlalazi conservation areas versus the size of sugarcane farms in 2020

The percentages of the various conserved ecosystems and the total of the sugarcane farms against the total land coverage of the studied ecosystems in uMlalazi is presented in figure 4.18. The land coverage of each in 2020 was 72%, 16%, 8%, 2%, and 2%, respectively, for sugarcane plantations, the Ongoya forest, the Entumenu forest, the Dlinza forest, and the Mbolongwane wetland.

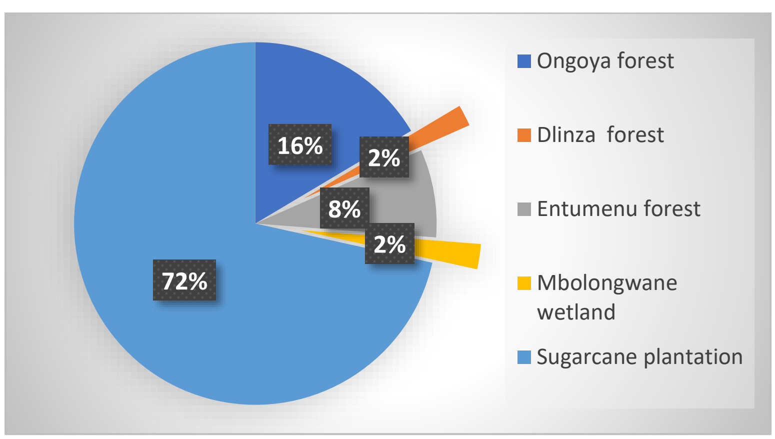


Figure 4.18: Percentage land coverage of the different studied ecosystems in 2020 you can remove the year from the figure

4.5 DISCUSSION OF RESULTS

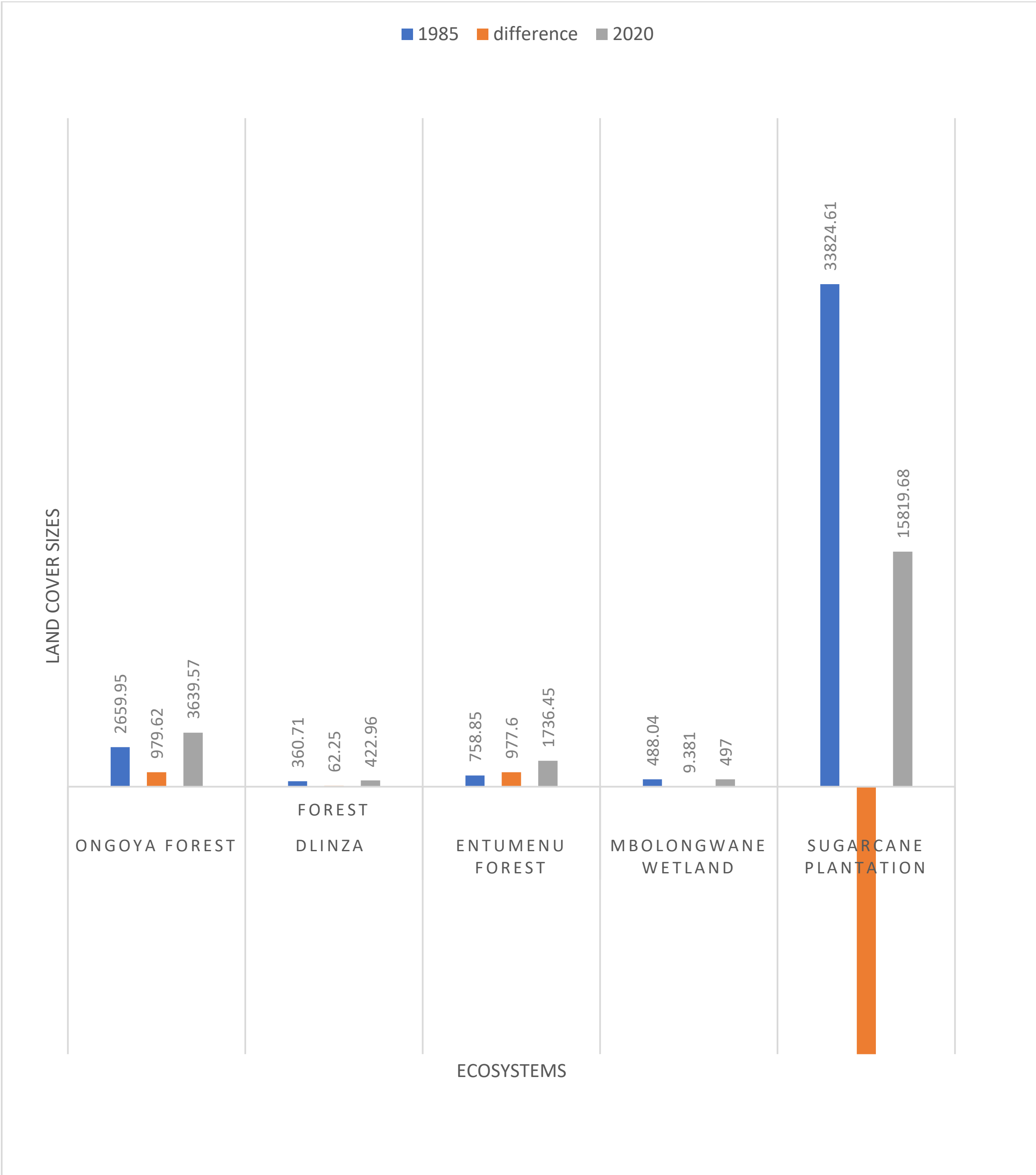


Figure 4.19: Comparing the overall percentage difference in ecosystem land coverage between 1985 and 2020.

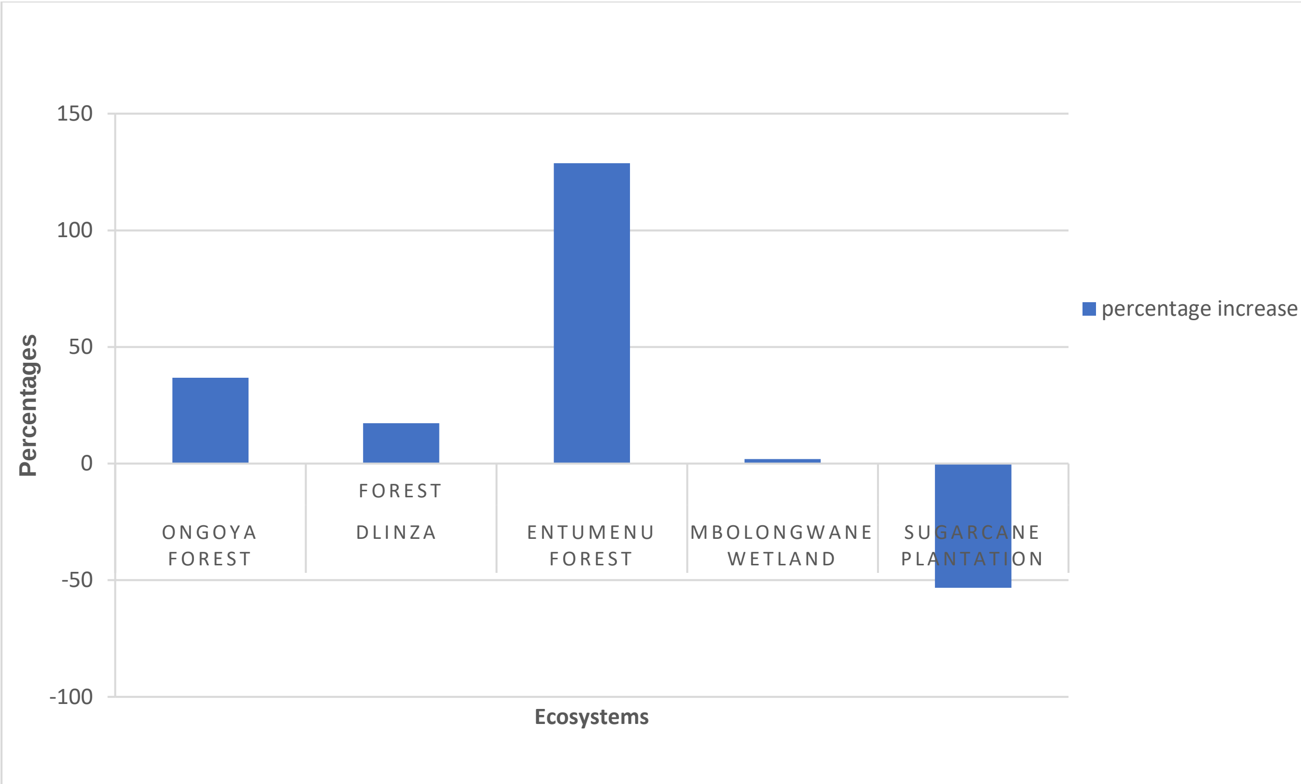


Figure 4.20: Comparing the overall percentage difference in ecosystem land coverage between 1985 and 2020

According to previous studies, the uMlalazi ecosystems have been under conservation due to reduced coverage sizes overtime due to anthropogenic activities such as sugarcane farming. However, as of 1980, there has been a trend of ecosystem land coverage recovery (Bruton, 1980). According to Bruton (1980), the uMlalazi forests were able to regenerate from surviving populations. This trend is also evident in the study conducted by Ramkaran et al. (2009). This is also evident in this current study, although some of the conserved ecosystems show only slight growth in land size since 1985. *For example, the Dlinza Forest is a beautiful forest that is an ideal tourist destination* (https://www.uMlalazi.gov.za/index.php/about/overview) and has only been recovered by 17% since 1985. Likewise, the Mbologwane wetland has had less than a 2% increase in its land coverage during the last 35 years. The Entumenu forest has shown 128% increase and the Ongoya forest also showed a 36.8% increase. Although the sugarcane farmland size has shown a 53% decrease over the same period, it is not evident that this farmland size loss was to increase the conservation areas.

4.5.1 Contributors to GHG emission in uMlalazi

With its low recovery rate, forest loss contributes to air pollution such as CO_2 which accumulates in the atmosphere with a limited O_2 supply. Forests are carbon sinks and therefore with deforestation this carbon is released in the form of CO_2 into the atmosphere. Plants cannot photosynthesize after deforestation. Deforestation thus prevents plants from absorbing CO_2 that results from animal respiration. Emission of this GHG, CO_2 will contribute to climate change. In addition, other industrial activities in uMlalazi, such as sugar milling, generate pollutant CO_2 that cannot be absorbed naturally by these forests.

4.5.2 Potential Socio-economic impacts.

These forests represent a natural capital in the uMlalazi area. With their relatively small sizes, the ecosystem provisions from these ecosystems would probably exceed the carrying capacity. With the low workforce and job opportunities within rural areas, the inhabitants will struggle to afford food and medical bills. Many rural inhabitants depend on firewood, food, and medicinal plants from these forests (Jewitt et al., 2015), thus depriving these natural resources.

From an economic point of view, the forests will not be able to supply timber that can be used for building and construction within the municipality. Although the sale of timber in South Africa is hardware chain based and or regional timber distribution-based, it would have been more sustainable if local forests could carry the capacity of their specific municipalities. Conversely, the municipality goes beyond its municipal boundaries to get wood when required. Furthermore, with the uMlalazi population increase between 2001 and 2016 of 221078 to 223140 people, the current natural ecosystems may not meet their human carrying capacity.

4.5.3 Potential loss of Biodiversity.

From this study, the primary driver of habitat loss is agriculture; as sugarcane agriculture has occupied the space which could have been used as an extension to conserve the more environmental sustaining ecosystems. Therefore, these ecosystems can be considered threatened due to their meagre recovery rate. Furthermore, the biodiversity thus present in them is threatened due to the loss of habitat and eventual food shortages.

Draining wetlands to be used for other anthropogenic activities also deprives the natural living organisms of their habitat. Such deprivation endangers them as the natural filtration services of the wetland are lost, the floral community depreciates in population size, and food chains, broken. The big question that could be asked after these findings is “how sustainable is the development in uMlalazi?”

4.6 RECOMMENDATIONS

Laws governing protected areas should be enforced with monitoring plans in place for all the conserved ecosystems.

Although most sugarcane farms within the municipal boundaries might be privately owned, the municipality (country as a whole) may buy portions of such land from the owners to conserve and develop them into the “original” natural ecosystems. Thus, more sugarcane land should be converted into forests land by increasing the land coverage size of the different forests. This will ensure more carbon is stored in the trees while more Oxygen is emitted into the atmosphere. Natural forests are sustainable as they provide basic human needs such as food. Forests regulate rainfall patterns through evapotranspiration and thus maintain sustainable levels in ground and surface water.

Although this study has shown potentials of biodiversity loss due to the slow rate of recovery of the different natural ecosystems, it is recommended for further studies to be done on examining the rate of biodiversity loss in these conserved areas over time.

The uMlalazi municipality should therefore aim at a 20% increase in land coverage space for the conservation areas within its municipality every 15 years. However, the reduction in sugarcane land should be accompanied by improved and more sustainable farming methods to maintain high production levels.

With uMlalazi particularly made of low-income earners who depend on subsistence farming, there is a need to integrate basic environmental education with their farming practices. This will improve their basis understanding of the impact of deforestation and the importance of using sustainable farming methods.

4.7 CONCLUSION

According to chapter 4 of the IPCC report for policy makers, (Olsson et.al., 2019), *land-use changes and unsustainable land management are direct human causes of land degradation (very high confidence), with agriculture being a dominant sector driving degradation (very high confidence).*

The results from the study showed that, although there is evidence of a general increase in the conserved ecosystems' land coverage sizes, this increase is very little for 35 years of the study period. Therefore, biodiversity will continuously be threatened if these conservation areas are not increased significantly. This is because the carbon sink functions of forests are lost while atmospheric oxygen gets depleted, thus negatively affecting animal respiration.

Land use changes from forests to agriculture, not only affect humans directly but also affect other ecosystems such as the aquatic ecosystem through the leaching of chemicals into ground and surface water; and arial ecosystems with increased GHG emissions such as CO_2 due to unsustainable farming practices such as burnt harvesting. Deforestation impacts negatively on plant photosynthesis and thus contributes to air pollution. These may be looked at as a form of human-induced climate change. On the other hand, converting wetlands into agricultural land, deprives humans and other biodiversity of the natural wetland eco-system services such as the natural filtration system, continuous soil fertility, and the depletion of aquatic habitats.

Chapter 5 focused on the different sugarcane farming practices that are considered unsustainable as they contribute to the emission of GHG and to the pollution of surface water.

CHAPTER 5 GREENHOUSE GAS EMISSION FROM SUGARCANE FARMS IN KZN.

5.1 INTRODUCTION

Sugarcane is a significant raw material for bioethanol production, and it is the most used for bioethanol production in sub-Saharan Africa (Deenanath, 2012). In this chapter the impact of sugarcane agriculture on the emission of GHG in some KZN areas was analysed. Greenhouse gas (GHG) emission remains one of the significant issues of concern worldwide due to its effect on the global climate. According to the United Nations report of 2014, agriculture is one of the critical contributors to global warming, second only to the energy industry contributing as much as 24 % of all global emissions of GHGs due to crop cultivation and livestock production (FAO, 2014). While livestock production has remained the major worry because of the weight of its contribution, land-use change from agricultural expansion has been reported as one of the significant sources of anthropogenic GHG emissions (Lam et al., 2021). Therefore, of interest in this chapter is the farm-level GHG emissions of sugarcane farming to evaluate the sustainability of bioethanol production from sugarcane in South Africa.

5.2 METHODOLOGY

5.2.1 Study Area

Data for this study was collected with reference to many indicators as informed by the requirements for GHG evaluation as stipulated in the CFT model. This evaluation was done with the use of pre-designed questionnaires issued to farmers with farms located in Richards Bay (-28° 46' 58.84" S 32° 02' 15.65" E), KwaDukuza (-29° 19' 41.38" S, 31° 17' 22.34" E,) uMlalazi (-28.956S, 31.757E), Pietermaritzburg (-29°37'0.44" S 30°23'34.01"E) and Port Shepstone (-30°44'28.93 " S 30°27'17.96" E). Sugarcane farms in the province differ in agricultural practices such as irrigation, burnt harvesting, fertilizer usage, and the extent of mechanization. The information collected was loaded onto the CFT model for the calculation of GHG emission parameters.

5.2.2 Description of the participants

The study participants comprised of 37 farmers, comprising commercial and emerging farmers from Richards Bay, KwaDukuza, uMlalazi, Pietermaritzburg, and Port Shepstone. Figure 5.1 highlights the distribution of various sugarcane farms in different categories in KwaZulu-Natal province. The availability of accessible participants limited decisions on the sample size to take part in the study. After the researcher's consent to meet with the farmers was granted by the organization's managers, participants were met during a sugarcane farmers' meeting in Glendhow, KZN. Out of the 55 registered farmers affiliated with the local association at the meeting, only 37 (67%) accepted an invitation to participate in the survey.

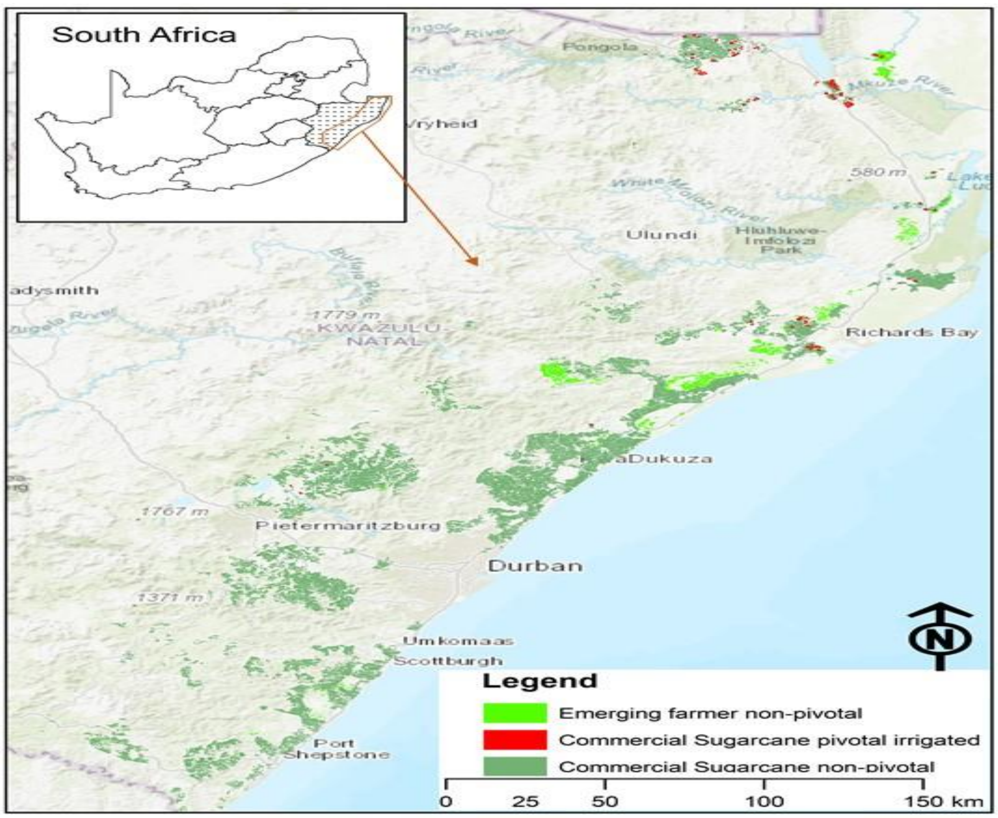


Figure 5.1: Various categories of sugarcane farms in the KZN province of South Africa in 2020

5.2.3 Study Scope

The study scope was limited to sugarcane agricultural stages that lead to the emission of GHG as well as manufacture of the inputs. The sugarcane agricultural stages include soil preparation, planting, fertilizer, chemical application, harvesting, and cane transportation. In addition, the manufacture of inputs accounts for the estimate of the total emissions during the production of fertilizer and chemicals. The various stages of interest in this study and the respective GHG released at each stage are indicated in Figure 5.2. Examples of such GHG are CO_2, NO_x, and CH_4, and other pollutant gases and particles such as SO_x, Ash, and PM_{10} are presented in Figure 5.2. For this study, an equivalent of CO_2 was calculated from the CFT.

Additionally, this chapter was narrowed to sugarcane agricultural practices that deal with pivotal irrigation systems and those that do not irrigate at all. The small emerging farmers and commercial farmers with non-pivotal irrigation consist of dryland sugarcane farming where irrigation is not applied. In contrast, commercial farms with pivotal irrigation involve the centre-pivot irrigation system that is power-driven.

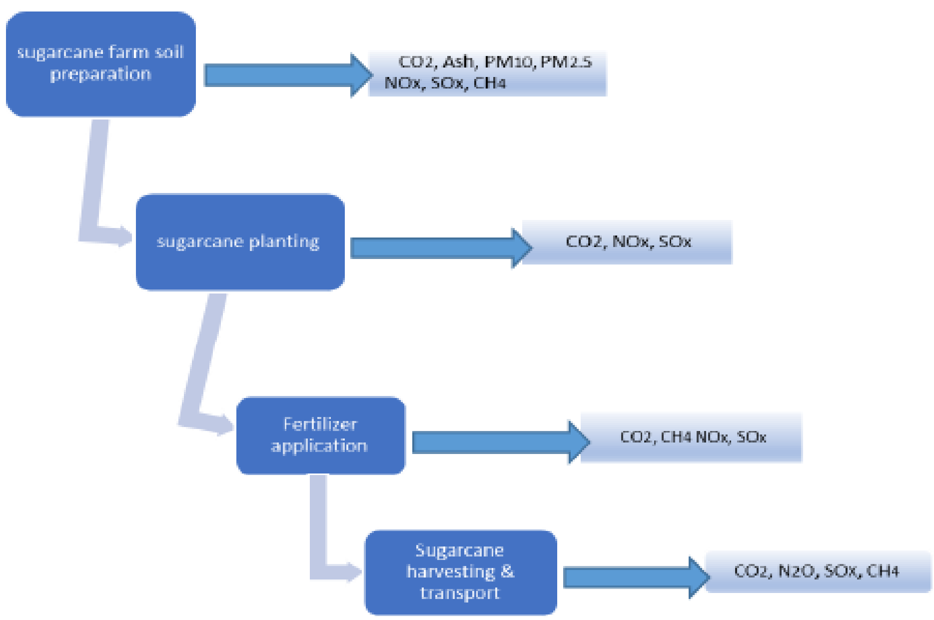


Figure 5.2: System boundary: Sugarcane agriculture processes and associated GHG emissions

5.2.4 GHG emission Data Collection

Qualitative and quantitative data were collected using a combination of primary and secondary sources. Primary data was collected from the sugarcane farmers using questionnaires collecting information on the various farming systems and practices, types and quantities of inputs, farm sizes, location, and other related information needed to evaluate GHG emission. The farmers were segregated into three groups for further analysis based on the irrigation type used: commercial farmers with pivotal irrigation, commercial farmers without pivotal irrigation, and emerging farmers without pivotal irrigation. The farmers' questionnaires were screened to verify the collected information and gaps before capturing the CFT. Out of the 37 questionnaires collected, five were rejected for missing information. Data from the screened questionnaires was captured into the CFT for modelling farm-level GHG emissions. Document analysis extracted secondary data concerning the general spatial, climatic, and edaphic information for the different study areas. Secondary quantitative data concerning GHG emission from the top 11 sugarcane-producing countries was collected from the FAOSTAT database (FAOSTAT, 2020).

5.2.5 Modelling of emission data

The inventories were collected following defined sustainability indicators based on the sustainability indicators as informed by the CFT. The following sustainability data were manually captured and processed on the CFT, enabling various analyses to be modelled:

- farm size,
- crop yield,
- seed (sugarcane cuttings) amount,
- soil texture,
- soil pH,
- the use of and type of fertilizers, the application rate and application method,
- seed treatment stage,
- the use of energy, type of and quantity of energy used,
- the names of various fuel requiring machinery used on the farm,
- the use of any kind of irrigation system,
- the harvesting method, and
- mode of cane transport and distance from farm to sugar mill.

These various agricultural sustainability indicator inventories from multiple farms in the segregated groupings were computed into the software program, and the analysis of GHG emission was established. Consequently, tables and graphs were established.

5.3 RESULTS AND DISCUSSIONS

The results from the various sugarcane farms and applications of the CFT revealed several problems and hotspot areas for GHG emissions. The CFT combines all the different sources of GHG and converts them into a $CO_{2\text{-eq}}$ value. Specifically, CO_2, N_2O, and CH_4 are the leading greenhouse gases that were under investigation. Therefore, the CO_2 equivalence values for N_2O and CH_4 were calculated based on their global warming potential. In addition, the tool evaluated the direct & indirect emissions from N fertilizer application and the crop residue. Although fertilizers production within the study scope, the CFT considers the GHG emission impacts from fertilizers production, which gives an overall view of the impact of using fertilizers on farms in terms of their GHG emission effects. As a result, the CFT was able to identify several GHG emission hotspots in the various activities involved in sugarcane agriculture. The following sections discuss these results in detail.

5.3.1 Evaluation of emission from individual sugarcane farms

The modelled data generated from the individual farms were further segregated based on the location of the farm of concern. This segregation accounted for differences in transport distances from sources of inputs and the sugarcane market after harvest. Finally, averages of the data for each farming system were calculated. These averages were calculated for Richards Bay, KwaDukuza, Pietermaritzburg, and Port Shepstone. The results of the calculations are presented in Tables 5.1 to 5.6. The results in Tables 5.1-5.3 below, highlight the contribution of each GHG type for the various farming systems. The tables show that CO_2 is the dominant GHG emitted by different farming processes in sugarcane farms. While N_2O and CH_4's impact is much more significant than CO_2, their sources on sugarcane farms are limited. Residue management is the primary source of CH_4 and N_2O, while N_2O is emitted from the soil and fertilizers.

Table 5.1: GHG emission (Kg) profiles for emerging sugarcane farms with no irrigation in the KZN region of South Africa, highlighting the contribution of CO_2, N_2O, and CH_4 to total emission.

SOURCE OF EMISSION	KDZ ENP			RB ENP			PMB ENP			PS ENP		
	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4
Seed production	0	0	0	0	0	0	0	0	0	0	0	0
Residue management	0	1.92	73.98	0	58.8	2270	0	7.06	272.16	0	38.37	1480
Fertilizer production*	397000	0	0	56490	0	0	106060	0	0	67540	0	0
Soil / fertilizer	0	103.23	0	0	239.62	0	0	625.37	0	0	179.82	0
Paddy methane	0	0	0	0	0	0	0	0	0	0	0	0
Crop protection	820	0	0	0	0	0	820	0	0	0	0	0
Carbon stock changes	115540	0	0	286240	0	0	115540	0	0	187130	0	0
Energy use (field)	1010	0	0	1230	0	0	1070	0	0	1070	0	0
Energy use (processing)	0	0	0	0	0	0	0	0	0	0	0	0
Wastewater	0	0	0	0	0	0	0	0	0	0	0	0
Off-farm transport	4910	0	0	12330	0	0	103290	0	0	90040	0	0

Table 5.2: GHG emission (kg) profile for commercial sugarcane farms with no irrigation in the KZN region of South Africa, highlighting the contribution of CO_2, N_2O, and CH_4 to total emission.

SOURCE OF EMISSION	KDZ CNP			RB CNP			PMB CNP			PS CNP		
	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4
Seed production	0	0	0	0	0	0	0	0	0	0	0	0
Residue management	0	299.18	11540	0	217.29	8380	0	317.3	12240	0	317.77	12260
Fertilizer production*	92250	0	0	141190	0	0	443020	0	0	224460	0	0
Soil / fertilizer	0	238.2	0	0	538.32	0	0	2850	0	0	915.9	0
Paddy methane	0	0	0	0	0	0	0	0	0	0	0	0
Crop protection	2050	0	0	6970	0	0	3280	0	0	0	0	0
Carbon stock changes	229020	0	0	606710	0	0	403980	0	0	585170	0	0
Energy use (field)	2930	0	0	5010	0	0	4690	0	0	5250	0	0
Energy use (processing)	0	0	0	0	0	0	0	0	0	0	0	0
Wastewater	0	0	0	0	0	0	0	0	0	0	0	0
Off-farm transport	24380	0	0	392390	0	0	51160	0	0	2170000	0	0

** Calculated with validated default values for fertilizer production.*

Table 5.3: GHG emission profiles (Kg) from commercial sugarcane farms with pivotal irrigation systems in the KZN region, highlighting the contribution of CO_2, N_2O, and CH_4 to total emission.

SOURCE OF EMISSION	KDZ CP			RB CP			PMB CP		
	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4
Seed production	0	0	0	0	0	0	0	0	0
Residue management	0	448.77	17310	0	262.28	10120	0	390.99	15080
Fertilizer production*	138860	0	0	208770	0	0	423790	0	0
Soil / fertilizer	0	358.64	0	0	846.96	0	0	3350	0
Paddy methane	0	0	0	0	0	0	0	0	0
Crop protection	107620	0	0	10460	0	0	0	0	0
Carbon stock changes	333820	0	0	485390	0	0	403980	0	0
Energy use (field)	6200	0	0	5110	0	0	4510	0	0
Energy use (processing)	0	0	0	0	0	0	0	0	0
Wastewater	0	0	0	0	0	0	0	0	0
Off-farm transport	36110	0	0	809920	0	0	7700000	0	0
** Calculated with validated default values for fertilizer production.*									

CO_2 is emitted in large amounts from several processes directly involved with sugarcane growing, such as energy use in the farm and crop protection. At the same time, secondary processes that are indirectly involved with agricultural crop production, such as fertilizer production and off-farm transport, are also significant contributors. GHG emissions due to residue management and crop protection are more dominant for commercial farmers than they are for emerging farmers (Table 5.1 vs. Tables 5.2 and 5.3). From these results, it is evident that a few agricultural practices on the farms contribute to increasing GHG emissions levels.

Tables 5.1-5.3 show the evaluation of total CO_{2eq} in Kg per hectare of farmland was done by considering the conversion factors for N_2O and CH_4. This evaluation was carried out to enable the comparison of results for the different farming systems. The results of these calculations are presented in Tables 5.4-5.6. The CFT shows that carbon stock changes significantly impact the total CO_{2eq} emissions in sugarcane farming, with a total emission contribution between 20 % and 50 % (Figure 5.3 and Figure 5.4). Carbon stock refers to the absolute quantity of carbon held within a pool at a specified time, measured in units of mass. Carbon stock change values are a result of land cover and land use changes over time.

Table 5.4: Table showing total GHG emission in Kg CO2-eq and GHG emission in Kg CO2-eq per hectare from emerging sugarcane farms with no irrigation in the KZN region of South Africa.

Sources	KDZ ENP		RB ENP		PMB ENP		PS ENP	
	Total CO_2 eq	Per ha	Total CO_2 eq	Per ha	Total CO_2 eq	Per ha	Total CO_2 eq	Per ha
Seed production	0	0	0	0	0	0	0	0
Residue management	2420	121.05	74220	3230	8910	445.33	48430	1610
Fertilizer production*	397000	1990	56490	2460	106060	5300	67540	2250
Soil / fertilizer	30760	1540	71410	3100	186360	9320	53590	1790
Paddy methane	0	0	0	0	0	0	0	0
Crop protection	820	41	0	0	820	41	0	0
Carbon stock changes	115540	5780	286240	12450	115540	5780	187130	6240
Energy use (field)	1010	50.61	1230	53.6	1070	53.6	1070	35.73
Energy use (processing)	0	0	0	0	0	0	0	0
Wastewater	0	0	0	0	0	0	0	0
Off-farm transport	4910	245.58	12330	535.95	103290	5160	90040	3000
TOTAL EMISSION	**552460**	**9768**	**501920**	**21830**	**522050**	**26100**	**447800**	**14926**
** Calculated with validated default values for fertilizer production.*								

Table 5.5: Table showing total GHG emission in Kg $CO_{2\text{-}eq}$ and GHG emission in Kg CO_2-eq per hectare for commercial sugarcane farms with no irrigation in the KZN region of South Africa

Sources	KDZ CNP		RB CNP		PMB CNP		PS CNP	
	Total CO_2 eq	Per ha	Total CO_2 eq	Per ha	Total CO_2 eq	Per ha	Total CO_2 eq	Per ha
Seed production	0	0	0	0	0	0	0	0
Residue management	377650	7550	274290	3230	400520	5010	401120	4460
Fertilizer production*	92250	1840	141190	1660	443020	5540	224460	2490
Soil / fertilizer	70980	1420	160420	1890	848610	10610	272940	3030
Paddy methane	0	0	0	0	0	0	0	0
Crop protection	2050	41	6970	82	3280	41	0	0
Carbon stock changes	229020	4580	606710	7140	403980	5050	585170	6500
Energy use (field)	2930	58.65	5010	58.96	4690	58.65	5250	58.37
Energy use (processing)	0	0	0	0	0	0	0	0
Wastewater	0	0	0	0	0	0	0	0
Off-farm transport	24380	487.54	392390	4620	51160	639.52	2170000	24160
TOTAL EMISSION	**799260**	**15977**	**1586980**	**18681**	**2155260**	**26949**	**3658940**	**40698**
** Calculated with validated default values for fertilizer production.*								

Table 5.6: Total GHG emission in Kg $CO_{2\text{-eq}}$ and GHG emission in Kg $CO_{2\text{-eq}}$ per hectare for commercial sugarcane farms with pivotal irrigation in the KZN region of South Africa

Sources	KDZ CP		RB CP		PMB CP	
	Total CO_2 eq	Per ha	Total CO_2 eq	Per ha	Total CO_2 eq	Per ha
Seed production	0	0	0	0	0	0
Residue management	566480	7550	331070	3890	493540	6170
Fertilizer production*	138860	1850	208770	2460	423790	5300
Soil / fertilizer	106880	1430	252390	2970	999150	12490
Paddy methane	0	0	0	0	0	0
Crop protection	107620	1440	10460	123	0	0
Carbon stock changes	333820	4450	485390	5710	403980	5050
Energy use (field)	6200	82.64	5110	60.11	4510	56.43
Energy use (processing)	0	0	0	0	0	0
Wastewater	0	0	0	0	0	0
Off-farm transport	36110	481.52	809920	9530	7700000	96220
TOTAL EMISSIONS	**1295970**	**17284**	**2103110**	**24743**	**10024970**	**125286**

** Calculated with validated default values for fertilizer production.*

Terrestrial and oceanic ecosystems play a crucial role in reducing the build-up of CO_2 from anthropogenic sources by reabsorbing it. Soils being stores for organic carbon and nitrogen have a significant role in controlling the amounts of atmospheric GHG, and therefore their importance of various agricultural practices. For this reason, improved methods of management of the land and crop growing are some of the ways how GHG emission can be managed in agriculture. According to Baldock et al. (2012), initiating agricultural production results in a 20–70% reduction in the amount of carbon stored in soils, depending on the crops, farming practices, soil types, and many other factors. As highlighted earlier, most of the land used for sugarcane agriculture was forests and was completely transformed into agricultural lands over time. Carbon stock changes are considerable for commercial farmers due to the sizes of their farms that are generally larger than those of emerging farmers. However, the values for CO_2-eq emitted per hectare due to carbon stock changes are comparable for emerging farmers and commercial farmers around the same areas.

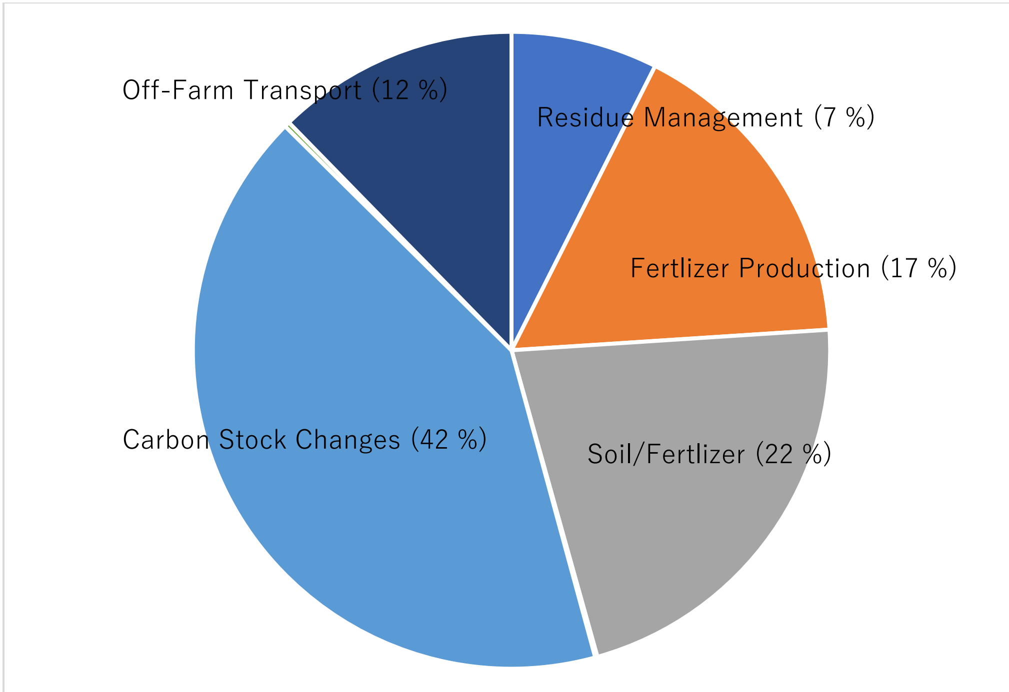


Figure 5.3: Sources and contribution to the total GHG emission in kg $CO_{2\text{-eq}}$ per hectare calculated average of all areas from data in Table 5.4 for emerging sugarcane farms with no irrigation in the KZN province.

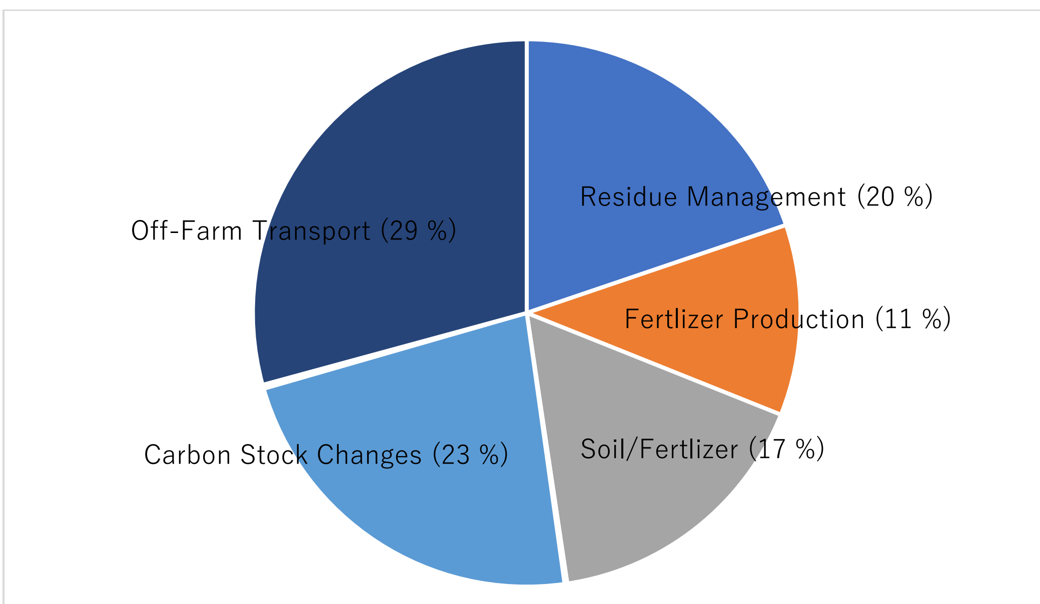


Figure 5.4: Sources and % contribution to the total GHG emission in kg $CO_{2\text{-eq}}$ per hectare calculated average of all areas from data in Table 5.5 from commercial sugarcane farms with no irrigation in the KZN province.

The other GHG emission hotspots include crop and land management practices such as soil/fertilizer management practices and residue management. Soil/fertilizer management practices include liming, a process performed to control soil pH, and synthetic fertilizers as part of crop management. According to Tongwane et al. (2016), synthetic fertilizers and lime are the primary sources of GHG emissions in sugarcane agriculture, constituting 38.7 % and 42.6 % of total sugarcane farming emissions. Synthetic fertilizers are sources of N_2O which is a GHG. However, the study looked at the use of synthetic fertilizers, liming and residue management as the three primary sources of GHG emission for crop production and management, contrary to the results from the CFT, where there is a further breakdown of the various sources. Figures 5.3 and 5.4 show that soil and fertilizer have a considerable contribution to the carbon footprint.

Emissions due to residue management are because of the decomposition of the plant matter that is not used as the product like the straws, stalks, leaf litter, and others. Degradation of this matter generates CH_4 and N_2O. Residue management after sugarcane crushing is of particular concern if used on farms generally because of the potency of these gases emitted, which are multiple times more severe in terms of their impact on global warming than CO_2.

Burnt harvesting is a significant component of residue management in sugarcane agriculture, with as much as 16 % of the total sugarcane residue burnt (Tongwane et al., 2016). The collected data showed that most farms surveyed practiced burnt harvesting, contributing immensely to the carbon footprint and other environmental impacts such as air pollution. However, recommendations from the IPCC suggest that estimations of GHG emissions for residue management should consider only N_2O and CH_4 (Bordonal et al., 2012).

While crop protection and residue management appear less challenging for small emerging farmers, they are a significant concern for commercial farms mainly due to the volumes of methane gas emitted. Crop protection involves the application of chemicals such as pesticides and herbicides. However, the total emission due to crop protection is negligible compared to other sources, as reported in Tables 5.4-5.6. This small value is because the use of chemicals for crop protection is standard practice for commercial farmers and not so much for emerging farmers who try to limit production expenses. The emissions of N_2O due to the application of fertilizers are much higher in volume for commercial farms, but the amounts emitted per hectare of farmland are very similar for emerging and commercial farms.

The CFT also picked field energy use as one of the processes leading to emissions of GHGs. The use of diesel during the ploughing session, machinery aided harvesting, and the transportation of sugarcane from the farm to the sugar mills are standard practices leading to field energy use. In general, irrigated farms have higher GHG emissions partly because of higher on-field energy use due to pivotal irrigation systems and crop protection. More pesticides are generally used in irrigated crops than those without irrigation. The pivotal irrigation system is powered by electricity, and according to their life cycle analysis, it requires more energy than the border check irrigation system (Lukose, 2006; Jacobs, 2006; Archrya et al., 2015). However, the pivot irrigation system is used chiefly in SA because of its relatively lower setup cost and longer life expectancy (Amaya, 2000; Bert, 2000; Douglass, 2000; Foley, 2001). Therefore, the production of the system and the generation of electricity required to drive the pivot irrigation system are the main contributors to GHG emissions. Compared to border check irrigation and subsurface drip irrigation systems, due to the source of its fossil fuel-energy, the pivot irrigation system generates the most GHG during its use (Jacobs, 2006).

The percentage contribution of emissions due to fertilizer production and off-farm transport is of particular interest as they may not be directly involved with crop management. Yet, they contribute up to about 30% of the total emissions (Figure 5.3 and Figure 5.4). Off-farm transportation consists of the transportation of sugarcane from the farm to the sugar mill. The transport distance and the amount of diesel used in the carrier trucks play a significant role in determining the GHG emission. Just as observed with residue management, the contribution of off-farm transport increases rapidly for commercial farming compared to emerging farmers (Figures 5.3 vs. 5.4). The figures recorded for off-farm vehicles varied extensively from one location to another, with farms considered in PMB varying from 639.52 – 9622 kg $CO_{2\ eq}$/hectare. Fertilizer production is a considerably heavy emitter of GHGs, contributing over 10% of total emissions.

Therefore, crop management practices that seek to reduce synthetic fertilizers may likely greatly benefit sugarcane production and the environment as its effect is twofold. Although this may tend to reduce the economic activities of fertilizer producing companies, it will go a long way to improve on sustainable environments. Such companies can embark in producing other organic components for soil nutrient enrichment such as compost. With the ideology of thinking globally and acting locally, such a move will contribute to sustainable environments one industry at a time.

The trends in the total GHG emissions per hectare of farmland from one farming system to another were unclear. Although all three commercial farms practiced pivotal irrigation, there are considerable differences in the other farm activities. For instance, the farm to sugar mill distances is different. Thus, the amounts of GHG generated are different. Additionally, the vast variability of the collected data for off-farm transport also rendered prediction of total emission trends between farming types unreliable as they recorded hugely varying figures. However, using the data from KDZ for emerging farmers with non-pivotal irrigation, commercial farmers with non-pivotal irrigation, and commercial farmers with pivotal irrigation, an increase in total CO_2eq emission is observed in that order, respectively. This is as well shown in Figure 5.5 below.

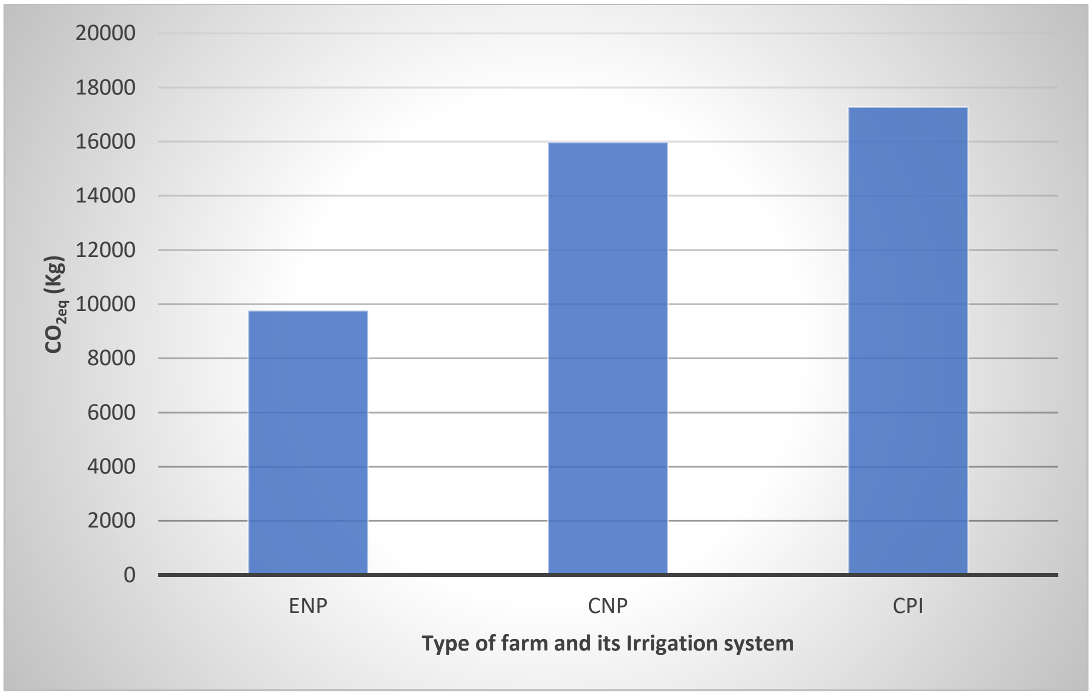


Figure 5.5: Trends for total GHG emission in Kg of $CO_{2\text{-eq}}$ per hectare for ENP, CNP, and CPI for farms in KDZ in the KZN province.

The farm-level data for average emission of GHGs due to sugarcane farming from this study seems to be much higher than the results (1300 Kg/ha) reported by Tongwane et al. (2016), which is between 7-30 times smaller than values reported in Tables 5.4-5.6. The differences could be explained by the approaches used. In addition, the CFT considers several other factors responsible for GHG emission due to sugarcane and the three (use of synthetic fertilizers, liming, and residue management) mentioned in that study.

An analysis of the quantities of GHG emission per tonne of sugarcane produced was also retrieved from the CFT together with the GHG emission per hectare of sugarcane farmland cultivated. These analysed results indicate data that represents sugarcane farms in PS, PMB, RB and KDZ (Table 5.7). In addition, quantities of GHG produced per tonne of sugarcane harvested from the different sugarcane farm categories such as commercial and non-pivotal farms, commercial and pivotal farms, and emerging farms, respectively in KDZ, PS, PMB, and RB are presented.

Table 5.7: GHG emission per tonne of sugarcane harvested from PS, PMB, RP, and KDZ as different farming categories.

Sources	CNP sugarcane farms				CPI sugarcane farms			ENP sugarcane farms			
	PS	PMB	RB	KDZ	PMB	**RB**	**KDZ**	PS	PMB	RB	KDZ
Seed production	0	0	0	0	0	0	0	0	0	0	0
Residue management	47.19	47.12	48.81	46.91	47	47.3	56.65	484.3	8.91	50.83	6.34
Fertilizer production*	26.41	52.12	25.12	11.46	40.36	29.82	13.89	675.45	106.06	38.69	103.93
Soil / fertilizer	32.11	99.84	28.54	8.82	95.16	36.06	10.69	535.88	186.36	48.91	80.53
Paddy methane	0	0	0	0	0	0	0	0	0	0	0
Crop protection	0	0.39	1.24	0.25	0	1.49	10.76	0	0.82	0	2.15
Carbon stock changes	68.84	47.53	107.96	28.45	38.47	69.34	33.38	1870	115.54	196.05	302.47
Energy use (field)	0.62	0.55	0.89	0.36	0.43	0.73	0.62	10.72	1.07	0.84	2.65
Energy use (processing)	0	0	0	0	0	0	0	0	0	0	0
Wastewater	0	0	0	0	0	0	0	0	0	0	0
Off-farm transport	255.81	6.02	69.82	3.03	733.11	115.7	3.61	900.44	103.29	8.44	12.86
TOTAL GHG (Kg/Tonne)	**430.98**	**253.57**	**282.38**	**99.28**	**954.53**	**300.44**	**129.6**	**4476.79**	**522.05**	**343.76**	**510.93**

Except for PMB, the ENP farms emitted more GHGs compared to the commercial farms. However, the commercial farming system without irrigation showing the least GHG emission per tonne of sugarcane (Figure 5.6) produced in the different regions. On the other hand, CPI farms had the most GHG compared to the CNP farms. These results can be compared with studies done by Sapkota et al., (2020), comparing the GHG emission from 3 irrigation systems and the central pivotal irrigation system emitted the most GHG.

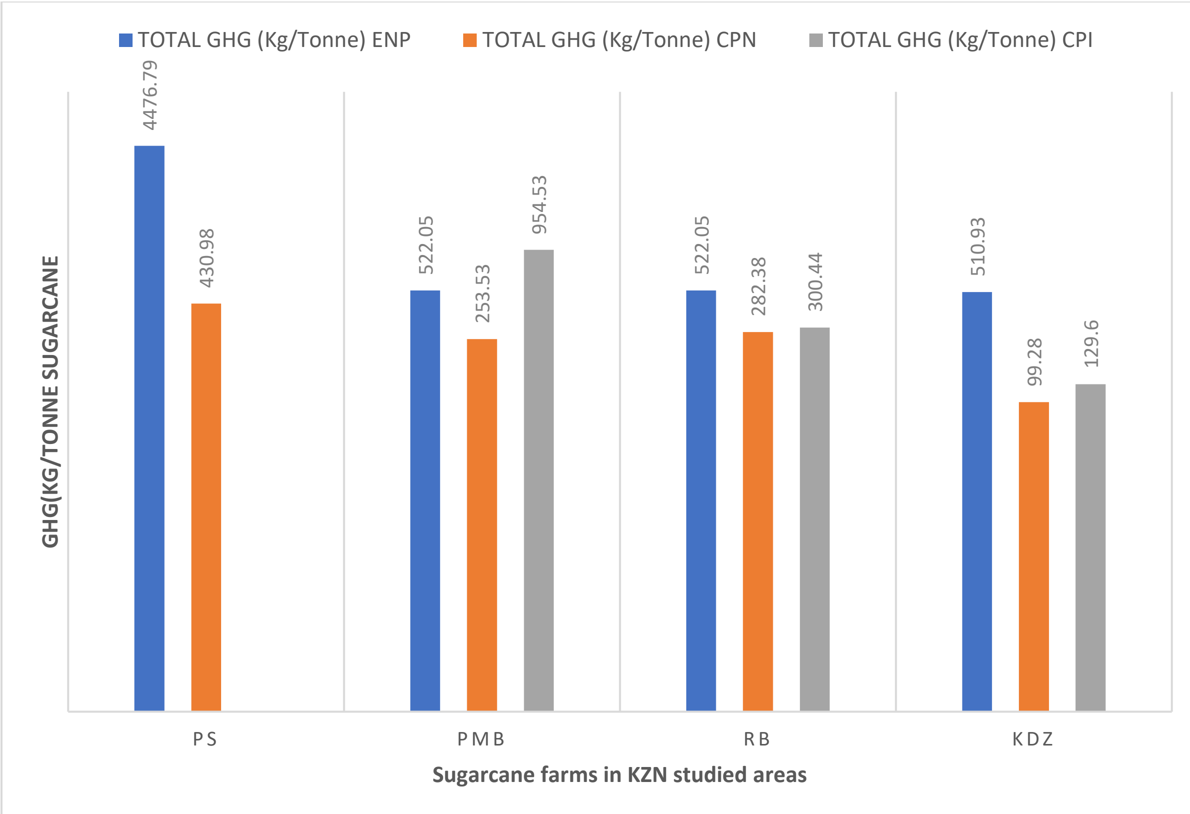


Figure 5.6: Total GHG emission in Kg of $CO_{2\text{-}eq}$ per tonne of harvested sugarcane for ENP, CNP, and CPI for farms in PS, PMB, RB, and KDZ in the KZN province.

Commercial farmers would be expected to have better sugarcane farming practices in plant population and various agricultural inputs. Such practices could be the reason for the lower GHG emission per tonne of harvest. However, commercial farming with irrigation remained marginally higher than without irrigation because of additional on-field energy usage due to the pivotal irrigation system. This finding in the KZN sugarcane farms is also like the case of Brazil in a study by Cardozo et. al, (2015). Furthermore, emerging farmers do not have sufficient knowledge of the quantities of synthetic fertilizers to be used on their farms. Thus, they used higher amounts compared to the other farming types (Table 5.7). Using high doses of synthetic fertilizers explains the very high GHG emission levels in all the regions studied compared to other farming methods. Synthetic fertilizers contain synthetic nitrogen (EPA 2021). Plants absorb nitrogen in the form of nitrates and if this is not all absorbed which is the case of the KZN sugarcane farms as they were no evidence of soil tests being done before applying fertilizers to their farms, farmers are tempted to apply more than the required amounts. This contributes to unabsorbed nitrogen which will be emitted into the atmosphere in the form of N_2O.

5.3.3 Sugarcane agriculture and GHG emission profiles from other regions in the world.

The results of the study were compared with those from other countries. The summary of results collected from FAOSTAT data, a platform that provides food and agricultural data for 245 countries' territories covered by FAO, is presented in Table 5.8 and Figure 5.7. The summary of the results shows the average farm sizes, the average GHG emissions (Gg), and the average quantities of GHG emitted per hectares of farmland from the top eight sugarcane-producing countries in the world between 2010 and 2017. The plots in Figure 5.8 represent emissions of GHG (in Gg) per 100000 hectares of land. Being number eleven on the list, South Africa was included in the plots to compare it with other top nations in sugarcane production. As can be observed from the data, although its average GHG emission is not in the maximum numbers, India is the leading country in terms of average farm sizes globally.

Table 5.8: Average farming sizes, total GHG emission, and total GHG emission/ha of sugarcane farmland for the top eight sugarcane-producing countries in the world (FAOSTAT, 2020)

Top sugarcane producing Countries	Average Farm Area/ Hectares	Total GHG emission /Gg	Total GHG Emission/ Gg/100000 ha	Total GHG Emission/ Kg/ ha
India	4819200	245.61	5.097	50.97
Thailand	1290139	66.27	5.137	51.37
China	1637440	83.43	5.095	50.95
Pakistan	1123964	55.93	4.976	49.76
Mexico	751149	38.28	5.096	50.96
Australia	372405	19.22	5.162	51.62
USA	360491	19.22	5.333	53.33
Guatemala	260271	13.30	5.112	51.12
South Africa	260271	13.30	5.112	51.12

Although there is a significant difference in the sugarcane farm sizes between the various top producing countries, there is no significant difference in GHG quantities emitted per 100000 hectares. This could be because there are standard agricultural practices globally concerning sugarcane agriculture as the issues around GHG emission have taken centre stage, influencing various farming practices around the world. For instance, different countries use different types of machinery; irrigation systems could be diesel-fuelled, while most will most likely use electrical energy to irrigate the farms, while the harvesting process is also most likely different from one country to another, with most practicing burnt harvesting.

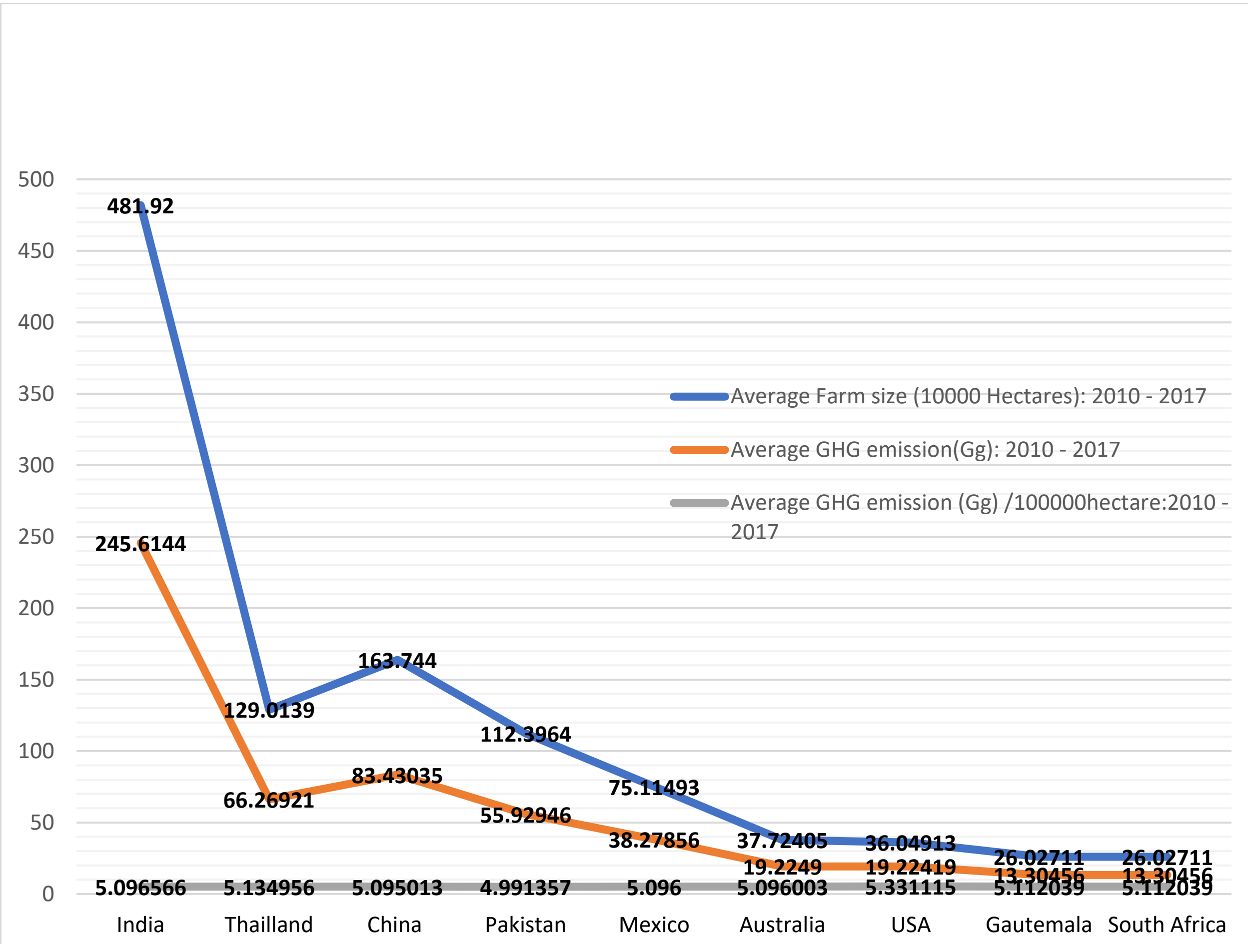


Figure 5.7: Comparison of average GHG emissions concerning farm sizes from top sugarcane- producing countries. Source: https://knoema.com/FAOEMAGBCR2018/emissions-agriculture-burning-crop-residues. [17th June 2020]

Pakistan had the lowest average GHG emission with 4.991 Gg/100000 ha. This low figure is most likely because of stringent regulations and, therefore, is most probably due to adhering to more sustainable agricultural methods compared to the USA, which has the highest amount of GHG emission with 5.333 Gg/ 100000 ha of farmed land as shown in

Figure 5.8. Compared to the rest of the top sugarcane-producing nations around the globe, the average GHG emission per 100000 ha for South Africa is comparable with those of many advanced countries in terms of sugarcane production. These results thus reject the hypothesis of South Africa sugarcane farms emitting comparatively higher levels of GHG due to their practice of unsustainable sugarcane agriculture.

The values of GHG emission from the sugarcane farms in South Africa are in the same range of values from other nations. However, the risks posed by increased agricultural emissions due to the expansion of agricultural land, unsustainable farming methods, and population increase are significant concerns throughout the world (Mbow et al., 2019). These risks have called for the development of methods for accurate estimation of corresponding emissions, identification of hotspot areas to mitigate the impacts of climate change, and global warming at the farm level. One of the most used methods in estimating GHG emissions and their emission hot spots at farm level is the CFT, which was used in this study to investigate the farm-level GHG emissions in sugarcane farms in South Africa.

Although the calculation tools are different with probably different variables considered, the results from the current study using the CFT tool were markedly higher (200-10000 times) than those reported by FAOSTAT data. FAOSTAT data rely on national data, which may be substantially different in terms of the inventories used for collecting data for calculating farm-level GHG emission using the CFT as observed earlier with data from a study by Tongwane et al. (2016).

5.4 CONCLUSION

The use of synthetic fertilizers and residue management is traditionally regarded as the most critical indicator in most studies. Residue has been gaining so much attention because of burnt harvesting, which impacts GHG emission and pollution due to NO_x, particulate matter and general disturbance of the ecosystem. Green harvesting has been touted as a better approach, with much better outcomes in pollution, ecosystem, and a resultant decrease in GHG emission (Bordonal et al., 2012). The study has further highlighted the impact of other indicators that are indirectly involved with crop management, such as off-farm transport and fertilizer production. Both were observed to contribute to the GHG emission due to sugarcane farming significantly. These two indicators are also traditionally not considered in some studies, for instance, the survey by Tongwane et al. (2016). Therefore, the absence of these indicators, and the differences in the results obtained, highlight the importance of including all indicators when collecting inventories in the sustainability studies of bioethanol production.

This study seemed to show that GHG emission by KwaZulu-Natal sugarcane farms is much higher than in other places around the world. For instance, an average commercial farm in KZN emits 17284 Kg $CO_{2\text{-eq}}$ /hectare of sugarcane farmland. The results from several studies evaluating the GHG emission from sugarcane farms show values between 5 -20 times smaller compared to the results reported in the current study. For example, de Figueiredo et al. (2010) reported emission data showing between 2.4-3.2 tonnes $CO_{2\text{-eq}}$ per hectare of farmland. Other values include 2.406 $CO_{2\text{-eq}}$ per hectare of farmland per year (de Figueiredo et al., 2010), 1824 and 2231 kg $CO_{2\text{-eq}}$ per hectare per year (Acreche & Valerio, 2013), and 2651.9 and 2316.4 kg $CO_{2\text{-eq}}$ hectare per year have been reported in other studies. These results seem to show a markedly higher emission profile for sugarcane farms in South Africa. However, it should be noted that while models provide accurate predictions of sets of data as feedback, they also have limitations in some circumstances and should be considered in determining the accuracy of the results. The cool farm tool has considered all aspects that may contribute to the emission of GHG emission such as the type of irrigation methods used, and the source of the fuel used in running the irrigation system. Thus, the results of this study may have been impacted by the input parameters required by the CFT model. Thus, it cannot give definitive answers to the questions of the differences highlighted above. Nevertheless, the study has highlighted some farming practices flagged as GHG emissions hotspots from a qualitative approach. These practices could be improved to mitigate the impact of sugarcane farming on the environment.

5.5 RECOMMENDATIONS FOR FURTHER STUDIES

The study was carried on a smaller sample of farms, and the study results may not necessarily represent the population. It is thus recommended that; future studies should be taken on a larger sample to investigate more on the disparities between GHG emission per hectare of sugarcane farms and per tonne of sugarcane produced in KwaZulu-Natal.

South African Departments such as the Department of Agriculture, the Department of Environmental Affairs and the Department of Fishery, Forestry and the Environment could include local farmers in basic GHG calculations from their various farms, thus encouraging sugarcane farmers to take part in such studies that are aimed at seeking solutions towards the reduction of their GHG footprints. On another breath, precision agriculture may be introduced in the farming industry in general to ensure minimal rates of environmental degradation while maintaining high yields. Being precise in farming practices enables farmers to know how much of the different inputs such as nutrients, water, seeds, and other agricultural inputs to apply on their farms that will grow more crops in a wide range of soil environments. This will reduce the risk of over-fertilization and pesticide use, thus reducing the risk of chemical leaching and run-off causing water pollution. However, further research should be carried out to determine the types and levels of nutrients to be applied to the KZN sugarcane farms that will not be detrimental to the natural environment.

One of the much talked about approaches to deal with residue management is green harvesting (Bordonal et al., 2012). This kind of a study needs to be carried out in KwaZulu-Natal in the future to determine how much such a farming practice would impact GHG emissions at the farm level. Such studies will also consider the social and economic benefits of green harvesting as a method.

Additionally, green harvesting is believed to be a better approach to eliminating CO_2 coming from burning organic material. An important note from the performed calculations in the CFT model indicated a lower amount of CO_2 in the case of farms that practice green harvesting. However, the only considered environmental impacts in such farms are from of CH_4 and N_2O, products of decomposition of the unburnt and unused components of the sugarcane plant (Bordonal et al., 2012). Management of sugarcane residue is, therefore, a crucial process linked with the elimination of burnt harvesting. A study of the relationship between these two approaches could be investigated. Such a study will explore the impact of leaving the organic matter of the fields, especially in wet fields where sugarcane is grown, where there is potential for the generation of CH_4 and N_2O. The residual matter could be used to make organic fertilizers used in the same fields, thus reducing the burden of unwanted organic matter. The use of organic matter for commercial agriculture has not taken off. Future studies to look at the effectiveness of organic fertilizers in commercial sugarcane farming compared to synthetic ones should be carried out to investigate the social, economic, and environmental benefits of shifting towards such a sustainable farming practice. In chapter 6, an evaluation of sugarcane farming and its impact on water resources was done. As part of the results, chemical fertilizers are seen to pollute surface water resources.

CHAPTER 6 EVALUATING THE IMPACT OF SUGARCANE FARMING ON WATER RESOURCES IN uMlalazi CATCHMENTS IN KWA-ZULU NATAL PROVINCE

6.1 INTRODUCTION

Water is an integral part of the environment, and the protection of surface and groundwater is of vital importance because of its social and economic value (Serbu et al., 2016). Both urban and rural communities of South Africa, commonly use surface water for domestic, industrial, and recreational purposes (Edokpayi et al., 2017). Polluted water is a threat to the health and biodiversity of waterways. Pollution of surface and subsurface water systems arises from many causes. As seen in chapter 4 of this study, LULCC due to converting natural ecosystems into agricultural land are significant drivers of environmental degradation. According to Hess et al., (2016) and Namugize et al. (2018), the geomorphology, soil properties, hydrological processes, and other ecological consequences in various ecosystems worldwide are impacted by LULCC. Of these environmental impacts, the degradation of water quality due to anthropogenic activities is one of the several critical issues facing the world in both developed and developing countries (Tahiru et al., 2020). For years, waste discharge coming from chemical and allied industries has been regarded as the primary source of water pollution (Namugize et al., 2018).

Focus on agricultural sources of water quality degradation for inland and coastal waters has drawn so much attention of researchers due to the expansion of commercial agriculture. Agriculture will be responsible for up to 70% of water withdrawals worldwide by 2050 (FAO, 2011). Therefore, it is a critical source of water pollution, overtaking contamination from settlements and industries in many developed and emerging markets (Water Quality, Nd). According to the UN-Water report on water pollution from agriculture (2018), up to 38% of the water bodies in the European Union are under pressure from agricultural pollution. Agricultural sources are regarded as the primary sources of pollution in rivers and streams in the USA (Mateo-Sagater et al., 2017). Farms discharge large quantities of pollutants such as agrochemicals, organic matter, drug residues, sediments, and saline drainage into water bodies (Namugizeet al., 2018). Agrochemicals include the chemicals used to manage the ecosystems in the agricultural sector, such as pesticides, herbicides, and fertilizers. According to Parris (2011), the pressure of agriculture on water quality in rivers, lakes, groundwater, and coastal waters had improved since the early 1990s due to the decline in nutrient surpluses and pesticide use. However, the levels of agricultural nutrient pollution such as phosphorus and nitrogen remain significantly high in many countries (Parris, 2011). These nutrients are discharged from both synthetic fertilizers as well as waste byproducts. These nutrients are transported into the water bodies from various sources, including run-off from agricultural soils, domestic sources, and industrial effluents. In addition to the nutrients, other agricultural pollutants such as metals, pathogens, and pesticides are attributed to have several impacts on the environment and public health (Water Quality, Nd; Shabalala et al., 2013).

Of interest in this study was assessing the impacts of commercial sugarcane agriculture on the surface water resources in South Africa. Over the years, KZN has drawn much attention following the transformation rate of the natural landscape in the KZN, as noted by Namugize et al. (2018). Namugize et al. (2018) projected that only 22% of its natural vegetation would be left by 2050. Due to pollution, these significant changes in the natural habitat have been suggested to negatively impact surface water resources, hydrological processes, and water quality. Sugarcane growing expanded rapidly in the 1990s in South Africa, covering around 430 000 hectares countrywide in 2000 and producing 24 million tons of cane yield (Singels et al., 2019). The expansion was driven by a rapid increase in small sugarcane growing farmers and economic opportunities created by the rising demand of sugarcane products following the growth in bioethanol production (Singels et al., 2019; Zulu et al., 2019). Sugarcane farming in South Africa, however, entered a decline at the beginning of the early 2000s and has continued to progressively decline to a total hectarage of about 370 000 hectares in 2018, producing about 19 million tons of sugarcane (Singels et al., 2019; Zulu et al., 2020). Despite the decline in sugarcane production around the country, sugarcane farming in KZN communities has remained one of the significant economic activities. Sugarcane farming in KZN is carried out through both irrigated and dryland farming. The uMlalazi local municipality relies on the agricultural sector, with a significant portion of the region covered by sugarcane plantations. These sugarcane plantations remain essential for the economic development of the KZN province. Farmers expand the area of their farms they put up for sugar cultivation following the soaring demand for sugar and sugarcane products over the years. Despite the benefits of using bioethanol as a sustainable energy source, Chandel et al. (2007) and Wu et al. (2018) have asserted that large-scale sugarcane production for bioethanol production can exert serious negative consequences on water as a resource. This affirmation gives rise to a research question for this study focused on investigating the environmental implications of the expansion of sugarcane farming on the water quality in KZN.

As a water-scarce country, South Africa may potentially incur a massive price with far-reaching consequences for the country's primary freshwater sources because of pollution of surface water due to anthropogenic activities (Duse et al., 2003). According to Griffin et al. (2014), water quality in South Africa has declined for some time. Earlier studies investigating the linkages between land use and water quality of surface and subsurface water sources have concluded that a significant relationship exists between land use and water quality parameters at a catchment level (Kibena et al., 2013; du Plessis et al., 2014; Teixeira et al., 2014; Namugize et al., 2018). According to Zia et al. (Nd), surface water contamination in a catchment is mainly attributed to outdated farm management practices. While agriculture is a significant contributor to surface-water pollution, groundwater pollution by nitrogen is exclusively attributed to agriculture (Gasparatos et al., 2012). Mitigating these water pollution problems demands proper agriculture management practices to meet domestic water quality standards. The focus of the current project was to assess the water quality degradation due to sugarcane farming specifically. Understanding the detrimental effects of sugarcane farming is pivotal for environmentally appropriate decision-making and practices to mitigate their environmental impacts, especially on the water resources. Mitigating water pollution due to sugarcane agricultural sources is a critical element of waste management policies for releasing hazardous substances, nutrients, and other water pollutants into aquatic ecosystems. Diagnosis, prediction, and monitoring are crucial requirements for managing agricultural practices that mitigate these harmful impacts on water resources (Gasparatos et al., 2012; Water Quality, Nd). The focus of modern-day farm programmes has been to transition the farmers towards progressive agricultural practices with both agronomic and environmental benefits. The current project sought to investigate the impacts of sugarcane farming on water quality in uMlalazi water catchments, KZN, South Africa, with a particular interest in helping decision-makers and planners decide whether an expansion of sugarcane farming for purposes of bioethanol production is sustainable in KZN. Although it has become evident following this study that surface water pollution could not be entirely linked to sugarcane farming but to other point sources of pollutants such as sugar mills and the dilution of surface water by oceanic water, surface water resources are crucial for various activities such as domestic, industrial, or agricultural uses, therefore deterioration in the quality of these water resources renders them less valuable for human and aquatic life use.

6.1.1 Water Quality Assessment

The presence of toxic chemicals and pathogenic micro-organisms in water bodies are water quality drivers and trends within a catchment. Therefore, to investigate the link between land use and land cover changes with water quality, the extent of contamination, and to advise whether specific water bodies need remediation or not, it is imperative in understanding the dynamics of such dissemination (Quinatto et al., 2019). Of the various water quality assessment tools available, the water quality index (WQI) is the most common tool used to assess the impact of various land-use projects on the degradation of the ground and surface waters (Quinatto et al., 2019; Othman et al., 2020). The (WQI) is a single aggregated value determined by applying a statistical functional tool on complex water quality data collected from any body of water and aggregated into a single value (Dede et al., 2013). According to Banda and Kumarasamy (2020), the WQI is a simplified approach to presenting water quality data to non-technical individuals, policymakers, and water scientists. This model aggregates complex data into a single value that can indicate whether the water is good or bad based on a relative scale ranging from zero (worst quality) to one hundred (best quality).

The WQIs are generally developed and designed for applications in watersheds or regions, with limited applicability to other water bodies unless different basins share similar attributes (Banda & Kumarasamy, 2020). For this reason, several WQIs techniques have been developed and used for various purposes, with most having a predetermined weight of water pollutants, the parameters considered, the intended application (Quinatto et al., 2019; Banda & Kumarasamy, 2020; Uddin et al., 2021). Many different standard WQI models have been used in various research works. These include The Horton Index, National sanitation Foundation WQI, Scottish Research Development Department index, Canadian Council of Ministers of the Environment WQI, and Bascaron index, among many others (Uddin et al., 2021). According to Uddin et al. (2021), the general structure of most WQI models consists of the following features: decisions on the water quality parameters to be considered for WQI evaluation, the generation of the parameter sub-indices, assignment of the parameter weight values depending on their significance to the assessment, and lastly the statistical or aggregated function used for computation of the WQI. In a review of the various WQI models by Uddin et al. (2021), of about 21 models discussed in the study, varying approaches in terms of the number of parameters used in the generation of WQIs to assess water quality, the parameter sub-indices, the approach to generating the WQI are highlighted.

The decision on the aggregation function and the approach to evaluating the weights of the water quality parameters are essential in modelling the WQI and, therefore, important in determining the value and interpretation. According to Sutadian et al. (2017), there is no accepted standard method to assess parameter weights, and thus it varies from one model to another, each one with its own merits. According to the review by Uddin et al. (2021), some WQI uses unequal weighting techniques where the sum of all parameter weight values was equal to 1. Other designs use an equal weighting approach where all parameters were assigned an equal weighting, while other models do not require weight values for estimating the final score. The weighting approaches are generally classified into two broad categories, those where weights are assigned based on statistical methods (objective) and those based on the judgement of related experts, policymakers, and practitioners (subjective or participatory-based methods).

Even though the WQI has been used for the evaluation of water quality, the aggregation of the water parameters provides a bigger picture of the water quality assessment but loses information due to generalization; a term referred to as the eclipsing problem (Akhtar et al., 2021; Uddin et al., 2021). The eclipsing problem is further compounded by other factors such as inappropriate sub-indexing rules. As a result, these parameter weightings do not reflect the actual relative influences of parameters or improper aggregation functions (Uddin et al., 2021). Thus, according to Mladenović-Ranisavljević et al. (2018), water quality aggregation can provide either camouflage or exaggerate short-term water quality problems. One way of dealing with this challenge is to expand the evaluation of water quality parameters by applying multi-criteria decision-making (MCDM) approaches to evaluate the parameter's weight separately (Akhtar et al., 2021). There are several MCDM methods for solving problems related to water resources, such as the analytical hierarchical process (AHP). For example, data envelopment analysis (DEA), measuring attractiveness by a categorically based evaluation technique (MACBETH), simple additive weighting (SAW), a technique for order preference by similarity to ideal solution (TOPSIS) have been used in water quality analysis (Mladenović-Ranisavljević et al., 2018; Akhtar et al., 2021).

The MCDM methods like AHP and the Delphi method are some of the most common approaches used in different models and have been successfully used to evaluate the different factors, including the weights of various pollutants using expert opinion-based criteria weighing (Mushtaq et al., 2015; Kumar and Alappat 2009; Uddin et al., 2021). This chapter's objectives were achieved using multi-criteria decision analysis based on geographic information systems (GIS-MCDM) methods to assess catchment water quality. AHP is used to evaluate criteria weights by decomposing the decision process into several levels of hierarchy that allow quantifying opinions and transforming them into a coherent decision model (Saaty, 1980; Saaty and Vargas, 1994). The use of AHP-based weighing of pollutants helps in giving due importance to the characteristics and conditions of the study area of interest, which may not be reflected in non-expert opinion-based criteria weighing (Kapasi et al., 2010). The integration of a GIS and Analytic Hierarchy Process (AHP) greatly facilitated the decision-making process since the visual interface of GIS allows researchers to establish a more precise and smoother communication channel, which can significantly enhance the efficiency of problem-solving (Serbu et al., 2016). The application of GIS technology allows temporal, spatial, and scale variations to be analysed.

Consequently, this study was aimed at evaluating the impact of sugarcane farming on water resources in uMlalazi water catchments in Kwazulu-Natal Province using secondary data collected by the Department of Water and Sanitation (DWS).

6.2 OBJECTIVES

Three specific objectives were set for this study as follows:

- to assess the spatial variability of bio- and Physico-chemical water quality parameters of the uMlalazi quaternary catchment areas W11C, W12E, W13A, and W13B using secondary data collected by the Department of Water and Sanitation (DWS) for the period 2014 and 2018, together with the extrapolated data used in filling the existing data gaps,
- to compare the differences in the levels and concentrations of these water quality parameters between 2014 and 2018 and
- to establish a relationship between sugarcane farming and the water quality variables at crucial sites in the uMlalazi quaternary catchment areas of W11C, W12E, W13A, and W13B.

Limited literature is available on GIS-based water quality impact assessment of sugar plantation projects in KZN. Moreover, there is also limited knowledge on the spatial analysis of the individual water pollutants in the study area. It is thus recommended to expand on this study to close these knowledge gaps.

6.3 METHODOLOGY

6.3.1 Study Area

The study was conducted in the uMlalazi catchment area that is located within the uThungulu district in the KZN Province, South Africa, shown in Figure 6.1. This municipal area is characterised by commercial farming areas in a broad and continuous band, with agricultural production dominated by sugarcane farming and some timber production. The uMlalazi catchment area is characterised by four (4) quaternary catchment areas, W11C, W12E, W13A, and W13B, located between longitudes 31°25′ and 31°50′ East and latitudes 29°34′ and 29°52′ South, as shown in Figure 6.2 below. According to the DWS (formerly Department of Water Affairs and Forestry) report on groundwater resources (Denis and Denis, 2009), quaternary catchments W11C, W13A, and W13B are in the Mtunzini and Matikulu catchments. The two small coastal catchments are characterised by high rainfall, large areas of dryland sugar cane, limited amounts of irrigation, and afforestation. The site is predominantly agricultural. The W11 and W13 catchments include the Amatikulu and the Mlalazi River catchments, respectively. W12E quaternary catchment forms part of the Mhlathuze catchment (Denis and Denis, 2009). The Mhlathuze catchment is the economic hub of the Usutu to Mhlathuze WMA, with many industries and the world’s largest coal export terminal. The water requirements of the Mhlathuze catchment are substantial, with sectors such as mining, industry, irrigation, and domestic uses having large water requirements (Denis and Denis, 2009). The water resources of the Mhlathuze catchment are well developed with the large Goedertrouw Dam, which is the primary regulating storage in the catchment. The Mhlathuze River system supplies water to the urban, domestic, industrial, and mining sectors situated around Richard’s Bay and Empangeni on the north coast of KwaZulu-Natal and the agricultural sector, irrigating mainly sugarcane and citrus.

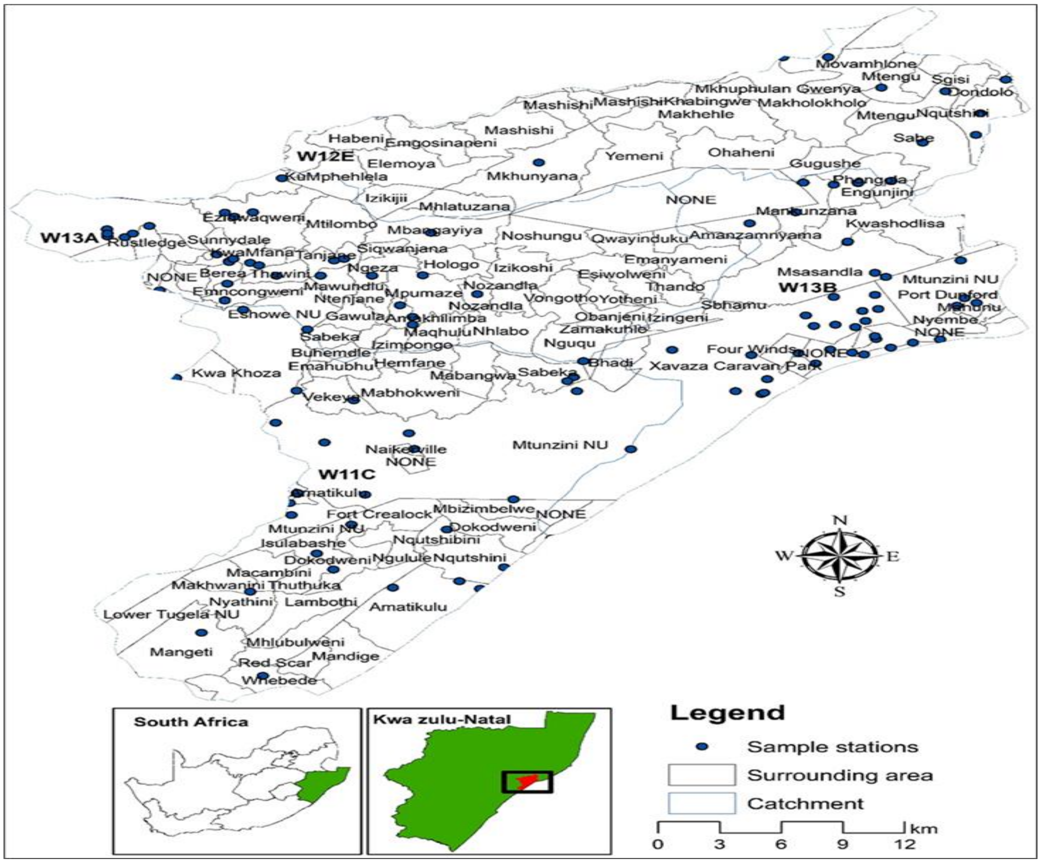


Figure 6.1: Map showing the uMlalazi catchment areas

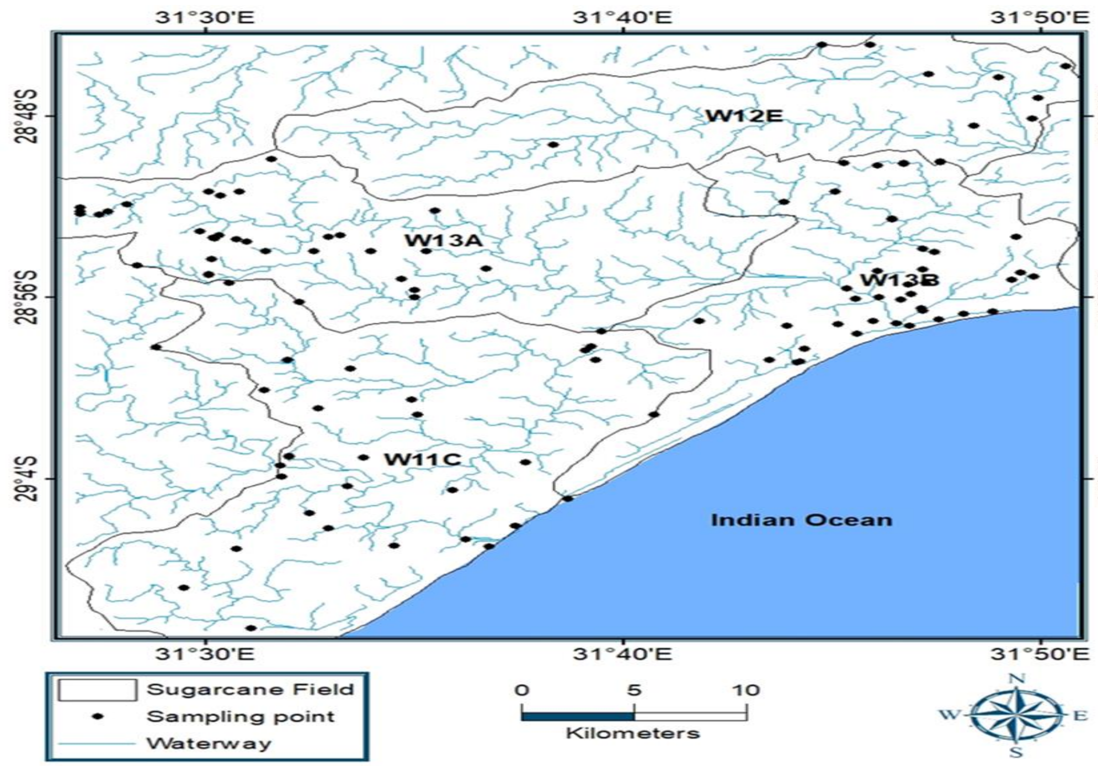


Figure 6.2: Map showing the quaternary catchments making up the study area and sampling points. The waterway layer is superimposed on the map

6.3.2 Sampling

This study was based on the analysis of secondary data collected from the DWS and additional predicted and extrapolated data using machine learning algorithms (MLA). Specifically, deep learning or artificial neural networks was used where the neural networks were trained on the available data. The trained models were then used in predicting the missing data. The neural networks learn patterns embedded in the data such that there accurately interpolate missing values. The model showed a 94% accuracy. The low values were not included as those would require a more comprehensive dataset to predict with an acceptable degree of accuracy.

The DWS has approximately 40 active surface water sampling points, which are located at strategic locations for monitoring surface water. Data from DWS show that all the existing groundwater monitoring points are no longer active and thus there is no evidence of sampling after 1995. The sampling points for surface water samples include rivers, dams, lagoons/estuary. Details of the sampling design and specifications of the samples are not specified on the secondary data.

6.3.3 Study Scope

Water Quality Monitoring Data

The study combined two approaches, firstly analysing the historical water quality records to distinguish sub-catchment water quality trends and investigating the links with land use activities by mapping water quality drivers within the sub-catchments. Historical surface water quality data of the uMlalazi catchment area of KZN were obtained from the DWS. The DWS has extensive records of historical and current water quality data. There is weekly, to bi-weekly to monthly data for ions such as Ca^{2+}, K^{+}, Mg^{2+}, CO_3^{2-}, Cl^{-}, Na^{+}, and SO_4^{2-}, nutrients such as NO_3^{-}, NH_4^{+}, PO_4^{3-} and in-situ field measurements (pH, dissolved oxygen, electrical conductivity, temperature). The highlighted monitoring sites in Figures 6.1 and 6.2 include both surface and groundwater routine monitoring sites. The locations of these quaternary catchments were delineated using the Geographical Information Systems (GIS) as highlighted in Figures 6.1 and 6.2, respectively. The monitoring stations in the catchment of interest have been recording data for varying parameters, with more established stations measuring a considerable collection of parameters from as early as 1977. Some stations excluded some water quality parameters from their water quality monitoring program. With these data gaps the scope of study was limited to surface water analysis for 2014 and 2018 as presented in Table 6.1.

Analysis of Surface Water quality parameters and preparation of thematic map layers

Selected physicochemical water quality parameters were analysed based on the historical data records for surface water and the extrapolated data records for surface water as pointed out above. Six parameters including chloride, total dissolved solids, Electrical conductivity, Water hardness, the water pH and the Total Alkalinity were analysed for surface water.

To select water quality parameters, a series of relevant WHO, the South African Department of Water and Sanitation (DWS) and the South African Department of Water Affairs and Forestry (DWAF), water quality guidelines, provided the basis for evaluating surface water quality. The choices of water quality parameters assessed to determine the WQI and to draw the thematic maps were guided by the availability of data from the records provided by the DWS. However, these data set presented a few gaps that could be ignored (indicated with red blocks in Table 6.1), since the average values for each parameter per catchment were used in determining the overall water quality.

The analysis involved assessing the temporal profiles and the evaluation of the mean over the entire recording period. Water quality assessment was approached from the perspective of "aquatic ecosystem health". With the aid of previous studies (Poddar and Sahu, 2017; Wallace et al., 2017), the water quality parameters considered for this chapter were scaled down to 6 parameters because of the data limitations realized with the data from DWA and the guidelines provided in DWAF (1996). Therefore, the parameters considered for assessing water quality include electrical conductivity, pH, total hardness, total alkalinity, dissolved major salts, and chloride.

6.4 RESULTS AND DISCUSSION

Table 6.1 represents the results from the various measurements of the levels and concentration of water quality parameters for 2014 and 2018. It was noted that different monitoring points were measured for the different years. The number of monitoring points are also different for the different years.

The dataset obtained for this study covers 44 years, extending from 1977 through 1994/1995 to 2018/2019 for some monitoring stations, with some limited to the last 5-10 years.

The available borehole data was limited for the period between 1994/1995, with all groundwater monitoring stations currently no longer active. In addition, different monitoring stations recorded different sets of parameters, with some limited to only a few of the parameters of interest for this research. Thus, with such limitations and data gaps, boreholes (groundwater) data was only available for the period of 1994 for 10 water quality parameters while the surface water was available but with gaps for 8 water quality parameters for both 2014 and 2018. Although with data gaps, the researcher considered the more recent data that will generate more reliable and valid results upon analyzing. Thus, this study focused only on surface water analysis.

Due to the data gaps, the existing data from DWS was used to extrapolate the missing data. Machine learning algorithms (MLA) was used to predict the missing data with regards to the surface water, using available data. According to Kersting (2018), machine learning and artificial intelligence are equal and equal to deep learning as they share the same fundamental hypothesis that computation is a useful way to model intelligent behavior in machines. MLA thus assists with collecting data, understanding it, and translating it into knowledge, conclusions, and actions (Kersting, 2018). However, the robustness of the model cannot be guaranteed given the sparsity of available data from DWS.

6.4.1 Water Quality Assessment for Surface Water

The most common threats to the water quality and the life of species in the aquatic systems are increased nutrient loads, salinity, and dissolved and suspended solids (Hess et al., 2016). Unfortunately, because of limited data for some of the water quality parameters, especially the nitrogen and phosphate nutrient content in the surface water, they were not analysed in the surface water. Environmental impacts of surface water and groundwater resources such as ecotoxicity, eutrophication, and acidification can result from sugarcane farming environments. These impacts result from sugarcane farming practices, such as irrigation, and fertilizer, pesticides, and herbicides application.

Table 6.1: Water quality parameter monitoring for the uMlalazi water catchment area in 2014 and 2018 with data from DWA and MLA

Catchment area	Lon	Lat	Years	pH	Cl-Diss-Water (CHLORIDE) (mg/L) Result	TDS-Tot-Water (DISSOLVED MAJOR SALTS) (mg/L) Result	EC (mS/cm)	Total WATER HARDNESS AS CACO3 CALCULATED) (mg/L) Result	TAL-Diss-Water (TOTAL ALKALINITY AS CALCIUM CARBONATE) (mg/L) Result	LEGEND
W13B	31.8146	-28.943	2018	8.2422	170.93	637.20	51.70	238.09	160.14	
	31.8146	-28.943	2014	8.16273	160.95	597.01	50.42	223.42	148.78	2014 DATA
	31.8027	-28.946	2018	8.1945	159.84	594.84	50.27	222.49	148.91	2018 DATA
	31.8027	-28.946	2014	8.24261	113.73	433.07	44.21	161.81	111.15	Missing Data
	31.793	-28.949	2018	8.08863	113.04	422.50	44.27	158.43	105.65	Data from MLA
	31.793	-28.949	2014	8.24417	105.83	404.76	43.15	151.20	104.40	

	31.7866	-28.943	2018	8.12517	38.71	167.94	19.99	59.96	52.20
	31.7866	-28.943	2014	8.13625	60.95	240.41	37.01	88.36	66.06
	31.7813	-28.954	2018	8.1851	68.61	269.48	38.04	99.94	72.39
	31.7813	-28.954	2014	8.13737	89.14	340.45	41.10	127.26	87.59
	31.7775	-28.935	2018	7.9601	42.79	162.90	16.94	58.69	44.94
	31.7775	-28.935	2014	7.96813	56.85	216.77	36.08	74.79	65.36
	31.776	-28.952	2018	7.921	37.59	166.33	22.00	59.64	52.01
	31.776	-28.952	2014	8.23625	60.96	243.65	36.50	89.79	67.33
	31.7687	-28.933	2018	7.61375	53.70	154.18	6.71	55.50	30.43
	31.7687	-28.933	2014	7.86059	57.85	241.32	34.59	80.85	81.49
	31.7593	-28.934	2018	8.118	51.87	156.35	2.95	56.25	33.30
	31.7593	-28.934	2014	7.69	36.18	195.67	31.98	64.15	78.18
	31.7558	-28.927	2018	8.52667	46.87	160.90	1.51	57.94	40.18
	31.7558	-28.927	2014	7.64647	34.92	189.58	30.95	64.10	72.82
W12E	31.7458	-28.748	2018	8.15	39.75	174.20	0.27	48.99	58.2
	31.7458	-28.748	2014	8.19845	35.84		0.27	52.93	72.74
W11C	31.6444	-29.081	2018	7.55429	58.50	134.88	19.57	51.58	11.83
	31.6237	-29.101	2018	7.23833	56.55	148.63	8.62	54.15	23.85
	31.6132	-29.116	2018	7.235	54.73	152.58	5.19	55.04	28.45
	31.6041	-29.111	2018	7.315	54.29	153.44	4.86	55.25	29.48
	31.5569	-29.072	2018	6.36429	57.84	146.02	0.46	53.51	20.82
	31.5331	-29.05	2018	7.2	53.59	154.94	0.26	55.57	31.26
	31.5331	-29.05	2014	7.578	53.12	155.77	0.35	55.78	32.27
W13A	31.4728	-28.909	2018	6.955	54.23	153.66	0.57	55.28	29.73
	31.4728	-28.909	2014	6.812	54.79	152.53	0.55	55.02	28.38
	31.4575	-28.873	2018	7.8	52.91	155.98	0.30	53.94	23.10
	31.4575	**-28.873**	2014	7.80146	39.86		0.23	46.85	40.66
	31.45	-28.872	2018	7.86667	62.25	139.41	0.30	50.00	15.00

	31.45	-28.872	2014	7.25267	45.71		0.21	34.46	18.98	

The qualitative analysis of these water quality parameters was obtained because of the constructed spatial distribution maps (Figure 6.3 to Figure 6.8) using the inverse distance weighted (IDW) tool available in ArcGIS and shown in the next paragraphs and sections.

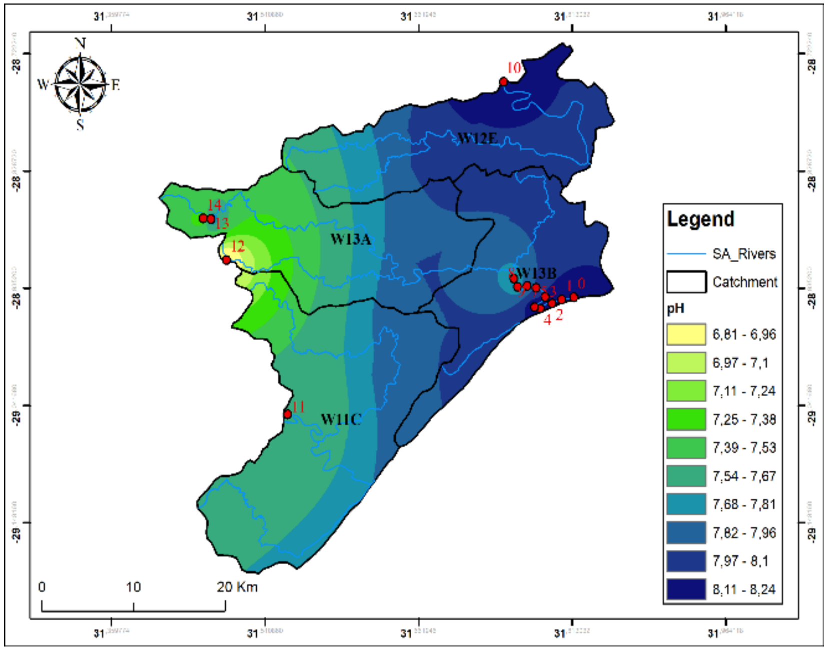
The location of sugarcane plantations shown in Figure 6.12 supports the hypothesis that sugarcane farming is partly responsible for the deterioration of water quality in this catchment, while point source pollution from either the ocean or the sugar mills around (SM1 and SM2 on Figure 6.12) may also be a contributing factor to the poor water quality. The values are comparatively higher in quaternary catchments W13B and W11C for both 2014 and 2018. The analysis of these individual parameters is presented in the sections 6.4.1.1 - 6.4.1.8 for both 2014 and 2018, below.

6.4.1.1 The Surface water pH

The map showing the spatial distribution profile for the average annual pH recorded by each monitoring station for each quaternary catchment is shown in Figure 6.3. The calculated average pH ranges from 6.36 to 8.51. The pH of surface water is affected by a wide range of factors such as algal blooms, level of hard-water minerals, releases from agricultural and industrial activities, carbonic acid from respiration or decomposition, and oxidation of sulphides in sediments, among others. The pH values for these quaternary catchments are within the acceptable range of pH considered permissible for surface water and agricultural purposes according to the South African National Standard for aquatic ecosystems (Department of water and forestry – DWAF, 1996).

The 2014 profile shows a general pH range of 6.81 -8.24 and 2018 shows a 6.37 -8.52 range. The quaternary catchments W13B and W12E and a portion of W13A showed evidence of mineralisation of water, with pH results well over 7.5 for both 2014 and 2018 profiles. Except for the monitoring points W13A12 in 2014 and W11C15 in 2018, the pH for the catchment is between 7.3 and 8.5.

Figure 6.9, showing information on the land use, shows that around monitoring station W11C15, there is a sugar milling company. The profile of the pH distribution around W11C15 seems to point to a point source of pollution.



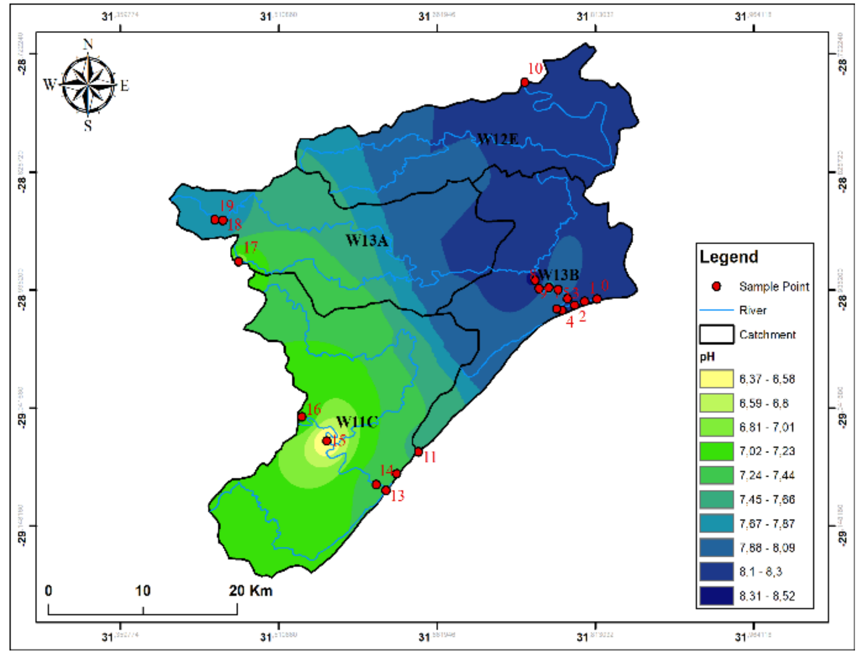


Figure 6.3a: Spatial distribution of the pH for surface water based on the average monthly pH values for the year 2014.

Figure 6.3b: Spatial distribution of the pH for surface water based on the average monthly pH values for the year 2018.

Water effluent from sugar milling companies is acidic, with pH around 5-6. The map, Figure 6.9, appears to show that the sugar milling company could be responsible for the contamination of water in this quaternary catchment. This contamination would also explain why the pH of surface water in W11C was generally acidic in 2018 even though there is significant sugarcane farming in this quaternary catchment.

The type of farming management practices also significantly impacts the water quality of the water bodies around (Hess et al., 2016). Application of fertilizers, irrigation and irrigation types, and residue management all contribute to the nutrient quantities of the runoff water, and therefore the concentration of the nutrients in the water. Heavy irrigation increases the volume of runoffs into water bodies. Irrigation exacerbates the leaching of nutrients and is worse for other irrigation types compared to others. Quaternary catchment W12E, which has the least rainfall, dominates others in terms of irrigation. As a result, their impact on the water pH is more pronounced even though the land use map shows smaller sugar farming plantations for W12E. The results also show that the effects of sugarcane farming on water quality can extend to catchment levels through rivers and lakes, well beyond the confines of the field from which they are coming (Hess et al., 2016).

6.4.1.2 Electrical Conductivity – Surface water

The electrical conductivity (EC) of water is one of the main parameters used to determine the suitability of water for irrigation and an indicator for pollution load (Omer, 2019). Electrical conductivity in the streams and rivers indicates a higher load of total dissolved ions and is primarily influenced by the area's geology through which they flow. For example, clay soils tend to have higher electrical conductivity due to salts that dissolve and ionise in the water, resulting in increased electrical conductivity values compared to other soil types (Shabalala et al., 2013). Figure 6.4a and 6.4b show the spatial distribution of electrical conductivity for the 2014 and 2018 profiles respectively of surface water for the 4 catchments studied.

According to DWAF (2003) threshold standards for EC in surface water is 30 mS/cm. This has been compared to the results of this study. Most of the 2018 EC readings for the studied catchments show a high EC value in all the quaternary catchments, compared to the threshold EC in pure water of 0.05-0.5mS/cm (Omer, 2019) and surface water, 30 mS/l (DWAF 1996). The 2014 profile for W11C11, W13A 12, 13, 14 and W12E10 and 2018 profile W13A17, 18, 19, W11C15 & 16, W12E10 and W13B8 show areas with the least EC, while W11B present highest EC values for 2018. Generally, the observed electrical conductivities for surface water for these catchments varied from 0.21 - 50.33 mS/cm for 2014 and 0.26 – 51.58 mS/cm for 2018. The average EC values for all studied catchments are beyond the recommended threshold value for EC of 30 mS/l.

In the case of 2014, the profile for EC for all the studied catchments shows average EC values that have levels beyond the threshold EC levels for surface water. W11B has recorded the highest EC values in 2014. W11B presents the highest average EC levels of 38.6 mS/cm amongst all the studied catchments. Therefore, all the studied catchments have shown evidence of very poor to poor water quality with respect to DWAF (1996). According to the revised general authorization in terms of section 39 of the National Water Act, of 1998 (Molewa, 2013), the authorized standards of wastewater to be discharged into natural water resources with respect to EC is between 70 mS/m and 150 mS/m. The EC for the current studied area is below this limit. However, this could be an indication of dilution of the chemicals being discharged into the water bodies.

There is a visible improvement of the water quality with respect to the EC levels from 2014 to 2018. This could be an indication of improved wastewater treatments from sugar mills and a more sustainable use of farm fertilizers. However, such waste treatment and sustainability in fertilizer usage is not yet at the level that will bring the surface water body to its optimum EC level.

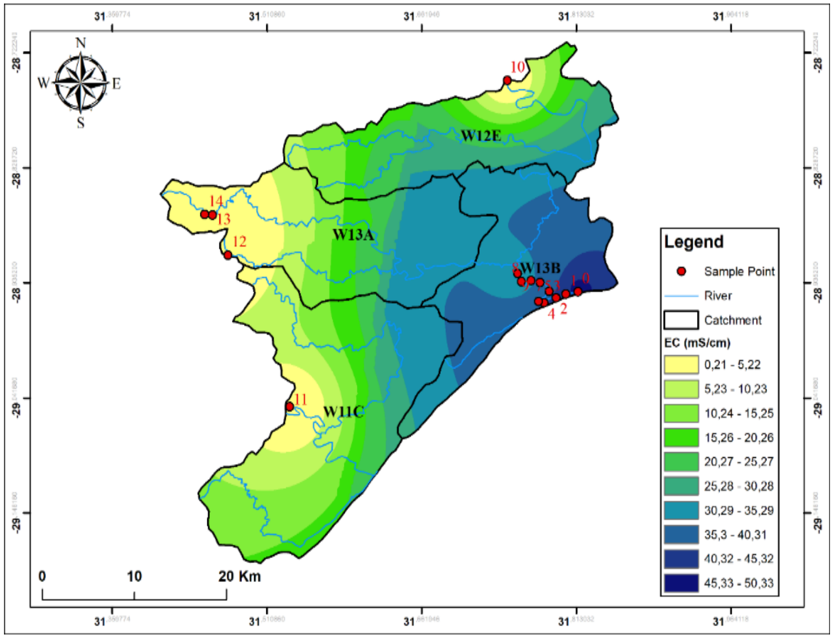


Figure 6.4a: Spatial distribution of Electrical Conductivity for surface water based on the average monthly EC values for the year 2014

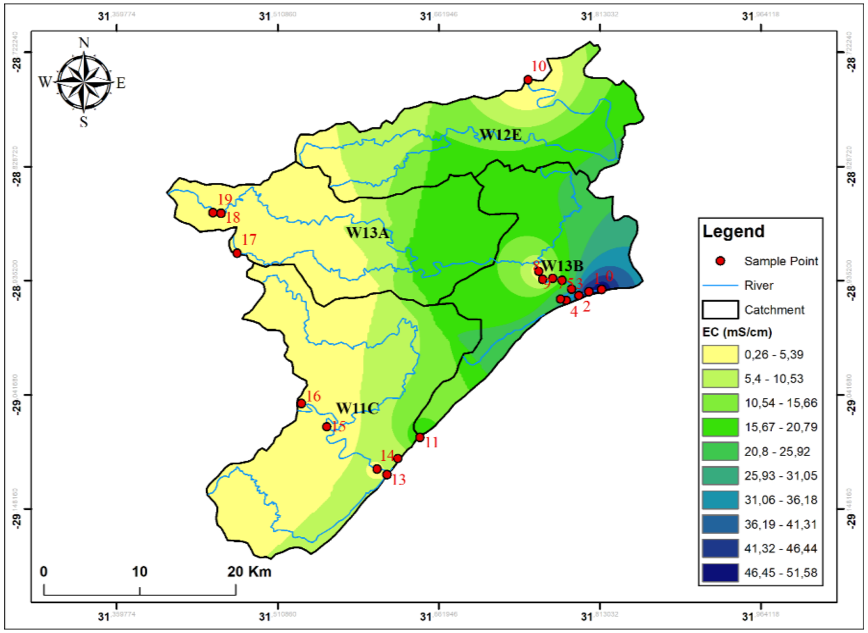


Figure 6.4b: Spatial distribution of Electrical Conductivity for surface water based on the average monthly EC values for the year 2018

High EC values for W13B are consistent with pH values observed for the area for both 2014 and 2018. The runoff could explain this water salinity from sugarcane farms and salts from seawater. Most of the readings for monitoring stations for W13B are from the Mlalazi River estuary, indicating seawater intrusion.

According to Poddar and Sahu (2017), electrical conductivity associated with salts (ions) runoff from sugar agriculture can reach up to 22.30 mS/cm. In sugarcane farming areas, contamination from cane farming practices, mainly associated with fertilizer and pesticide application, or due to the method of harvesting, all impact the total dissolved ions in the water, and therefore the electrical conductivity. According to Hess et al. (2016), manual harvesting with pre-burning increases dissolved and suspended solids in the water. In agreement with Figure 6.9 showing the location of sugarcane plantations in the uMlalazi catchment, higher values of EC above the limits in W11C and W13B correspond with the location of the farms, evidence that sugarcane farming may be responsible for excessive EC values obtained in these areas. Therefore, salts runoff from the upper regions of the catchment area could also contribute to the salinity of these catchments, especially for values above the water quality limits, which could signal significant wash-off of salts into the nearby water bodies. However, excessive values in W13B are more influenced by the sea rather than sugarcane farms. W12E has higher values even though there are fewer farming activities. This could be exacerbated by irrigation which dominates in that area.

6.4.1.3 Spatial profile of Chloride in the surface water

Chloride occurs in all types of natural waters. High chloride content in water indicates contamination attributable to the dissolution of salts, discharge of effluents from chemical industries, sewage discharges initiation drainage, contamination from refuse leachates, and seawater intrusion in a coastal area. The yearly average data recorded for chloride in surface water for the catchment areas ranged between 35.19 -160.29 mg/L for 2014 and 37.74 – 170.38 mg/L for 2018 (Figure 6.5a & b). The presented results show chloride content above the recommended limit in the catchment areas. Quaternary catchment, W13B for both 2014 and 2018, have presented the highest levels of chlorine with average levels of 77.4 mg/l and 78.3 mg/l respectively. According to the South African Water Quality Guidelines (DWAF, 1996), the target threshold for chloride in surface water is

5 mg/L. Therefore, these high values show extensive mineralisation of the water, a problem attributed to inorganic fertilizers. In the sugar industry, untreated effluents are characterised by high contents of chloride relative to treated effluents (Matkar and Gangotri, 2002; Poddar and Sahu, 2017), while using agricultural fertilizers, especially KCl, can be another significant source of chloride in freshwater. Other sources include the concentration and dissolution of salts resulting from irrigation and deep groundwater sources. The land use and landcover map presented below for 2015 (Figure 6.9) shows that sugarcane farming activities in the W11C and W13B quaternary catchments were much more pronounced than other regions in this water catchment for that year. In the 2014 profile, high chloride content is observed in W11B mostly and to some extend in W11C and W12E, could be linked with agricultural sources as the areas shown to have widespread sugarcane agriculture activities. However, the 2018 profile for W13B with the highest chlorine contents shows that this high chloride content seem to be coming from a point source around of a surrounding sugar mill (SM2) and the possibility of sea water mixing with this surface water sources.

From Figures 6.5a & b, there is a reduction in the Chlorine concentration between 2014 and 2018. This is evident from the reduction of sugarcane plantation farmland from 24161,75 ha in 2010 to 15819,68 ha in 2020 shown in chapter 4, Figures 4.13 and 4.17. As was noted before, the presence of a sugar milling company in the vicinity of the areas with high chloride content in W11C may indicate the contribution of other related sources. Wastes from milling companies are generally reused for improving the fertility of the soil. However, such wastes are also reported to have high salt content, which may be transferred into surface water when the organic fertilizers are overused in the fields (Formann et al., 2020). The presented results conclude that the high chloride content highlighted on the map may also have come from other sources.

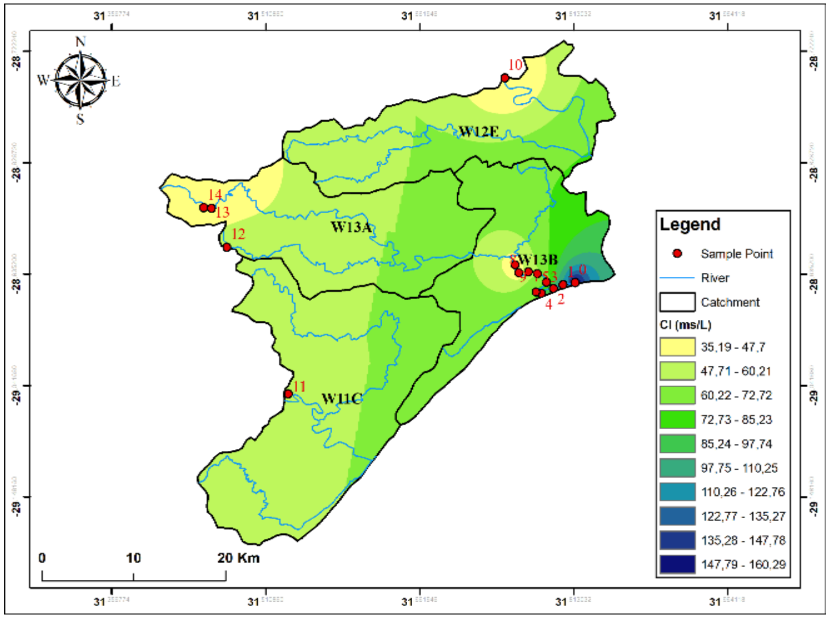


Figure 6.5a: Spatial distribution of chloride for surface water based on the average monthly Cl values for the year 2014.

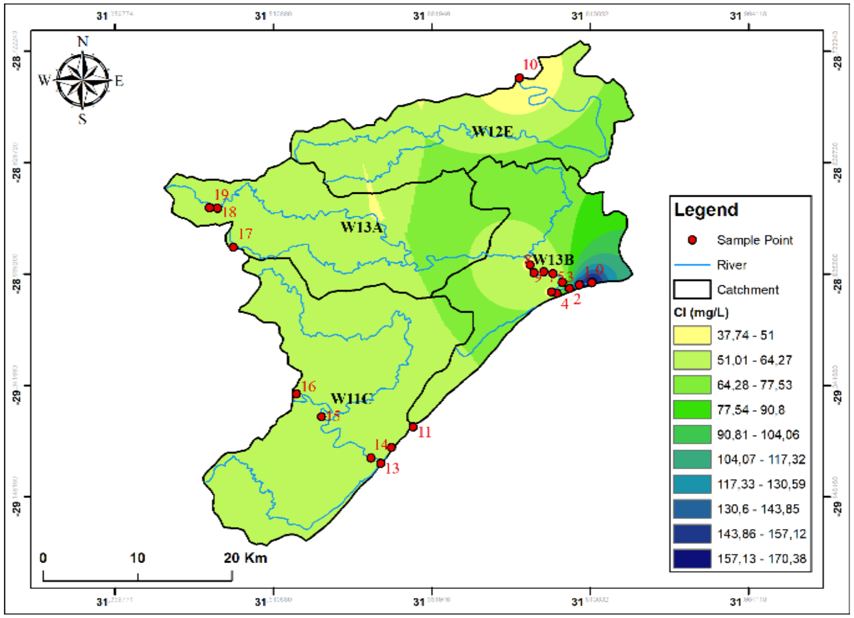


Figure 6.5b: Spatial distribution of chloride for surface water based on the average monthly Cl values for the year 2018

6.4.1.4 Spatial profile of total dissolved salts levels in the surface water

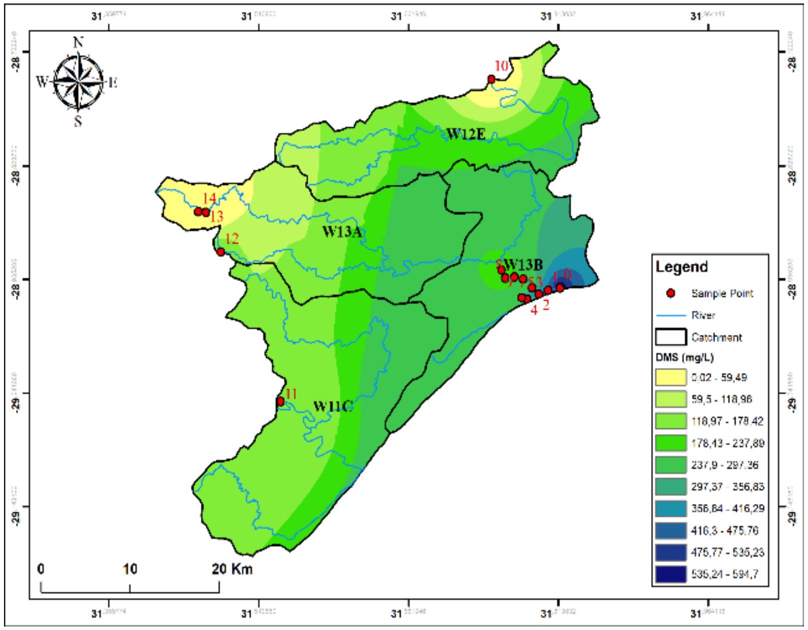
Total dissolved salts (TDS) refer to the total amount of soluble salts in water This parameter contributes to the salinity problems in aquatic ecosystems, where many forms of aquatic life are affected by its high values. With enough, salts are needed for the dehydration of the skin of animals. However, it may result in a laxative effect if consumed in large quantities. The dissolved salts release cations and anions into water. The sources of dissolved solids include hard water ions, fertilizer in agricultural runoff, urban runoff, salinity from minerals, or returned water from irrigation and acidic rainfall. The major cations contributing to salinity include Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}, and major anions are SO_4^{2-}, Cl^{-}, HCO_3^{-}, CO_3^{2-} and NO_3^{-}. These salts contribute primarily to total dissolved solids in freshwaters.

The results presented in Figure 6.6a & b represent the 2014 and 2018 dissolved major salts (TDS) or Total Dissolved Salts (TDS) respectively. For the year 2014, TDS level ranges from 0.2 mg/L in parts of W12E monitoring point 10 and W13A monitoring points 13 & 14 to 594 mg/L in W13B monitoring point 1. TDS levels for 2018 range from 134.9 mg/L in most parts of W11C and W13A with W12E monitoring point 10 to 636.17 mg/L in W13B monitoring point 1. These results agree with earlier observations of higher levels of chloride and the EC in the W13B catchments as discussed in the sections above. There has also been an increase in TDS levels between 2014 and 2018 with range 41,47 - 134.7 mg/L.

Chloride, nitrate, sulphate, potassium, and calcium ions are used in large quantities in agriculture as fertilizers. Therefore, excessive runoff of these ions into the surface water can considerably impact the value of TDS. According to DWAF (1996) the TDS standards for surface water range from 200 -1100 mg/l. The results from this study are within acceptable limits for surface water quality with respect to the dissolved mineral salt concentration.

According to the South African Water Quality Guidelines for aquatic ecosystem, TDS target for water quality range is 0-450 mg/L. Although most of the catchment area show TDS levels below the acceptable threshold, the presented results show values of TDS higher than the recommended range in over just 15 -20% of the W13B catchment area. This presents a negative impact on the aquatic ecosystem.

W13B with highest TDS values establishes a significant relationship between this parameter and sugarcane farming. The conclusion that can be drawn is that with only a few monitoring points from W13B indicating very high TDS values, the presented evidence indicates that high TDS value could only be partly due to sugarcane farming. Most of the contributing factors would therefore be caused by the flow of sea water into the catchment area. However, a study by Poddar and Sahu (2017) reporting TDS values from effluents from the sugar industry of 1650 mg/L and 1030 mg/L for untreated and treated effluents of the sugarcane industry show that while the farming practice might not contribute to the TDS, the milling process could be a significant player. The profile might support this in Figure 6.6, which points to two distinct TDS sources in W11C.



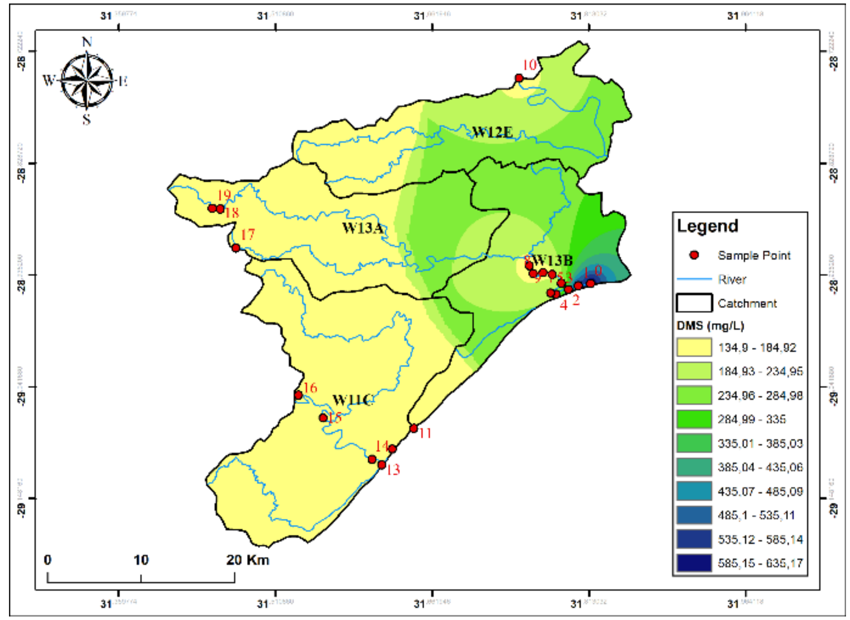


Figure 6.6a: Spatial distribution of TDS for surface water based on the average monthly TDS values for the year 2014.

Figure 6.6b: Spatial distribution of TDS for surface water based on the average monthly TDS values for the year 2018.

6.4.1.5 Spatial profile of total alkalinity in the surface water

Alkalinity measures water's capacity to neutralize acids and reflects its inherent resistance to pH change. This resistance is called buffer capacity. Poorly buffered water will have low or very low alkalinity and be susceptible to pH reduction (EPA, 2001). According to Omer (2019), the buffering capacity, particularly for protecting aquatic life, must be at least 20 mg/L $CaCO_3$. Figure 6.7a & b shows the spatial distribution of surface water's total alkaline (TALK) levels in the studied catchments for 2014 and 2018.

The average TALK values for 2014 from the results range from 19.15 to 148.26/L (Figure 6.7a) while values in 2018 range from 11.84 – 159.64. Corresponding with other parameters studied, this shows a slight increase in the TALK value from 2014 to 2018.

According to DWAF (1996) TALK standards for surface water range between 20 – 175 mg/l. Therefore, the alkalinity values for the study catchments are within acceptable levels for aquatic life. However, as highlighted earlier with other parameters, the total alkalinity shown in the profile for both 2014 and 2018 does not provide enough evidence to point to sugarcane farming as the primary contributor to the high values reported. Regions showing elevated total alkalinity values in the catchments are not corresponding with areas of extensive sugarcane agriculture.

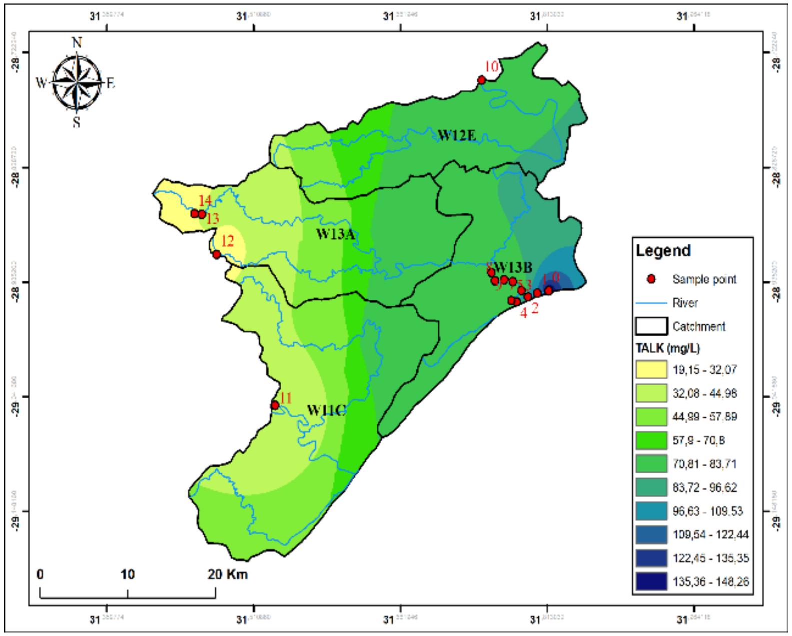


Figure 6.7a: Spatial distribution of TALK for surface water based on the average monthly TALK values for the year 2014.

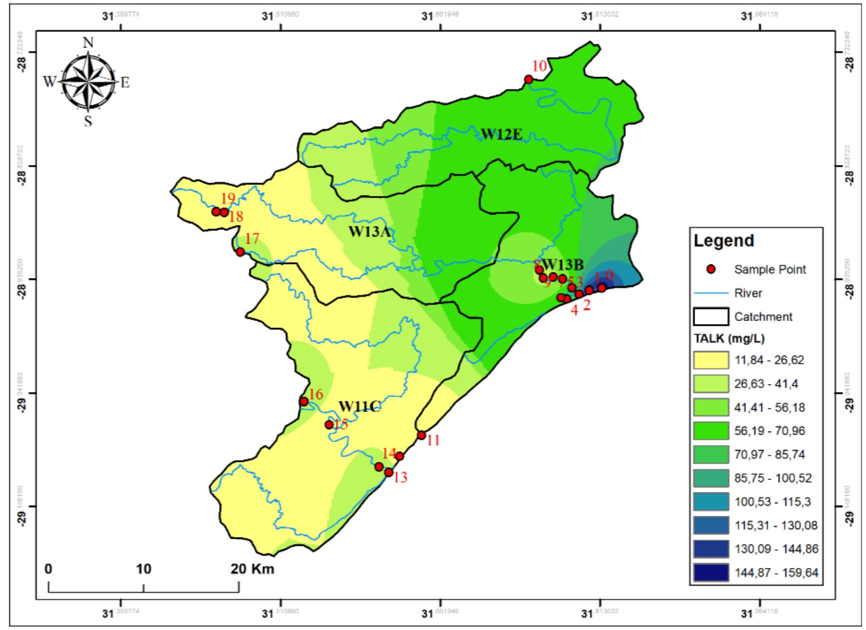


Figure 6.7b: Spatial distribution of TALK for surface water based on the average monthly TALK values for the year 2018

6.4.1.6 Spatial profile of total hardness levels in the surface water

Hardness is a term used to express the property of highly mineralised water, with calcium and magnesium being the main constituents of water hardness (Omer, 2019). According to the South African Water Quality Guidelines (Department of Water and Sanitation, 1996), total hardness is the sum of the calcium and magnesium concentrations, expressed as mg/L of calcium carbonate. Calcium is used in agriculture as a fertilizer for soil pH control. While magnesium is not a significant nutrient and not added in large amounts as fertilizers, it is a trace element in some fertilizers. The spatial profile for the total hardness of surface water showed a similar profile related to other ions.

The results for the total hardness (TH) of water usually vary and range from 0-1 00 mg/L $CaCO_3$ (Department of Water and Sanitation, 1996). According to the Environmental Protection Agency (EPA, 2011) water with hardness less than 61 mg/L is soft; while 61-120 mg/L is moderately hard; 121-180 mg/L, hard; and more than 180 mg/L is very hard very hard for human use. However, freshwater hardness rarely exits 100mg/l (South African DWAF, 1996). On the other hand, according to the South African Water Quality Guidelines, water with hardness exceeding 300 mg/L of $CaCO_3$ is very hard, whereas hardness less than 50 mg/L $CaCO_3$ is considered soft (Department of Water and Sanitation, 1996). From a health viewpoint, hardness up to 500 mg/L $CaCO_3$ is deemed safe to consume, but more than that may cause a laxative effect (Omer, 2019). Therefore, the South African Water Quality Guidelines recommend that total hardness be limited to between 50-100 mg/L $CaCO_3$ (Department of Water and Sanitation, 1996) and the recommended surface water hardness according to DWAF (1996) ranges between 20 – 100 mg/l $CaCO_3$. Based on the South African Water Quality and DWAF (1996) guidelines provided above, most of the water in the studied catchments fall within the acceptable range of water hardness for both aquatic ecosystems and domestic use. Some sections within W13B for both years, show a profiled total water hardness of more than 200 mg/ L $CaCO_3$.

The 2014 profile shows a TH range of 34.58 – 222.54 mg/L and between 48.99 – 237.33 mg/L for 2018. Corresponding with the other parameters studied, this shows a gradual increase in water hardness over the years. Extended profiles showing high values of total hardness in areas with significant sugarcane agriculture could point to some contribution of sugarcane farming to total hardness. Profiles in quaternary catchment W13B point to additional factors influencing total hardness, most likely coming from effluents from industrial processes from the sugar mill, SM1 and SM2 (Figure 6.9) and the flow of sea water into the catchment area.

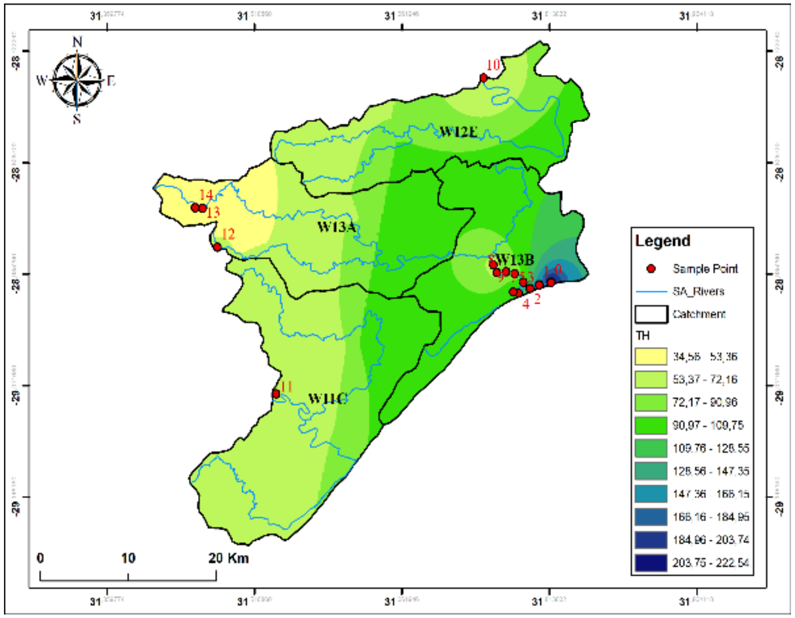


Figure 6.8a: Spatial distribution of TH for surface water based on the average monthly TH values for the year 2014

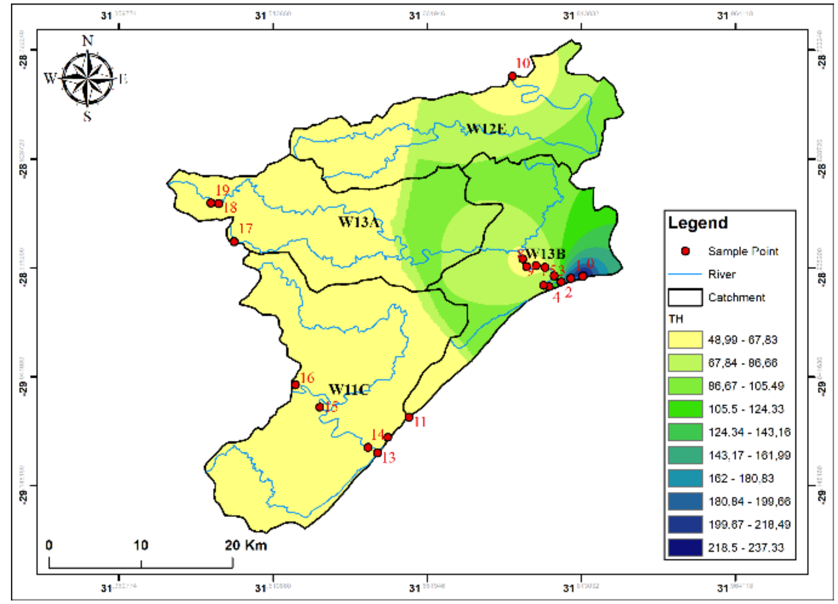


Figure 6.8b: Spatial distribution of TH for surface water based on the average monthly TH values for the year 2018

In summary, land-use profile derived for this region presented in Figure 6.9 below seems to reinforce the results presented in this section which represent the water quality profiles for the various catchments for 2014 and 2018 respectively. The area around Dlinza Forest Reserve has a significant concentration of sugarcane plantations and much of the quaternary catchments W11C and W13B. While large portions of W12E and W13A do not appear to show much sugarcane farming activities, the water pH and the general water quality is affected by movements of nutrients rich effluents from the surrounding sugar factory which diffuses in the surrounding water bodies.

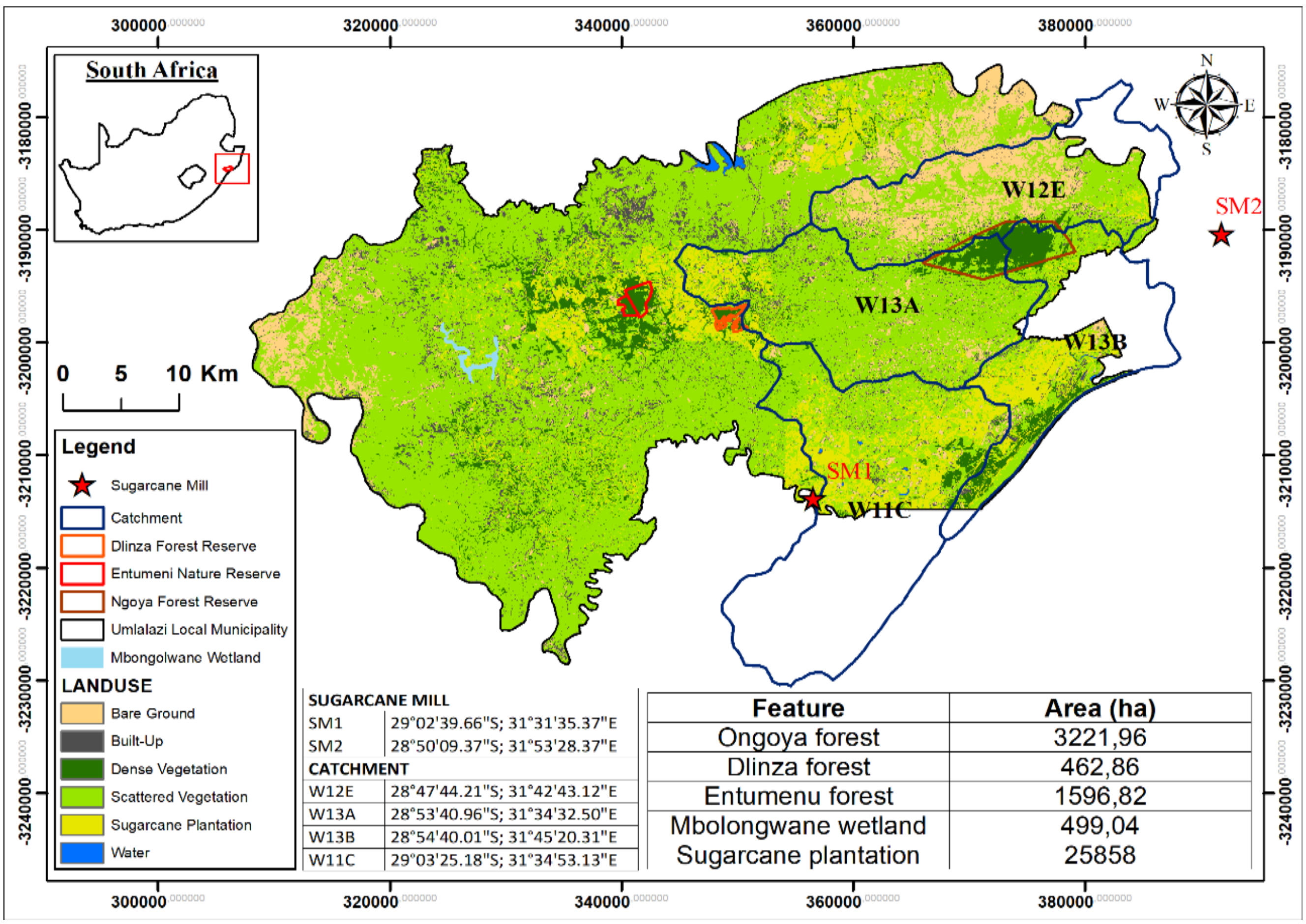


Figure 6.9: uMlalazi sugarcane farm distribution in water catchment areas W12E, W13A, W13B, and W11C in 2015

6.4.2. Comparing the water Quality Index (WQI) for the uMlalazi Surface water in 2014 and 2018.

Due to the complexity of analysing many measured water quality parameters, a method that reduces the multivariate nature of water quality data is used. This method introduces an index that mathematically computes the results of all analysed water quality parameters and provides a general and readily understood description of the water quality (Pius et al., 2012). WQI is, thus, very useful and efficient in assessing the quality of water and communicating the results on overall water quality (Kawo and Karuppannan, 2018). This technique has been applied successfully in determining water quality for various purposes (Kawo and Karuppannan, 2018; Verma et al., 2020).

In formulating WQI, the relative importance of various water quality parameters depends on the intended use of the water. The parameters to consider for the formulation of WQI may depend on the intended use and the number of analysed parameters. In this study, both the intended use and the number of analysed parameters were triggered by the availability of such data seeing that the data used was secondary. In the studied quaternary catchments, 6 surface water's parameters were considered.

To compute WQI, assigning weight for each surface water parameter (W_i) and computing relative weight (RW) with a quality rating scale (Q_i) is of great significance (Kawo and Karuppannan, 2018). Weighted values (W_i) are assigned according to the relative significance of individual parameters for water quality. This is done on a scale of 1 to 5 (Kawo and Karuppannan, 2018; Verma et al., 2020). In this study, weighted values of 4 and 5 were assigned to pH, TDS, and EC, respectively. The following equation was used to compute the relative weight (RW) of individual parameters (Table 6.2) (Kawo and Karuppannan, 2018; Verma et al., 2020)

$$RW_i = \frac{W_i}{\sum_{i=1}^{n} W_i} \qquad \text{(Equation 1)}$$

Where W_i is the assigned weight depending on the relative importance of the parameter in water quality, and n is the number of parameters considered for the WQI analysis.

Table 6.2: Weights and relative weights, including recommended range and limit for the respective water quality parameters from DWAF (1996) surface water quality standard in mg/l.

Parameter	Weight	Relative Weight	DWAF Standard
pH	4	0,200	6.5 – 9
Cl	3	0,150	5
TDS	4	0,200	200
EC (mS/cm)	5	0,250	30
Hardness	2	0,100	100
Alkalinity	2	0,100	175,00
TOTAL	**20**	**1,000**	

The quality rating scale (Qi) for each parameter (Table 6.3 a & b) was computed using an analysed concentration of that individual parameter (C_i) and water quality standard (S_i), based on the surface water quality (DWAF, 1996). The following equation was used for the Qi computation (Kawo and Karuppannan, 2018; Verma et al., 2020):

$$Q_i = \frac{C_i}{S_i} \times 100 \qquad \text{(Equation 2)}$$

Table 6.3a: Values of water quality parameters and computed quality rating scale (Q_i) for 2014 and 2018

Lon	Lat	Drainage	Year	pH	Qi (pH)	Si (pH)	Cl	Qi (Cl)	Si (Cl)	TDS	Qi (TDS)	Si (TDS)	HARD	Qi (HARD)	Si (HARD)
31.81456	-28.9434	W13B	2014	8.2	46.5	9.3	161.0	3219	482.9	597.01	298.505	59.7	223.4	223.4	22.3
31.80268	-28.9455	W13B	2014	8.2	49.7	9.9	113.7	2274.6	341.2	433.07	216.535	43.3	161.8	161.8	16.2
31.79304	-28.9491	W13B	2014	8.2	49.8	10.0	105.8	2116.6	317.5	404.76	202.38	40.5	151.2	151.2	15.1
31.78657	-28.943	W13B	2014	8.1	45.5	9.1	61.0	1219	182.9	240.41	120.205	24.0	88.4	88.4	8.8
31.78128	-28.9537	W13B	2014	8.1	45.5	9.1	89.1	1782.8	267.4	340.45	170.225	34.0	127.3	127.3	12.7
31.7775	-28.9348	W13B	2014	8.0	38.7	7.7	56.9	1137	170.6	216.77	108.385	21.7	74.8	74.8	7.5
31.776	-28.9525	W13B	2014	8.2	49.5	9.9	61.0	1219.2	182.9	243.65	121.825	24.4	89.8	89.8	9.0
31.76875	-28.9331	W13B	2014	7.9	34.4	6.9	57.9	1157	173.6	241.32	120.66	24.1	80.9	80.9	8.1
31.75934	-28.934	W13B	2014	7.7	27.6	5.5	36.2	723.6	108.5	195.67	97.835	19.6	64.2	64.2	6.4
31.75579	-28.9267	W13B	2014	7.6	25.9	5.2	34.9	698.4	104.8	189.58	94.79	19.0	64.1	64.1	6.4
31.74583	-28.7478	W12E	2014	8.2	47.9	9.6	35.8	716.8	107.5		0	0.0	52.9	52.9	5.3
31.53306	-29.0496	W11C	2014	7.6	23.1	4.6	53.1	1062.4	159.4	155.77	77.885	15.6	55.8	55.8	5.6
31.47278	-28.9094	W13A	2014	6.8	-7.5	-1.5	54.8	1095.8	164.4	152.53	76.265	15.3	55.0	55.0	5.5
31.4575	-28.8725	W13A	2014	7.8	32.1	6.4	39.9	797.2	119.6		0	0.0	46.9	46.9	4.7
31.45	-28.8719	W13A	2014	7.3	10.1	2.0	45.7	914.2	137.1		0	0.0	34.5	34.5	3.4

Lon	Lat	Drainage	Year	pH	Qi (pH)	Si (pH)	Cl	Qi (Cl)	Si (Cl)	TDS	Qi (TDS)	Si (TDS)	HARD	Qi (HARD)	Si (HARD)
31.81456	-28.9434	W13B	2018	8.2	49.7	9.9	170.9	3418.6	512.8	637.2	318.6	63.7	238.1	238.1	23.8
31.80268	-28.9455	W13B	2018	8.2	47.8	9.6	159.8	3196.8	479.5	594.8	297.4	59.5	222.5	222.5	22.2
31.79304	-28.9491	W13B	2018	8.1	43.5	8.7	113.0	2260.8	339.1	422.5	211.3	42.3	158.4	158.4	15.8
31.78657	-28.943	W13B	2018	8.1	45.0	9.0	38.7	774.2	116.1	167.9	84.0	16.8	60.0	60.0	6.0
31.78128	-28.9537	W13B	2018	8.2	47.4	9.5	68.6	1372.2	205.8	269.5	134.7	26.9	99.9	99.9	10.0
31.7775	-28.9348	W13B	2018	8.0	38.4	7.7	42.8	855.8	128.4	162.9	81.5	16.3	58.7	58.7	5.9
31.776	-28.9525	W13B	2018	7.9	36.8	7.4	37.6	751.8	112.8	166.3	83.2	16.6	59.6	59.6	6.0
31.76875	-28.9331	W13B	2018	7.6	24.6	4.9	53.7	1074.0	161.1	154.2	77.1	15.4	55.5	55.5	5.6
31.75934	-28.934	W13B	2018	8.1	44.7	8.9	51.9	1037.4	155.6	156.4	78.2	15.6	56.3	56.3	5.6
31.75579	-28.9267	W13B	2018	8.5	61.1	12.2	46.9	937.4	140.6	160.9	80.5	16.1	57.9	57.9	5.8
31.74583	-28.7478	W12E	2018	8.2	46.0	9.2	39.8	795.0	119.3	174.2	87.1	17.4	49.0	49.0	4.9
31.64439	-29.0812	W11C	2018	7.6	22.2	4.4	58.5	1170.0	175.5	134.9	67.4	13.5	51.6	51.6	5.2
31.6237	-29.1012	W11C	2018	7.2	9.5	1.9	56.6	1131.0	169.7	148.6	74.3	14.9	54.2	54.2	5.4
31.61318	-29.116	W11C	2018	7.2	9.4	1.9	54.7	1094.6	164.2	152.6	76.3	15.3	55.0	55.0	5.5
31.60407	-29.1108	W11C	2018	7.3	12.6	2.5	54.3	1085.8	162.9	153.4	76.7	15.3	55.3	55.3	5.5
31.55685	-29.0717	W11C	2018	6.4	-25.4	-5.1	57.8	1156.8	173.5	146.0	73.0	14.6	53.5	53.5	5.4
31.53306	-29.0496	W11C	2018	7.2	8.0	1.6	53.6	1071.8	160.8	154.9	77.5	15.5	55.6	55.6	5.6
31.47278	-28.9094	W13A	2018	7.0	-1.8	-0.4	54.2	1084.6	162.7	153.7	76.8	15.4	55.3	55.3	5.5
31.4575	-28.8725	W13A	2018	7.8	32.0	6.4	52.9	1058.2	158.7	156.0	78.0	15.6	53.9	53.9	5.4
31.45	-28.8719	W13A	2018	7.9	34.7	6.9	62.3	1245.0	186.8	139.4	69.7	13.9	50.0	50.0	5.0

Table 6.3b: Values of other water quality parameters and computed quality rating scale (Q_i) for 2014 and 2018 and the overall WQI for all monitoring points

Lon	Lat	Drainage	Year	Alkalinity	Qi (Alkalinity)	Si (Alkalinity)	EC	Qi (EC)	Si (EC)	WQI	Water Quality
31.81456	-28.9434	W13B	2014	148.8	85.0	8.5	50.4	5.0	1.3	582.7	UW
31.80268	-28.9455	W13B	2014	111.2	63.5	6.4	44.2	4.4	1.1	417.0	UW
31.79304	-28.9491	W13B	2014	104.4	59.7	6.0	43.2	4.3	1.1	389.0	UW
31.78657	-28.943	W13B	2014	66.1	37.7	3.8	37.0	3.7	0.9	228.6	VPW
31.78128	-28.9537	W13B	2014	87.6	50.1	5.0	41.1	4.1	1.0	328.3	VPW
31.7775	-28.9348	W13B	2014	65.4	37.3	3.7	36.1	3.6	0.9	211.2	VPW
31.776	-28.9525	W13B	2014	67.3	38.5	3.8	36.5	3.7	0.9	230.0	VPW
31.76875	-28.9331	W13B	2014	81.5	46.6	4.7	34.6	3.5	0.9	217.3	VPW
31.75934	-28.934	W13B	2014	78.2	44.7	4.5	32.0	3.2	0.8	144.5	PW
31.75579	-28.9267	W13B	2014	72.8	41.6	4.2	31.0	3.1	0.8	139.5	PW
31.74583	-28.7478	W12E	2014	72.7	41.6	4.2	0.3	0.0	0.0	126.6	PW
31.53306	-29.0496	W11C	2014	32.3	18.4	1.8	0.4	0.0	0.0	187.0	PW
31.47278	-28.9094	W13A	2014	28.4	16.2	1.6	0.6	0.1	0.0	185.2	PW
31.4575	-28.8725	W13A	2014	40.7	23.2	2.3	0.2	0.0	0.0	133.0	PW
31.45	-28.8719	W13A	2014	19.0	10.8	1.1	0.2	0.0	0.0	143.7	PW

Lon	Lat	Drainage	Year	ALKALINITY	Qi (Alkalinity)	Si (Alkalinity)	EC	Qi (EC)	Si (EC)	WQI	
31.81456	-28.9434	W13B	2018	160.1	91.5	9.2	51.7	5.2	1.3	619.4	UW
31.80268	-28.9455	W13B	2018	148.9	85.1	8.5	50.3	5.0	1.3	579.3	UW
31.79304	-28.9491	W13B	2018	105.7	60.4	6.0	44.3	4.4	1.1	412.0	UW
31.78657	-28.943	W13B	2018	52.2	29.8	3.0	20.0	2.0	0.5	150.9	PW
31.78128	-28.9537	W13B	2018	72.4	41.4	4.1	38.0	3.8	1.0	256.4	VPW
31.7775	-28.9348	W13B	2018	44.9	25.7	2.6	16.9	1.7	0.4	160.8	PW
31.776	-28.9525	W13B	2018	52.0	29.7	3.0	22.0	2.2	0.6	145.7	PW
31.76875	-28.9331	W13B	2018	30.4	17.4	1.7	6.7	0.7	0.2	188.7	PW
31.75934	-28.934	W13B	2018	33.3	19.0	1.9	3.0	0.3	0.1	187.7	PW
31.75579	-28.9267	W13B	2018	40.2	23.0	2.3	1.5	0.2	0.0	177.0	PW
31.74583	-28.7478	W12E	2018	58.2	33.3	3.3	0.3	0.0	0.0	154.1	PW
31.64439	-29.0812	W11C	2018	11.8	6.8	0.7	19.6	2.0	0.5	199.3	PW
31.6237	-29.1012	W11C	2018	23.9	13.6	1.4	8.6	0.9	0.2	193.2	PW
31.61318	-29.116	W11C	2018	28.5	16.3	1.6	5.2	0.5	0.1	188.5	PW
31.60407	-29.1108	W11C	2018	29.5	16.8	1.7	4.9	0.5	0.1	187.9	PW
31.55685	-29.0717	W11C	2018	20.8	11.9	1.2	0.5	0.0	0.0	189.6	PW
31.53306	-29.0496	W11C	2018	31.3	17.9	1.8	0.3	0.0	0.0	185.2	PW
31.47278	-28.9094	W13A	2018	29.7	17.0	1.7	0.6	0.1	0.0	184.9	PW
31.4575	-28.8725	W13A	2018	23.1	13.2	1.3	0.3	0.0	0.0	187.4	PW
31.45	-28.8719	W13A	2018	15.0	8.6	0.9	0.3	0.0	0.0	213.5	VPW

Consequently, WQI was computed using Q_i and RW_i as shown in the following equation (Silva et al., 2008; Yesilnacar and Kadiragagil, 2013; Kawo and Karuppannan, 2018; Verma et al., 2019):

$$WQI = \sum_{i=1}^{n} Q_i \times RW_i \qquad \text{(Equation 3)}$$

A comparison was made between the computed WQI values of the surface water samples (Table 6.3b) and a range of WQI classes (Kawo and Karuppannan, 2018) in Table 6.4 to determine the water quality type of the samples.

Table 6.4: Range of WQI and type of water (Kawo and Karuppannan, 2018).

Range	Type of water
<50	Excellent water (EW)
50-100	Good water (GW)
100-200	Poor water (PW)
200-300	Very poor water (VPW)
>300	Unsuitable water (UW)

The spatial distribution maps below (Figure 6.10 a and b) show the overall water quality for the surface water in the studied catchments for 2014 and 2018 respectively. Based on all 6 water quality parameters, the uMlalazi water catchment has presented Unsuitable water, very poor water and poor to good water quality.

In the 2014 scenario, 20 % of the study area has unsuitable water conditions, 33 % shows and very poor water quality. Both scenarios are evident in the W13B catchment. However other parts of the study area in 2014 present poor to good water qualities (Figure 6.10a).

The 2018 scenario on the other hand has shown similar results with, 15 % of the study area has unsuitable water conditions, 10 % shows and very poor water quality. Both scenarios are evident in the W13B catchment. The other parts of the study area in 2018 present poor to good water qualities making up for 75 % (Figure 6.10b).

This poor to good water quality is observed chiefly in large portions of W11C11, W13A12, 13 7 14 with very few parts from W12E and W13B 8 & 9Similarly, this difference in water quality in the quaternary catchments can be associated to the presence of most sugarcane activities in quaternary catchments W13B.

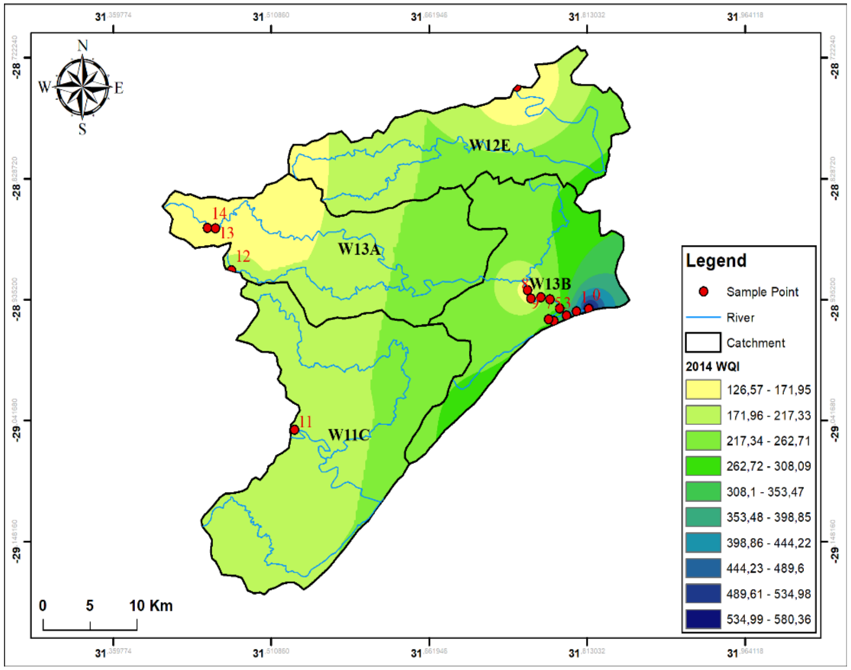


Figure 6.10a: Spatial distribution WQI for surface water for the year 2014 for the uMlalazi water catchment area.

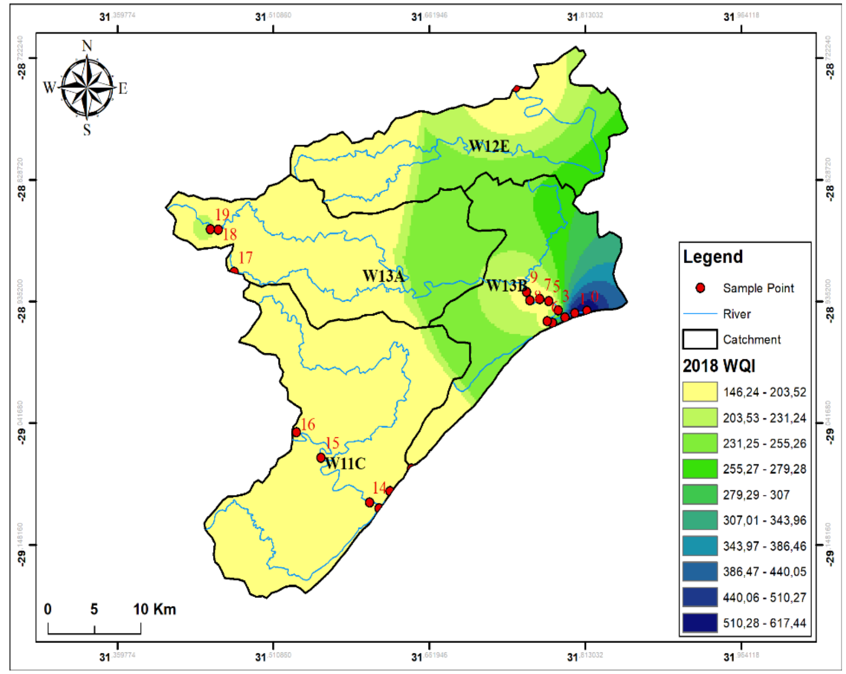


Figure 6.10b: Spatial distribution WQI for surface water for the year 2018 for the uMlalazi water catchment area.

6.5 CONCLUSION

This study was carried out using water quality data from two different periods,2014 and 2018 while focusing on the same objectives. The objectives included:

- to assess the spatial variability of bio- and Physico-chemical water quality parameters of the uMlalazi quaternary catchment areas W11C, W12E, W13A, and W13B using secondary data collected by the Department of Water and Sanitation (DWS) for the period 2014 and 2018, together with the extrapolated data used in filling the existing data gaps,
- to compare the differences in the levels and concentrations of these water quality parameters between 2014 and 2018 and
- to establish a relationship between sugarcane farming and the water quality variables at crucial sites in the uMlalazi quaternary catchment areas of W11C, W12E, W13A, and W13B.

The surface water profile from the WQI for 2018 indicates more contamination compared to the 2014 profile. In the same light, the individual water quality parameters show a similar trend of deviation from the standards prescribed by DWAF (1996) for surface water.

The interpreted data for surface water quality using the 6 parameters, electrical conductivity, pH, total hardness, total alkalinity, dissolved major salts, and chloride, that were analysed showed that evidence of contribution from sugarcane farming to the degradation of surface water quality is suggested in this study to be less significant compared to other sources. The lower pH profile for the surface water in W11C for both 2014 and 2018 indicates a point source of pollution in the area. This point source releases effluents with contaminants that push the water pH below 8. In this study, a sugar milling company is suggested to be an alternative contributor to the poor water quality instead of entirely sugarcane farming. The sugarcane industry is a heavy water user for both the planting and the processing stages. Water effluents from the sugarcane industry are acidic (Vaithiyanathan & Sundaramoorthy, 2017). This critical detail may indicate a significant impact of the sugar industry in KZN, however, not from the farming itself, but rather from the processing of the sugar into various sugar products and by-products such as molasses.

At least 1–3-point sources of water pollution are identified in W13B and are responsible for spreading pollutants to other areas in the water catchment area through water diffusion. The profiles presented seem to show that significant pollutions are coming from W13B and spreading into W13A and all the way to W12E. These point sources of pollutants into W13B include the sugar mill SM2 (Figure 6.9), the ocean and the various estuaries in W13B. The water quality profile for both 2014 and 2018 are similar with 2018 showing slightly lower water quality with respect to the WQI. While sugarcane farming will contribute to surface water pollution through the leaching of fertilizers and other agrochemicals, surface water pollutant load in the uMlalazi catchment is a result of many other collective sources.

The total alkalinity for the catchments is below the recommended standards for surface water for both 1014 and 2018 with consequently increased pH levels. However, the pH was still within the acceptable standards for surface water as set (DWAF, 1996). The KZN environmental department should continuously monitor the anthropogenic activities around the water catchments area to prevent further water degradation.

6.6 RECOMMENDATIONS

- Further studies with more recent data and more water quality parameters that were missing in this current study such as Nitrates, Phosphates, ammonium, sulphates and Nitrites should be performed to further validate the result of surface water quality in the uMlalazi water catchments. These parameters such as Nitrates, Nitrites and Ammonium should be considered in such studies as these are components of artificial fertilizers and that may contribute to water pollution.
- It would help to conduct a study where both surface and groundwater data will be collected during the same periods to study the relationships between pollutant load in surface water and groundwater in relation to sugarcane agriculture.
- The spatial profiles present a generalized picture without being specific and may not separate between different farming practices. Future work may also need to look at the impact of different farming practices on surface and groundwater pollution.

- As another area for further studies, the surface water quality scenario can be compared to those of other parts of the world.

CHAPTER 7 ASSESSING WASTE GENERATION IN THE SUGAR AND BIOETHANOL INDUSTRIES IN KZN, SOUTH AFRICA

7.1 INTRODUCTION

The sugarcane industry is one of the biggest employment providers globally and has become a source of livelihood for many rural communities worldwide (IISD, 2020). This trend has been propelled by the socioeconomic benefits of sugarcane farming, which has offered employment and business opportunities for millions of people worldwide. In South Africa, this industry offers business opportunities for small-scale farmers and jobs for over half a million people (IISD, 2020). In addition, sugarcane farming for use in bioenergy production has been expanding because of a rise in demand for renewable energy sources driven by initiatives to mitigate against environmental impacts caused using fossil fuels (Ndokwana & Fore, 2018). Fossil fuels have been the cornerstone of most of our energy needs for centuries. However, the alarming depletion of reserves as energy demand increases worldwide and the respective environmental impact associated with their use has necessitated the need for sustainable alternative sources of energy, better socio-economic benefits, and more eco-friendly (Ndokwana & Fore, 2018).

One bioenergy product that has drawn much interest is bioethanol, a renewable form of energy used as a petrol substitute in the transport industry. Bioethanol is produced by converting renewable non-fossil carbon, such as plant wastes and biomass matter, into fuel (Bušić et al., 2018; Fito et al., 2018, 2019). The most common process used worldwide involves the fermentation and distillation of sugars and starch-rich crops such as sugarcane, maize, sorghum, barley, and other related crops (Ndokwana & Fore, 2018). Bioethanol production in Brazil uses sugarcane as the feedstock crop while the USA from maize. In South Africa, the initial trajectory favoured using sugarcane and sugar beet to generate bioethanol (RSA, 2007). The sugarcane farming industry is vast and established in South Africa and has been producing more than enough sugarcane to be used as bioenergy feedstock (Sishuba, 2021). However, by arguing against using food crops as feedstocks and prioritising the crops that do not need irrigation, the Department of Mineral Resources and Energy proposed sweet sorghum as the preferred crop to produce bioethanol (Department of Mineral Resources and Energy, 2020). Sweet sorghum, unlike sugarcane, doesn't require irrigation and can grow in the semi-arid soils of South Africa (Malobane et al., 2018). However, sugarcane has remained in focus for bioethanol production in South Africa. The global sugar industry faces significant survival challenges due to the enormous excess of sugar (about 800 000 t yearly) currently being exported at a loss (Sishuba, 2021). The production of bioethanol from sugarcane would help revive the SA sugarcane industry. It would allow sugar mills to diversify their product offering, making sugarcane a critical strategic economic resource. Additionally, according to Mandegari et al. (2019), the ongoing research in expanding biofuels production from sugarcane includes several alternatives such as syn-fuels, n-butanol, and jet fuels that improve market access of the biofuels make sugarcane an essential bioenergy crop.

Ethanol contains 35% oxygen, which contributes to the complete combustion of fuel, and therefore bioethanol reduces air pollution and contributes to mitigating climate change by reducing greenhouse gas emissions (Bušić et al., 2018). Furthermore, bioethanol can be used in unmodified petrol engines with current fuelling infrastructure and is easily applicable in a present-day combustion engine (Bušić et al., 2018). These desirable advantages of bioethanol over fossil fuels have increased the demand for bioethanol around the globe and in developing countries like South Africa. Globally, the world is embracing bioethanol as one of the best alternatives to fossil fuels. The United States of America (USA) and Brazil are the global leaders in terms of production and consumption of bioethanol, with the two countries accounting for 89 % of the total global production (Fargione et al., 2008; Tsiropoulos et al., 2014; Filoso et al., 2015; Ndokwana & Fore, 2018). However, while bioethanol production has been expanding in developed countries as they attempt to reduce reliance on fossil fuels, in Africa, the process has been slow because of a lack of investment and slow policy development.

According to the South African Biofuels Regulatory Framework of 2019 (Department of Mineral Resources and Energy, 2020), the government has committed to a mandatory blending of a minimum of 2% bioethanol into petrol and a minimum of 5% blending of compulsory biodiesel into mineral diesel which was supposed to be enforced in 2015. However, while the government has pushed this policy since its proposal in 2007, this sector has not sufficiently taken off and the blending mandate had also not yet been enforced (Henley & Fundira, 2020; Sishuba, 2021).

Bioenergy provides several advantages over the fossil fuels, such as environmental friendliness and biodegradability. In addition, the possibility of biofuels from various crops makes bioenergy production more suitable for local production from multiple feedstocks, especially in poor communities where it can help alleviate rural poverty (Malobane et al., 2018). The bioenergy industry in South Africa remains one of the industries that can provide many economic opportunities to many people due to the country's large sugarcane sector that could contribute to ethanol production, alongside the large petroleum liquid fuel market. This industry is still growing and will play an essential role in the following decades as the drive for decarbonizing the transport sector over the next decades gains traction.

While the future expansion of bioenergy looks very promising, the biofuels industry has many sustainability issues such as food security, land use for agriculture, management, and disposal of effluent that need to be considered (Ndokwana & Fore, 2018). The increase in demand for bioenergy products such as bioethanol will have a resultant demand increase for high feedstock production and an increase in land usage (Bezerra & Ragauskas, 2016). Both factors have an impact on biodiversity and competition with food crops, threatening food security in addition to limited economic growth. For several industries, the core principles for sustainability include renewing, reuse, and recycle, which are applied to every production step and business practice (Eggleston & Lima, 2015). The cultivation of the crops required as feedstocks for biofuels such as sugarcane is associated with many socio-economic and environmental impacts (Quinattoa et al., 2019). The farming of crops for biofuel feedstock is commonly done under intensive agronomic practices. Such practices involve the use of fertilizers and other agrochemicals, irrigation, total removal of biomass, and other related consequences (El Chami et al., 2020). Sugarcane, for instance, is a water-intensive plant and, therefore, will most likely affect the nutrient load of the soil because of leaching and accumulation into ground or surface water, especially with the crop that is irrigated (El Chami et al., 2020).

Additionally, growing such a water-intensive plant in a water-scarce country like South Africa while simultaneously trying to accommodate both food and fuel is a considerable challenge (Ndokwana & Fore, 2018). Maize is one of the main crops used on a large scale in other places for bioethanol production. However, South Africa banned its maize from the list of bioenergy crops because of its possible impact on food security since maize is a staple food in the country (Ndokwana & Fore, 2018; Rycroft, 2019).

In addition to the impacts of crop production, energy use and the management and disposal of effluent from the production of biofuels are some of the significant challenges and areas of interest for bioenergy sustainability studies (Liboni & Cezarion, 2012; Eggleston & Lima, 2015). First and foremost, the reliance on energy derived from fossil fuels in sugar and bioethanol production presents a challenging question on sustainability. According to Ndokwana and Fore (2018), coal-based electricity is the second highest operational cost after the feedstock for the bioethanol plant (Ndokwana & Fore, 2018). This high cost presents a challenge of whether producing this renewable form of energy results in a net energy gain during feedstock production and whether the GHG emissions will overall be lower than those from fossil fuels (Eggleston & Lima, 2015). According to Formann et al. (2020), there are several waste products associated with the production of sugar and bioethanol that have not been fully exploited and therefore remain a waste management problem (Formann et al., 2020). Sugarcane and bioethanol production are associated with high consumption of water at all stages of sugarcane processing in addition to large amounts of solid and liquid sugarcane residue with high potential for pollution (Alvarenga et al., 2017; Bušić et al., 2018). According to Sahu (2018), excessive amounts of organic and inorganic effluents from sugarcane production are by-products of the life cycle of bioethanol production such as straw from fields, ashes from bagasse combustion, filter cake from sugar processing, vinasse from ethanol production, or the biogenic carbon dioxide all have significant consequences to the environment (Formann et al., 2020). These waste products have a high potential for pollution and changing the physio-chemical nature of water bodies if disposed of in them. In Brazil, an industry with high pollution potential, the Brazilian sugar industry generates 320 billion litres of vinasse, 88 million tons of filter cake, and 92 million tons of bagasse, in the form of waste, annually (Holanda and Ramos, 2016). Bagasse is produced in large quantities in sugar production, making up about 30% of the plant biomass (Bezerra & Ragauskas, 2016). When bagasse is reused as a fuel in the production, the ash produced also becomes a significant challenge. The inadequate and indiscriminate disposal of sugarcane vinasse in soils and water bodies has been noted for its environmental problems (Christofoletti et al., 2013). Vinasse is rich in organic matter, has a product range between 10 and 15 litres for each litre of alcohol produced (Alvarenga et al., 2017). It has had application in fertirrigation to improve the nutritional value of the soil. However, it has also been reported to negatively impact the soil and underground water resources when employed in excess (Alvarenga et al., 2017). Some of the waste products and effluents from these green energy projects do more harm than the common good from renewable bioenergy production. According to Rycroft (2019), jatropha, one of the bioenergy crops considered for biofuels production, was dropped because of the toxicity of the seedcake that it leaves behind.

The current trends in the production of biofuels show that there are opportunities in the sugar and sugar-bioproduct industries and could strongly contribute to the sustainability of the industry itself. However, these challenges will likely keep increasing in the future with its increased adverse effects as the sector expands further (Krishna and Leelavathi 2002; Amathussalam et al. 2002; Kumar and Chopra 2014; Kumar et al. 2016). With previous studies showing some evidence of disposal of various effluents into the environment without any treatment or partial treatment by sugar mills (Kisku et al. 2000), it is worth investigating South African sugar mills' situation concerning waste generation disposal methods. In some countries such as India, the sugar industry discharged large amounts of untreated effluent into water bodies creating major pollution incidences that had adverse effects on the plants and other living organisms in the aquatic ecosystems (Vaithiyanathan & Sundaramoorthy, 2017). South Africa has various policies aimed at guiding environment protection and waste management. The President of the Republic of South Africa signed into law the Carbon Tax Act No 15 of 2019, which came into effect from 1 June 2019, as announced by the Minister of Finance in the 2019 Budget. (South African National Treasury, 2019). The Act was gazetted on 23 May 2019 (Gazette No. 42483). The carbon tax act aims to manage the emission of GHGs in a sustainable, cost-effective, and affordable manner.

Literature review has highlighted that waste generated from the sugar milling, and bioethanol industry can pollute water and land if proper management strategies are not implemented (Konti et al., 2020; Fito et al., 2019). The research questions of interest in this chapter are - what are the waste products and the amounts produced in the sugar milling and bioethanol production plants in South Africa, and what sustainable waste management practices are employed by these two industries? The objective is to analyse the sustainability practices that the two sectors have taken in the face of the increasing bioethanol demand. A case study approach was used in this study to answer the research questions of interest. In this chapter, the researcher discusses the waste generation avenues and waste management practices employed by the sugar industry, leading to more sustainable practices, or mitigating any negative impacts. The knowledge from this research will help shape the efforts needed to create public policies that will regulate its expansion.

7.2 METHODOLOGY

7.2.1 Study Site

The focus of this chapter was to assess waste management practices at a bioethanol and sugar milling plant in a coastal region in KwaZulu Natal in South Africa, that is popularly known for sugarcane farming. A case study approach was used in this study, focusing on one KwaZulu Natal-based sugar mill and one bioethanol plant. The locations of the sugar mill and the bioethanol plant are shown in Figure 7.1 below. The sugar mill is in the middle of a sugarcane farming community, which supplies the mill with sugarcane. Some farms are privately owned, while the sugar industry companies own others. The sugar mill is a privately owned entity. The bioethanol plant is also privately owned, and it is close to major rivers that empty their content into the Indian Ocean.

7.2.2 Study Scope

Activities in the sugar mill and the bioethanol plant were studied with interest paid on the waste generated along the various processes of each plant. Critical attention was paid to the waste management strategies and the possible environmental impacts of improper disposal of wastes that showed a lack of proper management strategies. The study scope was guided by the processes involved in the production of sugar and bioethanol, as highlighted in Figures 7.2. Molasses is the product of interest in the sugar plant, while ethanol is of interest in the bioethanol plant.

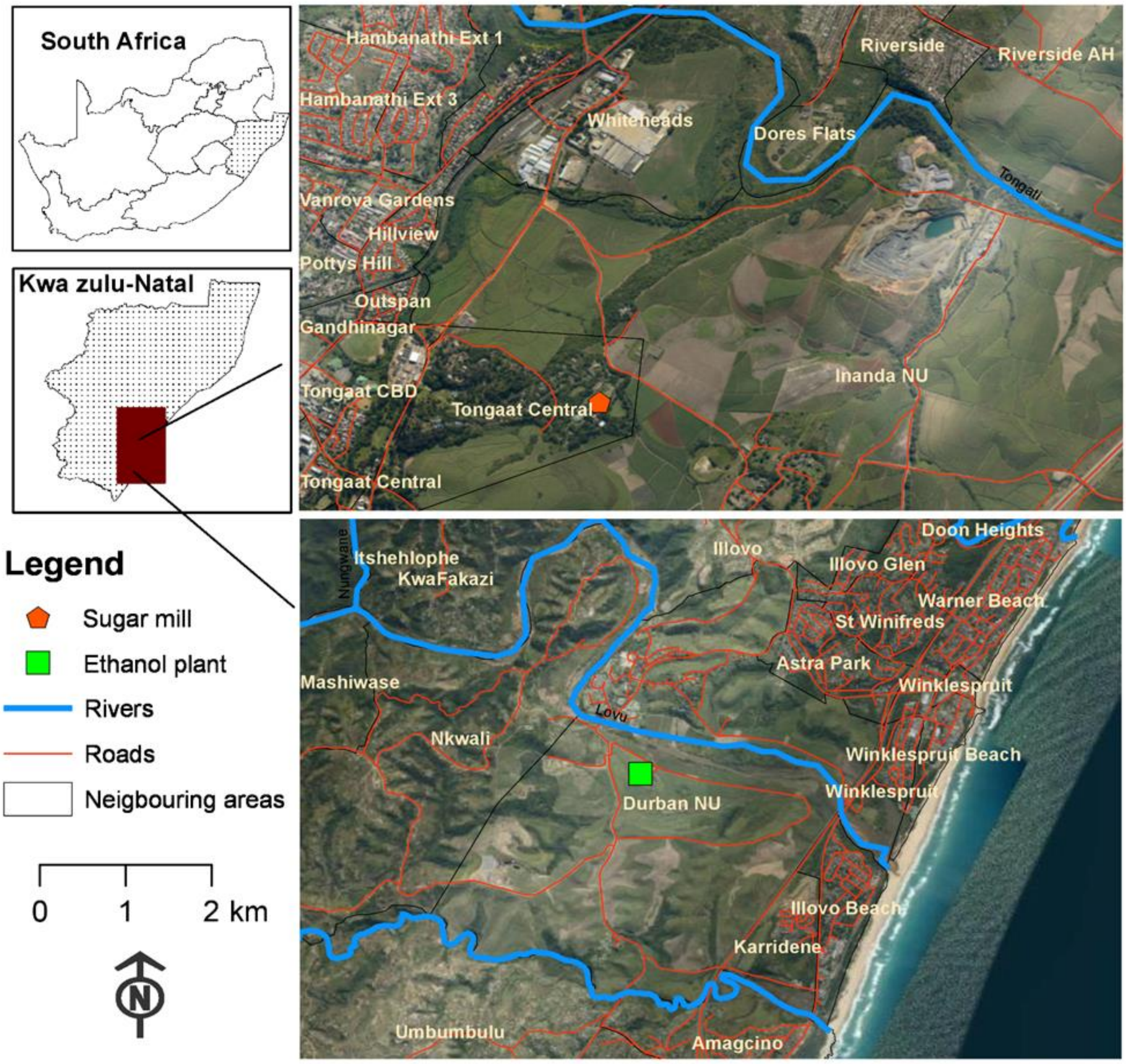


Figure 7.1: The location of the sugar plant and the bioethanol plant (highlighted in the legend) that were used for this investigation in KZN-South Africa.

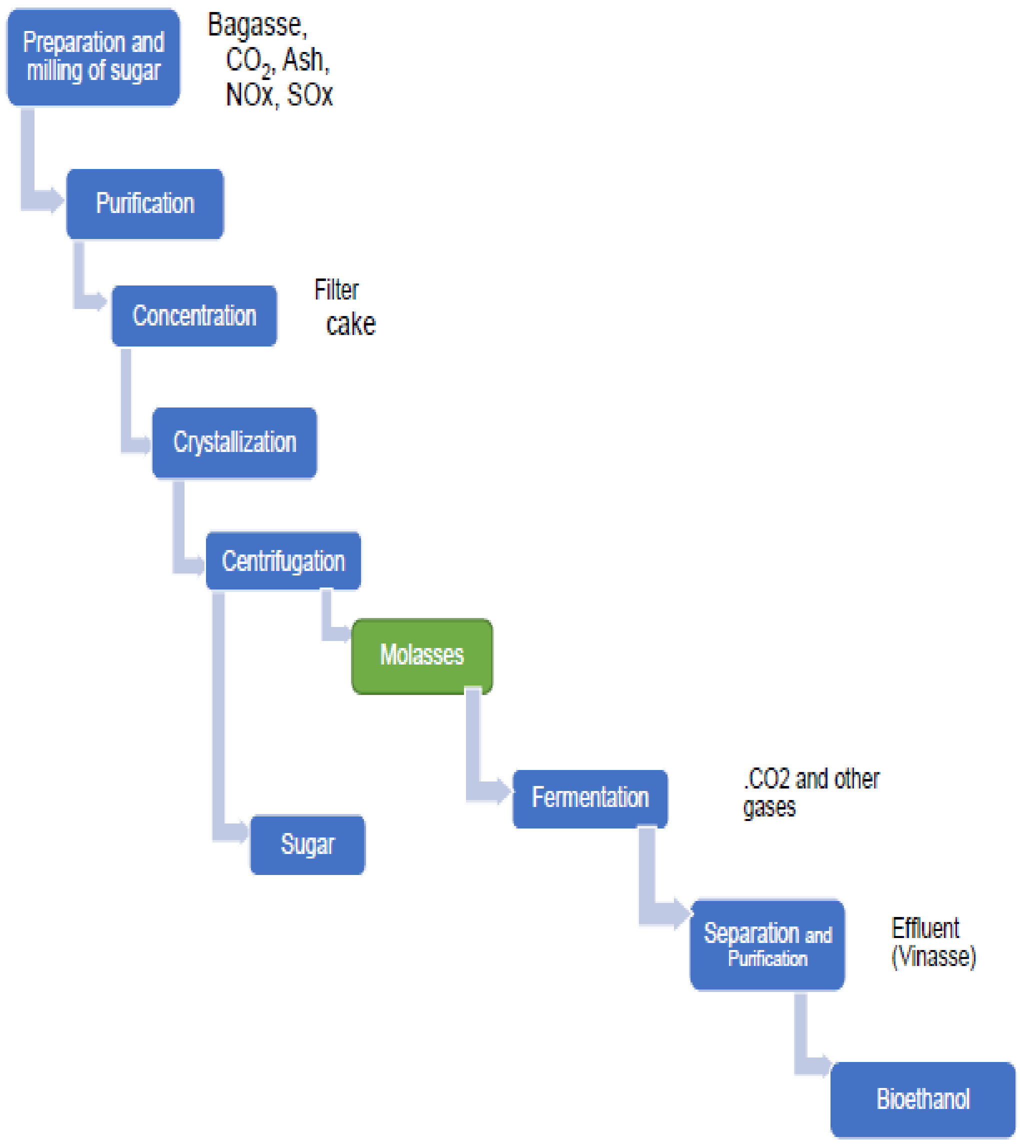


Figure 7.2: Studied system boundary, products, by-products, and wastes along the production chain of bioethanol

7.2.3 Research Methods and Data Collection Instruments

One of the sugar millings and a bioethanol producing plant, both located in KZN respectively, were used as case studies to investigate waste generation and management practices. To answer the research questions for this study, on-site observations and unstructured interviews were used as tools in collecting primary data. Interviews with the factory managers for the sugar milling and the bioethanol producing plants were used to collect data about the processes in the plants, waste generation, and waste management practices by the individual plants. Observation of the plants and the environment around the plants were performed in conjunction with the interview schedule. Document collection was used to gather information about the wastes, quantities of the wastes produced, and specific waste management practices and their impacts on running the projects. Data presented on excel sheets was collected included which composed of records with daily and monthly waste generation reports, waste re-utilisation, and waste recycling by the company. The obtained data consisted of documents on the types and the quantities of waste generated by the sugar plant for 2011 – 2019. The bioethanol plant mainly provided qualitative data, as the authorities didn't consent to the disclosure of additional data. Therefore, unstructured interviews and observation were used to collect primary qualitative data. The data obtained were analysed to generate reports on the type of waste generated and the potential environmental impacts of the generated wastes from the plants.

7.3. STUDY LIMITATIONS

Although several sugar and bioethanol plants are present in the KZN region, getting consent to collect data after seeking permission to carry out this study on their sites was a significant limitation. Only two plants accepted the request to collect data at their plants. However, one plant limited this data collection process to the observation of the plant and an interview with the manager. Employees were not allowed the opportunity to take part in the discussions. While on-site in the bioethanol plant, no photographs were permitted, and only an informal conversation with the plant manager was allowed.

7.4 RESULTS AND DISCUSSIONS

Averagely over 8 years between 2011 and 2018, the studies sugar plant has produced effluents that amounts to 310766 tons from milling an average of 100202 tons of sugarcane. Although the quantities of waste produced from the bioethanol plant were not accessible during this study, the study results revealed that vast amounts of wastes are produced by both the sugar milling and bioethanol plants. The wastes include GHGs, water effluents, and solid wastes, which were observed on the sites. Both companies are keeping track of their wastes, something that was very commendable as monitoring is critical to waste management projects. The wastes from each of the two industries are presented in the sections 7.4.1 and 7.4.2.

7.4.1 Wastes in Sugar Production

The first part of this work focused on waste production and waste management for the sugar milling processes in South Africa. The preparation and milling of sugar are responsible for the bulk of the waste produced in this process, as highlighted in Figure 7.2. During the field work, interviews and on-site observations showed that the sugar milling industries had liquid and solid waste in large quantities. The study could establish that the company continuously monitors, and records amounts of raw materials used and wastes produced and the physicochemical parameters of the waste effluents from sugar production. Table 7.1 below shows the amounts of the raw material used, the waste products produced, and some of the physicochemical parameters of interest for the waste products. In addition to the raw materials and wastes produced, data on the woodchips and coal burnt were recorded. Bagasse is used as a fuel for the processes in sugar production. Thus, the records of bagasse are vital since they represent data for carbon foot printing. It was very commendable that as much as eight years of data could be provided. Continuous monitoring is critical when it comes to investigations of environmental issues and policy development for waste management. The researcher concluded that although it is a requirement for the waste emission licence and authorisation, the company was taking environmental issues seriously as proper monitoring and recording of waste generation is very important in waste management.

The collected data from the provided information about the sugar mill and its activities show that the main by-products from production are bagasse, filter cake, molasses and ash. Gaseous pollutants such as NO_x, SO_x, CO_2, and other GHGs constitute some of the minor waste products released from the processes at this stage of sugar production. These results are highlighted in Figure 7.2. In addition, the on-site observation noted vast piles of solid waste on the outside of the plant. Part of the vast piles of solid waste was bagasse; the fibrous matter left over after producing sugar from sugarcane, which the company recycles as an energy source. By volume, bagasse is an essential by-product, produced in significantly massive amounts compared to filter cake (25-30 % vs. 3-5 % respectively) and is the primary source of fuel for the generation of steam and electricity to operate sugarcane factories

(Eggleston & Lima, 2015; Sahu, 2018). On average, 305322 tons of bagasse are produced yearly by the company (Table 7.1).

Table 7.1: The factory's inventory, as well as the yearly average data of the waste substances and other waste parameters recorded by the Sugar Milling Company - A South African Sugar producing factory's inventory from 2011 – 2019 (Sugar Factory records: 2019)

Year	2011-2012	2012-2013	2013-2014	2014-2015	2015-2016	2016-2017	2017-2018	2018-2019	8 Years Averages
Quantity of Cane Sugar (tons)	125165	132732	150648	119344	60274	30948	131154	51348	**100202**
Factory Effluent Produced (tons)	318205	351535	326518	252631	121481	221002	644619	250133	**310766**
Factory Effluent COD	5180	7980	8593	6081	11813	42354	12413	9769	**13023**
Factory Effluent pH	6.02	6.6	6.3	6.1	6.0	4.8	6.0	5.8	**6.0**
Factory Effluent Temp (ºC)	28.6	27.5	29.0	28.0	27.0	27.0	30.0	32.0	**28.6**
Bagasse (fibre) Produced	383235	387983	413477	346445	254347	67791	381541	207760	**305322**
Coal Burnt (tons)	13199	6733	10406	16261	4802	9826	12656	1475	**9420**
Wood Chips Burnt	2488	2580	3848	2685	2260	5611	4634	3011	**3390**
Filter Cake Produced (tons	79758	90145	88057	83477	41993	27411	88948	33980	**66721**
Molasses Produced (tons)	43253	44143	48915	44448	32966	19505	48824	11730	**36723**

The produced bagasse waste is burnt to provide energy for some of the processes that require energy. This practice reduces the amount of coal used, as coal is more detrimental to the environment. According to Eggleston and Lima (2015), the higher output of energy recovery from bagasse from sugarcane is one of the significant reasons sugarcanes has a higher net energy ratio and makes it a favoured crop for biofuel production. The use of bagasse as a fuel, however, produces an additional waste product, bagasse ash. Ash is discarded primarily as a soil fertilizer. According to Bezerra & Ragauskas (2016), bagasse ash can have economic value with suggested use for recycling purposes such as ceramic raw material, additive to cement, concrete, and fine aggregate in mortars because of its silica content.

The viability and sustainability of bioethanol from sugarcane are highly affected by the competition between energy provision and food security. Possibilities of using bagasse as a raw material for the second-generation biofuels may make sugarcane production of bioethanol more lucrative and sustainable as it provides a means for maximization of the utilization of the available resources (Bezerra & Ragauskas, 2016). According to Eggleston and Lima (2015), this involves converting cellulose and hemicelluloses into ethanol, a technologically more challenging prospect. However, looking at the volumes of bagasse produced during sugar production, this could be beneficial for both bioenergy production and food security. Additionally, the conversion of bagasse into valuable products is welcome since it presents storage and disposal problems for smaller companies as only a fraction of it may be used. Selling the rest of the portion that can't be used remains a viable option for these small factories, but it is dependent on the market situation and the transportation cost to the potential users (Formann et al., 2020).

Also produced by the sugar mill are filter cake and molasses. According to Sahu (2018), sugar production makes about 3-5 % of filter cake and molasses. As shown in Table 7.2, about 66700 and 36700 tons of filter cake and molasses are produced yearly as waste. While the amounts are much less compared to bagasse, results from the study showed that the two are not reused anywhere in the plant and are also not sold. The researcher could not establish the final fate of these two products. However, the amounts produced yearly bring so much concern because of possible environmental degradation if they are not correctly disposed of in the environment. The filter cake is the residue that comes from filtration and is considered one of the wastes that pose significant environmental pollution and cause many managements and final disposal issues (Formann et al., 2020). One of the common environmental issues associated with filter cake is the increase in insects and odours around industrial areas when disposed of by open dumping (Sahu, 2018). According to Sahu (2018), filter cake contains many inorganic substances such as sulphites, phosphates, trace nitrogen, phosphorous, calcium, iron, and magnesium.

Additionally, it also contains considerable amounts of organic carbon. According to Sahu (2018), the filter cake can be recycled, using it as a fertilizer, composting, and extraction of waxes and fats as some of the options. However, its use as a fertilizer or composting is reported to have significant drawbacks as it generates acid leachate and significant amounts of GHGs when it decomposes (George et al., 2010; Sahu, 2018; Formann et al., 2020). It can also be blended with bagasse and used as an energy source, another viable option considering its waste management challenge.

Molasses is generally regarded as the most valuable by-product of the sugar industry. According to Sahu (2018), molasses is mainly composed of sugars (54%), water

(20%), other carbohydrates (4%), nitrogenous compounds (4.5%), non-nitrogenous acids (5 %), ash (12%), and others (0.5%). Because of its high content of sugars, molasses is very important in producing bioethanol and therefore should not present significant waste management problems. However, this by-product exists in a range of grades such as edible molasses, cane and beet molasses, and refinery molasses, and therefore has implications on its uses. In addition to bioethanol production, molasses is used in the alcohol industry to produce rum and other alcoholic beverages, acetic acid production, chemical industry, animal feed additive, bakery yeast, and other fermentation processes (Sahu, 2018). However, storage issues may mean some molasses may find their way into the environment, causing environmental harm. In addition, molasses may contain significant amounts of heavy metals that remain after sugar extraction (Bhatti et al., 2019).

Water usage and the amount of wastewater produced from sugar processing are major concerns for a water-scarce country like South Africa. Vast amounts of effluent waste are produced, highlighting the extensive use of water resources for farming and processing stages (Sahu, 2018). The quantity of effluent produced over the years has remained steady. However, the quantities are much higher than the raw materials used, with the 2017/2018 period having a considerable amount released (Figure 7.3). The same is observed for the effluent COD, which, throughout, has remained high. Generally, critical parameters such as pH, electrical conductivity, acidity, total dissolved solids, biological oxygen demand, chemical oxygen demand, and other parameters in sugar mill effluent exceed limits for drinking water because of the processes involved (Fito et al., 2019; Rahim & Mostafa, 2021). According to Fito et al. (2019), water effluent from the sugar industry contains considerably high solids, BOD, COD, chloride, sulphate, nitrate, calcium, and magnesium. Some of these chemicals come in due to several substances like $Ca(OH)_2$, H_3PO_4, CO_2, HCl, and NaOH used in sugar industries mainly for coagulation of impurities and refining of end products (Podar & Sahu, 2017). According to South African National Standard guidelines for drinking water (SANS 241:2015), the permissible limits should be in the pH range of 5 – 9. As can be observed from Table 7.1, the pH of the effluent is generally within the acceptable range for release into the water bodies. However, values are sometimes below the acceptable range and are consistently acidic with average pH for the eight years around pH 6. Discharging of effluents with low effluent pH should be avoided as it results in the mineralisation of water bodies. Acidity in natural waters causes the dissolution of metals in the water bodies, which has large-scale environmental impacts on aquatic life (Fito et al., 2019). Unfortunately, there are no records of the other physicochemical parameters recorded by the company.

The reported effluent COD values are also exceedingly high throughout. Together with the BOD, the COD measures water and wastewater quality, providing information on the organic matter content of the wastewater. According to surface water quality standards, the reported 8-year average of 13023 mg/L for the COD is thousands of folds higher than the standard value for COD of 5 mg/L. The results show that these effluents cannot be released into the environment without treatment, which is a considerable risk for aquatic life. Suppose such effluent is discharged into a water body. In that case, this will increase the COD in that aquatic environment, impact the water pH, and most likely release a massive amount of nutrients and minerals that will negatively affect the living organisms, soil, and water quality (Fito et al., 2019).

Furthermore, it was alleged during the interviews that parts of this effluent are used for irrigation on the factory's sugarcane farms. Therefore, the nutrient and mineral components may easily seep into groundwater or runoff into surface water. Water with high values of COD and BOD can result in rapid depletion of the availability of oxygen content in the water bodies, which would endanger aquatic life. Therefore, improper management of this effluent creates severe environmental problems with far-reaching effects (Fito et al., 2019).

Additionally, improper wastewater management of this effluent is associated with the generation of foul-smelling hydrogen sulphide, which precipitates iron sulphide, making the water black and unsuitable for aquatic life and domestic uses (Fito et al., 2019). Therefore, treatment of these wastewater effluents before being discharged into the environment is very crucial to the sustainability of the sugar industry. However, despite the dangers associated with releasing these effluents, this research could not establish the management plan for effluent from the investigated sugar milling plant. According to Fito et al. (2019), proper treatment of industrial effluents is generally a problem in developing countries because of the complex nature of the waste generated coupled with the lack of the necessary technologies to deal with them.

The production of sugar and its by-products such as molasses requires a lot of energy. Figure 7.4 illustrates the amounts of coal that have been used over the years in the plant. In general, coal usage in the sugar milling plant remains the primary source of energy. Although with no direct correspondence to the amounts of sugar used, there has been a steady increase in the quantity of coal burnt in the sugar industry over the years. However, there was a drop in the years 2012 and 2018. On average, 9420 tons of coal is used annually, supplemented by 3390 tons of wood chips annually (Table 7.1). In the studied plant, coal is burnt in the sugar plant to provide energy for the plant's activities. However, this contributes significantly to the release of greenhouse gases (GHG), contributing to climate change. Woodchips, on the other hand, are used to supplement bagasse. Although it was not established from this study if this wood comes from natural forests or from plantations, the wood burning process also contributes to the release of GHG and particulate matter which impacts negatively on climate change.

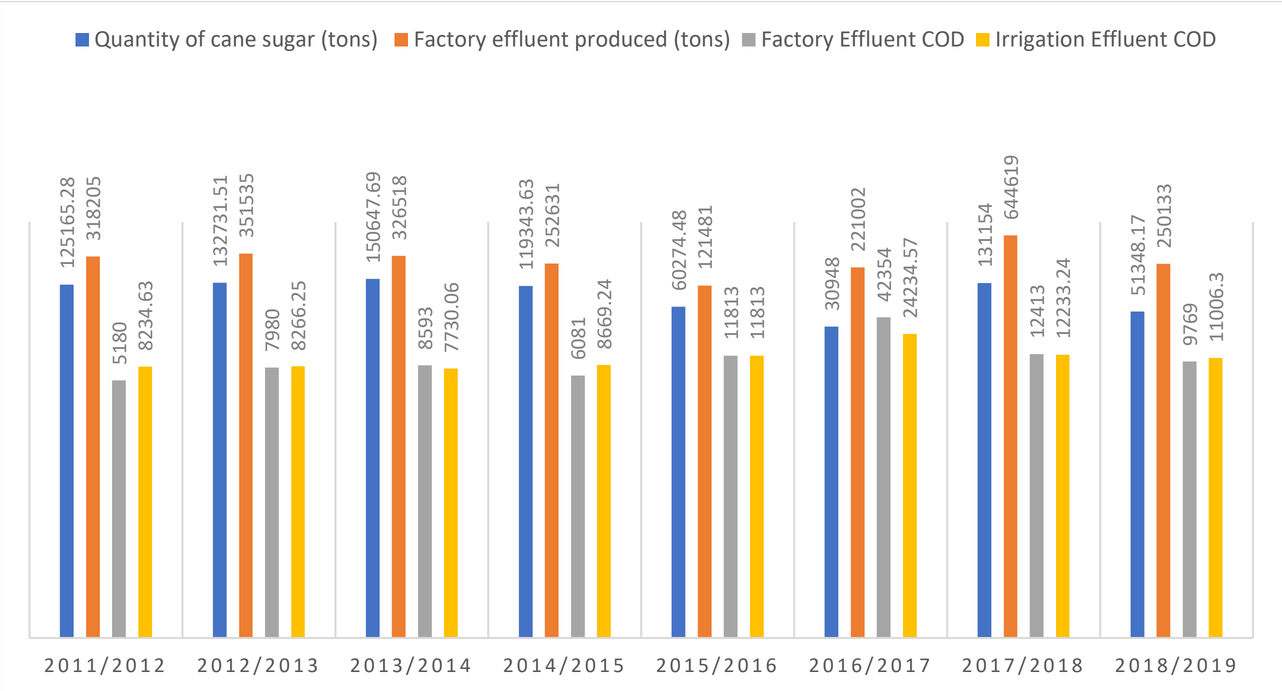


Figure 7.3: Quantity and trend of sugarcane used, factory effluent, and the COD of the effluent from 2011 – 2019 (SA Sugar factory statistics: 2019).

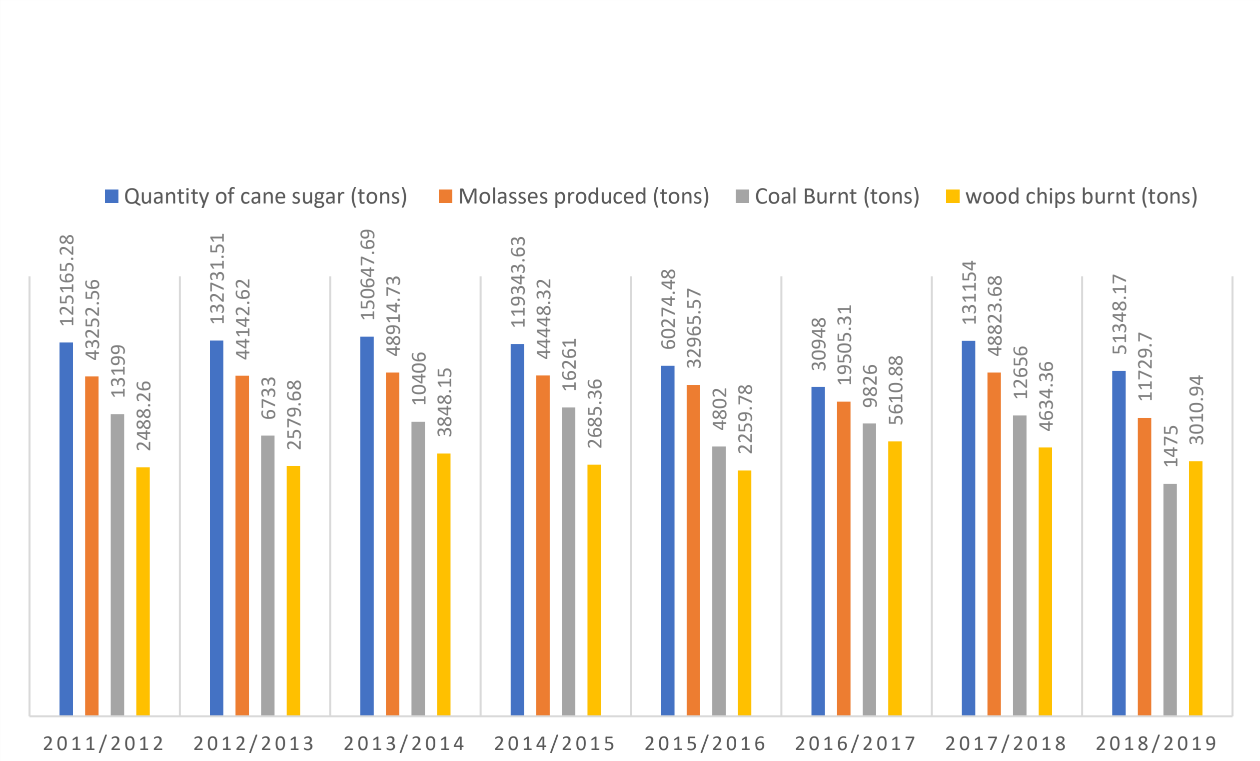


Figure 7.4: Trend of coal and wood chips burnt in sugar factory from 2011 – 2019 (SA Sugar factory statistics: 2019).

7.4.2 Waste in Bioethanol Production

The visit to the bio-ethanol production plant was limited to an interview with the manager without much secondary information obtained. Waste generation in bioethanol production is observed in various stages, as highlighted in Figures 7.2 and 7.6. The acidic waste stream is produced during the early stages known as the pre-fermentation stage. Waste forms include water effluents that have the potential for environmental impacts, if effective and best waste management approaches are lacking. If discharged in water bodies, acidic effluents alter the pH of the aquatic ecosystem, thereby affecting plant and animal life.

As shown in Figure 7.2, biogenic carbon dioxide and other GHGs are some of the by-products of the fermentation process. According to Formann et al. (2020), different amounts of carbon dioxide are released at almost all stages in the cycle of bioethanol production. Carbon dioxide is a greenhouse gas, which contributes to air pollution and climate change. While some of the stages in the whole process do not allow for the collection of the carbon dioxide produced because it is almost impossible, the fermentation stage in the production of ethanol is the stage where the collection of the gas is possible. According to Formann et al. (2020), capturing carbon dioxide can be a valuable, renewable carbon source for material applications in various industries. The authors also suggested geological storage of the biogenic carbon dioxide from the sugarcane industry with the idea of gaining carbon credits as another way of mitigating against its emission. The visited plant, however, releases carbon dioxide into the atmosphere.

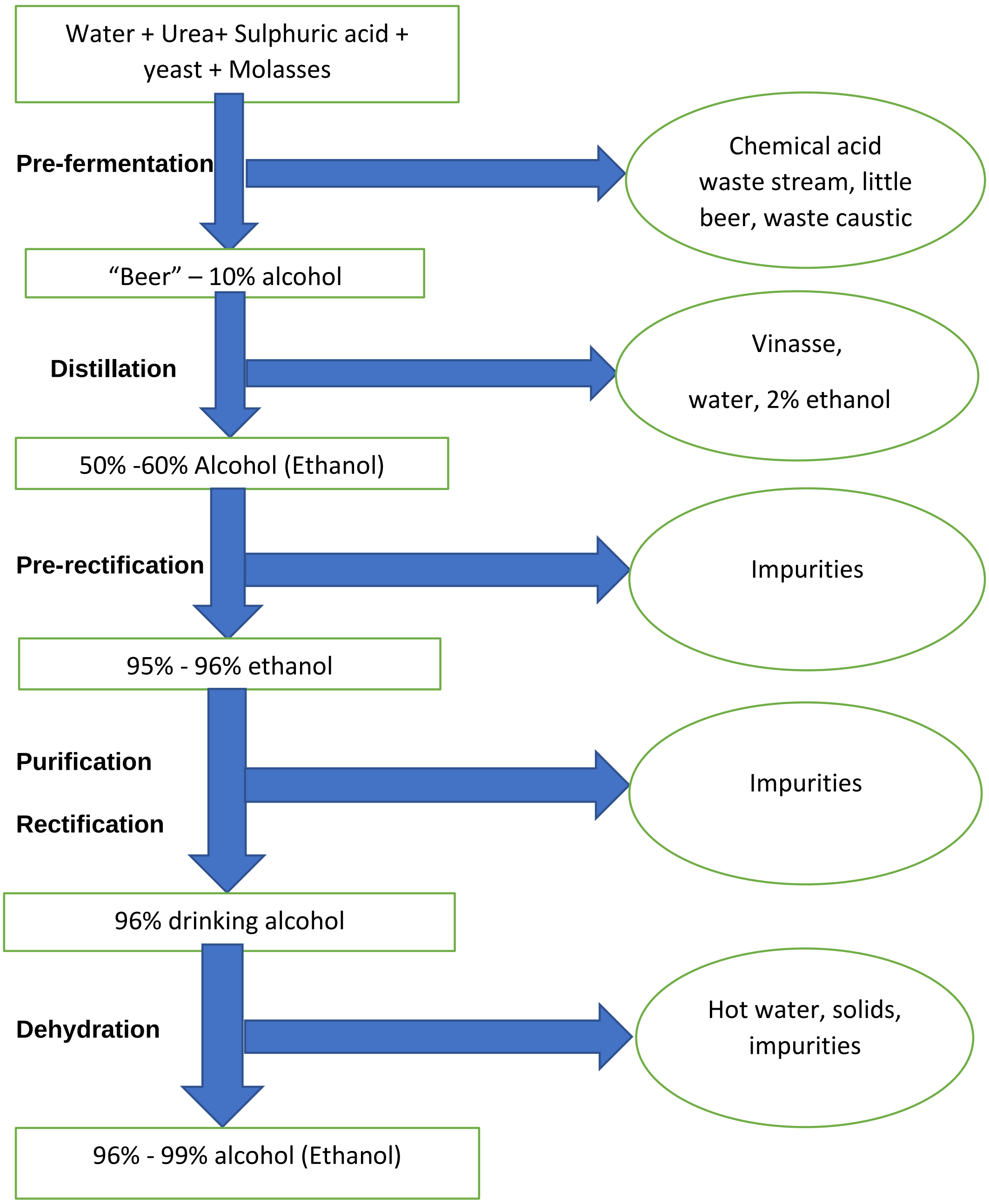


Figure 7.5: Diagrammatic representation of an informal discussion with the ethanol plant manager on the process and waste generated in the various stages of bioethanol generation

Vinasse is the final and the major by-product (at the distillation stage) of biomass distillation, mainly to produce ethanol from sugar crops and is produced in large amounts. Vinasse is the liquid fraction generated from rectification and distillation processes, as ethanol is isolated. Vinasse is sulphur-rich, with a low pH, dark-coloured, and odorous effluent produced 20 times volume-wise compared to the ethanol produced (Alvarenga et al., 2016; Reis & Hu, 2017). It also has high values of COD and BOD, with a carbon content of around 100 times more than wastewater (Bordonal et al., 2018). A study by Fito et al. (2019) shows that wastewater contains a much higher content of the physicochemical parameters discussed above. For instance, this study reported BOD and COD in 50-60,000 and 110-190,000 mg/L for ethanol distillery wastewater, while values in the ranges of pH 4-5 are recorded. The same trend is reported for the other physicochemical parameters as well. Because of the large quantities of vinasse produced at the bioethanol plant, both alternative treatments which are eco-friendlier and uses have been developed, and this includes recycling of vinasse in fermentation, fertigation, concentration by evaporation, and yeast and energy production (Christofoletti et al., 2013; Alvarenga et al., 2017; Formann et al., 2020). According to Bordonal et al. (2018), fertigation of vinasse has several agronomic benefits. These benefits include increased soil quality, improved soil inputs of C and N, reduced freshwater used in full salvage irrigation, and decreased synthetic fertilizers use. However, repeated use of vinasse in fertigation is also suggested to impact the soil quality negatively. Fertigation is believed to contribute to salinisation and the accumulation of minerals in the soil. These accumulated minerals may cause soil over-fertilization, groundwater soil acidification, leaching, and groundwater acidification. Therefore, causing soil and water contamination, among others (Bordonal et al., 2018).

Vinasse is also associated with other environmental impacts related to GHG emissions. The storage of vinasse in open storage ponds and lagoons is not suitable for the environment. It leads to the emission of methane, a more potent GHG than carbon dioxide (Formann et al., 2020). Hot water and solid wastes are also produced during the final stages of bioethanol production. This final stage is known as the dehydration stage. Hot water affects the temperature of the environment into which it is emptied. Organisms such as the exothermic ones in that environment will be negatively affected, as their metabolic activities will be impacted. It can be concluded that vinasse may be more potent to the environment compared to wastewater effluents from sugarcane processing because of the pollutant load it carries. Therefore, its management may be even more critical based on these studies. However, no information could be obtained about the quantities of vinasse effluents produced by the bioethanol producing plants, their physicochemical properties, or any information regarding the management of vinasse waste from the plants. The study could not establish any monitoring of the impacts associated with vinasse discharge that the sugarcane industry was recording and monitoring in South Africa.

7.5 CONCLUSION

The sugarcane processing and the sugarcane-based bioethanol production industries are amongst many developed and mature industries in the country and worldwide. Despite the recent developments in these industries and some other related technological developments elsewhere, several unresolved environmental issues still need to be addressed to achieve better environmental outcomes in South Africa. The study was aimed at investigating the sustainability of bioethanol production in South Africa.

Viability and sustainability depend on the mitigation efforts on the effects of these waste products. Previous studies on the sustainability of bioethanol production from sugarcane evaluating the parameters: energy balance, GHG savings, biofuel yield, and water footprint through the life cycle assessment showed that sugarcane-based ethanol had the best results when compared to other crops (Bordonal et al., 2018). This study, however, showed that waste products such as filter cake, molasses, vinasse, and water effluent from the sugar industry are some of the problems that need addressing. South Africa is a water-scarce country. Thus, it cannot tolerate vast amounts of water being drained into the environment, especially for such a water-intensive industry as the sugarcane industry.

Molasses should not be a problem as it is a raw material for bioethanol production. While fertigation has been one of the most economical and highly beneficial strategies used to deal with filter cake and vinasse wastes worldwide, both wastes also negatively impact the soil and groundwater quality (Formann et al., 2020). In addition, Vinasse provides storage nightmares as it releases methane, a more potent GHG than carbon dioxide. Alternative uses for filter cake and vinasse need to be investigated to avoid these detrimental effects on groundwater quality and the climate.

However, sustainable bioethanol production from sugarcane should focus on resource use maximisation through the conversion of bagasse into bioethanol. Bagasse is produced in large quantities as waste in sugar processing and is currently presenting a disposal challenge as not all of it is used for energy generation. This approach will have far more reaching consequences to the sugarcane industry and the country at large, in addition to the environmental impacts. The sugarcane industry is currently suffering because of an excess of sugar products produced and sold at a loss every year (Ndokwana & Fore, 2018; Sishuba, 2021). This has impacted small-scale sugarcane farmers and negatively affected the country's goal of alleviating rural poverty using sugarcane agriculture (Ndokwana & Fore, 2018; Sishuba, 2021). Pushing for large-scale bioethanol production in this sector would push for investment in and expansion of sugarcane growing, and therefore help revive small-scale sugarcane farming. Developing appropriate technologies and their transfer to farmers will be crucial to developing this sector into an economically viable industry and increasing productivity. Therefore, contributing to rural development and poverty alleviation.

The use of molasses, which is a by-product from sugarcane milling, in the production of bioethanol, minimises the use of food crops to produce bioethanol, thus minimizing the competition for food during bioethanol production.

Effluent from the bioethanol and sugar production process is also one of the significant observed challenges. The effluent coming from the plants is heavily polluted and should be treated before being released into the environment. Another solution is to use the water for irrigation. However, this water would not be suitable for food crops since the heavy metals in the effluent may be deposited in the plants' tissues and thus affects the consumer as the heavy metal goes down the food chain. Therefore, ornamental plants may be cultivated under effluent irrigation (Vaithiyanathan & Sundaramoorthy, 2017) but in minimal quantities to limit leaching and groundwater contamination.

7.6 RECOMMENDATIONS

Waste management challenges exist in the sugarcane and bioethanol industries in South Africa. Furthermore, a presentation on how some waste products, namely, bagasse, vinasse, or biogenic carbon dioxide, which could be harnessed for energy were seen to have been a lost opportunity. Considering that South Africa is a water-scarce country, prioritising context-specific studies on the management of vinasse and wastewater effluents would expedite and anchor the development of policies focused on waste management in the sugarcane industry. This study was limited to a single sugar plant and bioethanol plant. Proposed future work should thoroughly scrutinise waste management practices applied in the South African sugar industry on a more holistic and broader scale. In addition, the collection of carbon dioxide from the various processes in the production of sugar and bioethanol should be explored to prevent or decrease release into the atmosphere.

CHAPTER 8 SUMMARY OF KEY FINDINGS, GENERAL CONCLUSION AND RECOMMENDATIONS

8.1 SUMMARY OF KEY FINDINGS

Sugarcane farming, especially for small-scale sugarcane farmers, showed a period of growth from the 1980s to a peak in the 2000s driven by the deregulation of the industry in South Africa (Dubb, 2013). The South African government already plans to push for the development and implementation of bioethanol production projects, including sugarcane-based bioethanol production (Sishuba, 2021).

Despite data collection from a relatively small sample for the various actors in the broader sugarcane industry in KZN, the results highlighted some of the stages of interest whose impacts require mitigation measures in the bioethanol production chain. It is noted that bioethanol production from sugarcane faces several sustainability challenges, as identified during this study, and would need to be addressed.

The emission of GHG and the generation of waste and by-products such as filter cake, molasses, vinasse, and water effluent from the entire sugarcane/sugar/bioethanol industry are some of the problems that need solutions to be offered.

Clearing of forests and the use of other natural ecosystems such as wetland for sugarcane farming is associated with the potential loss in biodiversity. This seem to have been driven by sugarcane bioethanol production and may have significant impacts on the climate.

Common practices during sugarcane farming such as the use of inorganic fertilizers, residue management, especially straw management, and the reliance on fossil fuels in the farming tools and carrier trucks were found to be the most contributing factors of GHG emission. Fossil fuels were also seen to be one of the prominent sources of energy in both the sugar factory and the bioethanol factory, therefore contributing to GHG emissions. This study has highlighted these processes as factors that could significantly emit vast amounts of CO_2, N_2O, and CH_4. For example, an emerging farm in KwaDukuza emits 552460 kg $CO_{2\ eq}$ per hectare of sugarcane farmland.

While this study aims to investigate the carbon emission hotspots during sugarcane farming with the aim of suggesting strategies to minimise these emissions, it was discovered that practices, such as burnt harvesting and the use of fossil fuels are qualified hotspots.

The reliance on inorganic fertilizers is detrimental because of the release of GHGs and the deterioration of the soil, the surface, and groundwater quality. Chemical fertilizers are applied to sugarcane farms in huge quantities accounting for up to 18 percent of fertilizer use in South Africa (FAO, 2005). Given the sizes of the farms, tones of chemicals are applied each year, affecting both soil and water quality. Furthermore, the reliance on irrigation for some sugarcane farms exacerbates the risk of leaching these pollutants into the scarce freshwater sources in South Africa.

South Africa is a water-scarce country and cannot endure further pollution on its water resources. The sugarcane industry is water-intensive and water pollution is evident during all the phases of bioethanol production. During sugarcane farming, fertilizers and pesticides are washed away by heavy rains and they run-off to surface water. These chemicals also seep underground and, in the process, pollute both surface and ground water resources. Liquid effluent was also seen to be produced from the sugar and bioethanol industries. There was no evidence of such waste being treated before its disposal into the environment.

The South African sugar and ethanol plants are also seen to produce wastes which if not properly managed will cause pollution of the air and water. Filter cake and vinasse, by-products from the sugar and ethanol industry did not seem to be re-cycled, thus their potential to contribute to forming a baiting ground for mosquito larvae. With improper discharge and disposal, vinasse causes water and soil pollution by increasing the concentration of K^+, Na^+ and Mg^{2+} ions in soil and water.

The use of filter cake and vinasse in soil fertility improvements have been some of the approaches used to deal with waste from sugar processing but have also been reported to have problems with mineralisation of the soil and water resources (Fito et al., 2019; Rodrigues Reis & Hu, 2017). However, mitigation against the wastes due to vinasse and filter cake requires knowledge of their pollutant load to determine whether they need further treatment before use in agricultural soils. Such knowledge of pollutant load was not explored in this current study.

The sugar industry’s input and output records seem to focus mainly on the carbon content and pH, without regarding other physicochemical parameters. It can therefore be concluded that while vinasse and filter cake could be reused as organic fertilizers to reduce reliance on synthetic fertilizers, characterisation of these wastes is crucial to mitigate against further degradation of water and soil resources, thus, requiring proper management. We can thus learn from this study that with increased waste production due to the expansion of the sugarcane industry and should the commercialisation of sugarcane-based bioethanol production proceed, policy on managing wastes such as vinasse and filter cake should be developed.

On remediation cost, soil and surface water, as natural resources could expense up to millions of Rands in the future. Water pollution is thus particularly detrimental to the local municipalities due to the financial implications of water treatment to supply communities with drinking water.
From this study, a sugar milling company within the sugarcane farming community was suggested to be a significant contributor to water quality degradation. Analysing the spatial profiles and spreads of the investigated pollutants around that sugar milling company could point to the discharge of untreated effluents if the postulation is correct. Water effluents from the sugarcane industry are acidic and can significantly impact the mineralisation of water resources. Further studies may need to look at the current practices of such industries in South Africa and investigate their impacts on water quality as being a water-scarce country, South Africa cannot afford the large-scale pollution of its limited freshwater sources. Therefore, the viability and sustainability of sugarcane-based bioethanol production may depend on the waste mitigation efforts implemented on these waste products.

Wastewater treatment is essential in the bioethanol production plant as it is regarded as the highest consumer of raw water for non-process applications. Such non-process applications include cooling, generation of steam, cleaning, and others, while on the other side, the wastewater, vinasse, from the bioethanol distillery is heavily polluted. Vinasse is generally a highly complex effluent having an excessive organic matter in terms of high COD (80,000–160,000 mg/L), high temperature, high ash content, low acidity (pH 3.7–4.5) with a high content of dissolved inorganic salts (Fito et al., 2019). Moreover, it is particularly problematic because it provides storage nightmares as it releases methane, a more potent GHG than carbon dioxide. Vinasse is therefore highly toxic for discharge into the environment. Traditionally, conventional physicochemical methods such as coagulation-flocculation, sedimentation, filtration, pond treatment, and different combinations of these methods followed by discharging into the environment have been the most common methods for effluent treatment. However, the treatment of highly toxic wastewaters like vinasse has necessitated the development of various other methods for ensuring an eco-friendlier sugarcane agricultural method. Such methods include fertigation, bio composting, and concentration by evaporation (incineration). These methods have become popular worldwide (Fito et al., 2019). However, such treatment methods are not evident from the case studied in this study. It can therefore be concluded that the sustainability of sugarcane-based bioethanol production in South Africa will depend on the development and adoption of innovative approaches to waste management in the sugar industry, the development of strategic waste management policies and the implementation of such measures before the expansion of the sugar industry.

In general, it can be summarised that although biofuels are some of the best alternatives available that can help mitigate climate change by reducing greenhouse gas emissions while also reducing local air pollution and improving energy security, this is not without environmental implications. As discussed earlier, sustainable bioethanol production from sugarcane should focus on resource use maximisation. When used together with proper environmental management practices in the production phase, bioethanol offers an opportunity to produce renewable energy and reduce carbon emissions, develop more integrated and sustainable agricultural systems, and improve natural resource management.

As general recommendations in this study, sugarcane farmers must be skilled in calculating the amount of GHG emitted from their sugarcane farms and identifying the GHG hotspots in their agricultural practices to reduce the GHG from the source of its emission. Furthermore, various environmental management skills used to mitigate these environmental impacts at the different stages of bioethanol production have been suggested to solve ecological impact issues and create job opportunities. A complementary study should thus be done to identify possible environmental management skills gaps through a skills audit along the bioethanol production chain.

8.2 GENERAL CONCLUSIONS

South Africa (SA), just as the rest of the world has been trying to embark on the use of sustainable energy sources primarily to mitigate the risks of climate change which is already a global event. According to the Carbon brief profile for SA (2018), SA has pledged to peak its GHG emission by 2025 before stepping it down by 2030. With such a pledge, the use of renewable sources of energy such as bioethanol has been encouraged. Recently on the SA News 24 (30^{th} Oct. 2021), SA is the highest emitter of carbon in the region, and she needs over R3.2 trillion in investment to mitigate the risks of climate change in 35 of its cities. Europe is embarking on supporting South Africa in fast conversion from non-renewable energy sources to renewable energy sources (News 24, 30^{th} Oct. 2021), of which bioethanol is one of such renewable energies. The production of biofuels has however not come without environmental issues.

South Africa, being the 15th and 10th top sugarcane producing country globally in 2015 (Mohlala et al, 2016) and 2020 (OECD, 2020) respectively, and sugarcane being one of the main feedstocks for bioethanol production, it was necessary to carry out this study. The study was set out to evaluate the sustainability issues associated with sugarcane-based bioethanol production in South Africa and evaluating the environmental impacts of wastes associated with bioethanol production.

The investigation results showed several areas of concern in the value chain of bioethanol production where mitigation of environmental impacts is needed to promote sustainable development in this growing industry.

The LULC changes study of the uMlalazi catchment showed rising farming activities in the last ten years. These increases in sugarcane production from around 2010 align with a promised mandatory blending of 2% for bioethanol into petrol meant to be enforced in 2015 (Department of Mineral Resources and Energy, 2020). Chapter 4 demonstrated the fluctuation in sugarcane farm sizes against the various conservation areas found on the uMlalazi area. Between 1985 and 2020, on the one hand, a general increase of 36.8%, 17.3% 128%, and 1.9% were observed for the conserved areas in the Ongoya forest, Dlinza forest, Entumenu forest and the Mbolongwane wetland respectively. On the other hand, the sugarcane plantation experienced a 53% decrease in the farmland sizes. It can thus be concluded that although the conservation areas have not increased as would have been expected over 35 years, the sugarcane farmlands have lost their ground spaces to other ecosystems that are not necessarily threatened and to uncultivated bare ground. It can also be concluded that the KZN Department of Fishery, Forestry and the Environment has not relented its efforts in controlling this land use changes and maintaining the conservation areas. Ecosystems of these conserved areas thus seemed to be sustainable according to this study.

With regards to the emission of greenhouse gasses from the sugarcane farms, this study has made findings on the major GHG emission hotspots that needs to be considered by sugarcane farmers during their GHG control measures. Although these hot spots differ with respect to the agricultural type, generally, they include the use of fossil fuel in their farm machineries, the practice of burnt harvesting, the use of synthetic fertilizer, the use of fossil fuel in their transport trucks for transporting sugarcane to the production plant and of other chemicals to the farm, residue management and carbon stock changes which includes the conversion of natural forest ecosystems to sugarcane farms. Although South Africa has shown an 18% decrease in GHG emission from sugarcane agriculture from the 2017 statistics, this study has explored the possibility of individual sugarcane farmers being able to control their emissions by quantifying their yearly or seasonal emissions using the CFT. This tool identifies the GHG emission hotspots which could be used as a basis for sustainable management and mitigating the risk of emissions. This study found that each farm and field respond differently. From the different farm types studied, carbon stock changes have contributed to the most CO_2eq emissions in sugarcane farming, with a total emission contribution between 20% and 50%. Other GHG emission hotspots include the irrigation system, type of fuel, type of harvesting method.

The different emerging farms that took part in this study have emitted between 9000 kg and 26000 kg CO_2 eq per hectare of sugarcane farmland cultivated. Commercial and non-pivotal farms have emitted between 15977 and 40698 Kg CO_2 eq per hectare of sugarcane farmland cultivated. On the other hand, Commercial farms using pivotal irrigation systems have emitted between 17284 and 125286 Kg CO_2 eq per hectare of sugarcane farmland. These differences in GHG emission rates are brought about by the difference in variables such as the quantities of fertilizers used per farm, the size of farm burnt during harvesting, the distance between farm and sugar mill, and the quantity of fossil fuel used on each farm.

This study therefore gives the idea that GHG mitigation strategies and management cannot be left for the government alone but for individual farmer to also take it as a priority in ensuring better farming practices that will reduce their GHG footprints. Sugarcane farmers will be able to determine more sustainable agricultural practices without compromising the quantity and quality of the product.

Evaluations done on the surface water quality of the uMlalazi water catchments have not only pointed to sugarcane farming but also to other point source pollution such as the surrounding sugar factories and the dilution of water catchment's water with oceanic water. For both the 2014 and 2018 data, the most polluted catchment is W13B followed by W11C as these catchments have shown highest values with respect to their spatial variability of bio- and physico-chemical water quality parameters of the uMlalazi quaternary catchment areas W11C, W12E, W13A, and W13B. The pH range for all the studied catchments is 7.2 – 8.19 for 2014 and 7.15 to 8.15 in 2018 compared to the DWAF (1996) standards of 6.5 – 9. The total dissolved salts ranges are 152 – 310.27 mg/l in 2014 and 149.68 – 289.29 mg/l in 2018 are within the acceptable standards prescribed in DWAF (1996) for surface water (20 -175 mg/l). The 2014 total alkalinity range from 29.34 – 88.32 mg of calcium carbonate per liter of water while 2018 showed a range of 22.61 – 74.02 mg of calcium carbonate per liter of water. These results co-relate with the WQI calculated for these catchment areas. According to the WQI values calculated, all the water catchments have shown evidence of good to excellent water quality.

Following on-site observations and structured interviews from both the sugar and ethanol industries, including a 9-year waste production data from the sugar mill, analysis was made of the various wastes produced from these different SA industries and their environmental impacts. Sugar plants and bioethanol plants have been studied and found to generate greenhouse gases, solid wastes, and liquid effluents.

Record keeping on raw material inputs and wastes generated from the sugar industry was noted in this study as this forms the basis of both natural resource management and waste management. Conclusively, the results from the sugar industry shows that not only gaseous wastes in the form of greenhouse gases and ash is generated but also solid by-products such as bagasse, filter cake, and molasses. The average annual by-product generated from the sugar mill are 305322 tons of bagasse, 66721 tons of filter cake, 36723 tons of molasses. Bagasse is burnt by the sugar mill as a source of fuel to run the turbines, but it was not clear what filter cake and molasses are used for by the industry. On the other hand, the factory's average annual effluent is 310766 tons with a BOD of 13023 mg/L and pH 6.

8.3 GENERAL RECOMMENDATIONS

Bioethanol production is accompanied by environmental issues such as issues related to LULCC, air, water, and land pollution causing ecological instabilities. The White Paper for renewable energy (2003), does not specify the management strategies for the environmental problems associated with biofuels. With a considerable literature gap in the South African context, it is also not clear if these impacts have been identified and mitigated by South Africa in their attempt to venture into bioethanol as an alternative to fossil fuel. Therefore, there is a need to consider the environmental perspectives and investigate the sustainability of the total bio-ethanol production, use and end of life system for the impacts of and mitigation to LULCC issues, waste generation, and waste management.

Only a limited scope was considered with conserved areas such as the Mbongolwana wetland, the Ongoye forest, the Dlinza forest, and the Entumeni nature reserve. It is thus recommended that the entire uMlalazi ecosystem and the rest of KZN province be studied with regards to sugarcane expansion and its implications on natural ecosystems. This will help in analysing the actual biodiversity gain or loss as an integral part of environmental management and sustainable ecosystem. Following the recommendations from NEMA (1998) chapter 1, S $_{(3)}$ which stipulates that; "Development must be socially, environmentally and economically sustainable" and chapter 1, S $_{(4)}$ $_{(a)}$ which also states that sustainable development requires the consideration of all relevant factors, such study on a more elaborate basis will ensure better environmental sustainability strategies in place.

The CFT used during this study, has predicted the hotspot activities on sugarcane farms that produce the most GHG. It is thus recommended that, due to the simplicity of the tool, local farmers could be trained on using the tool to work towards consciously and strategically reducing their individual GHG footprints.

Data gaps were realised during the analysis of the waste generated by sugar and bioethanol industries. The gaps were in connection with the diversifying of the respondent to both the questionnaire and structured interviews. There was a limitation of the extent of interaction between the researcher and the workers in the plant. The researcher could thus not establish where the different types of waste generated from these 2 plants were discharged and if they were treated before being discharged. For a more detailed analysis and for waste managers and policy implementers to bring forth sustainable and strategic waste management solutions, it is imperative that these data gaps be closed by conducting further studies.

From the sugar industry studied and the generation of averagely large quantities of both molasses and filter cake, it was not evident what the industry does with these by-products and if and how they treat them, thus a recommendation that such by-products be used in the production of bioethanol and as organic fertilizers for the sugarcane farms. It is also recommended that specialist by-product managers are employed to evaluate strategic by-product and waste management measures for such significant by-products.

It is suggested that the most critical aspect that policymakers should develop when developing best waste management practices in the industry is strategies for continuous monitoring of the wastes from the industry. The data collected from the sugar industry was valuable as it shows a decrease in the quantity of factory effluent from 318205 tons in 2011/2012 to 250133 tons in 2018/2019. Filter cake and molasses have also shown considerable decline from 79758 tons to 33980 tons and from 43253 tons to 11730 tons respectively within the same period. However, such detailed data was not available in the case of the bioethanol industry that was studied. The results of such monitoring should guide decisions on the best approaches for remediation of water resources or reuse.

Non or improper wastewater management of sugar and bioethanol industry's effluent is associated with the generation of foul-smelling hydrogen sulphide, which precipitates iron, making the water black and unsuitable for aquatic life and domestic uses (Fito et al., 2019). It is thus recommended to have waste management policy that speaks to such waste.

In a nutshell, wastes generated along the value chain of bioethanol needs to be reduced, re-used, recycled, treated, and managed sustainably to ensure the total sustainability to bioethanol as a more sustainable alternative to fossil fuels.

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ANNEXURES

A. ETHICAL CLEARANCE AND INFORMED CONSENT FORM

A1. FIRST AND FINAL ETHICS CLEARANCE FOR THIS STUDIES.

UNISA university of south africa

CAES GENERAL RESEARCH ETHICS REVIEW COMMITTEE

National Health Research Ethics Council Registration no: REC-170616-051

Date: 24/03/2017

Ref #: **2017/CAES/044**
Name of applicant: **Ms F Tembon Mbamuku-Nduku**
Student #: **45900655**

Dear Ms Tembon,

Decision: Ethics Approval

Proposal: Life cycle assessment modelling of bio-ethanol: Environmental issues in South Africa

Supervisor: Prof M Tekere

Qualification: Postgraduate degree

Thank you for the application for research ethics clearance by the CAES Research Ethics Review Committee for the above mentioned research. Approval is granted for the project, *subject to submission of the relevant permission letters.*

Please note that the approval is valid for a one year period only. After one year the researcher is required to submit a progress report, upon which the ethics clearance may be renewed for another year.

Due date for progress report: 31 March 2018

Please note the points below for further action:

1. The Committee acknowledges that permission has been requested from the relevant authorities and is awaited. The researcher is reminded that data collection may not commence at any institution before the relevant permission has been obtained and submitted to the Committee for record purposes.

The application was reviewed in compliance with the Unisa Policy on Research Ethics by the

University of South Africa
Preller Street, Muckleneuk Ridge, City of Tshwane
PO Box 392 UNISA 0003 South Africa
Telephone: +27 12 429 3111 Facsimile: +27 12 429 4150
www.unisa.ac.za

CAES Research Ethics Review Committee on 24 March 2017.

The proposed research may now commence with the proviso that:

1) *The researcher/s will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.*
2) *Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study, as well as changes in the methodology, should be communicated in writing to the CAES Research Ethics Review Committee. An amended application could be requested if there are substantial changes from the existing proposal, especially if those changes affect any of the study-related risks for the research participants.*
3) *The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study.*

Note:

The reference number [top right corner of this communiqué] should be clearly indicated on all forms of communication [e.g. Webmail, E-mail messages, letters] with the intended research participants, as well as with the CAES RERC.

Kind regards,

Signature
CAES RERC Chair: Prof EL Kempen

Signature DM Modise
Acting CAES Executive Dean: Prof MJ Linington

UNISA university of south africa

UNISA-CAES HEALTH RESEARCH ETHICS COMMITTEE

Date: 25/03/2020

NHREC Registration # : REC-170616-051
REC Reference # : 2017/CAES/044
Name : Ms F Tembon Mbamuku-Nduku
Student #: 45900655

Dear Ms Tembon

Decision: Ethics Approval Renewal after Third review from 01/04/2020 to 31/03/2021

Researcher(s): Ms F Tembon Mbamuku-Nduku
fakanah@gmail.com

Supervisor (s): Prof M Tekere
tekerm@unisa.ac.za; 011-471-2270

Working title of research:

Life cycle assessment modelling of bio-ethanol: Environmental issues in South Africa

Qualification: PhD Environmental Management

Thank you for the submission of your progress report to the UNISA-CAES Health Research Ethics Committee for the above mentioned research. Ethics approval is renewed for a one-year period. After one year the researcher is required to submit a progress report, upon which the ethics clearance may be renewed for another year.

Due date for progress report: 31 March 2021

*The **low risk application** was **reviewed** by the UNISA-CAES Health Research Ethics Committee on 24 March 2017 in compliance with the Unisa Policy on Research Ethics and the Standard Operating Procedure on Research Ethics Risk Assessment.*

The proposed research may now commence with the provisions that:

1. The researcher(s) will ensure that the research project adheres to the values and principles expressed in the UNISA Policy on Research Ethics.

2. Any adverse circumstance arising in the undertaking of the research project that is relevant to the ethicality of the study should be communicated in writing to the Committee.
3. The researcher(s) will conduct the study according to the methods and procedures set out in the approved application.
4. Any changes that can affect the study-related risks for the research participants, particularly in terms of assurances made with regards to the protection of participants' privacy and the confidentiality of the data, should be reported to the Committee in writing, accompanied by a progress report.
5. The researcher will ensure that the research project adheres to any applicable national legislation, professional codes of conduct, institutional guidelines and scientific standards relevant to the specific field of study. Adherence to the following South African legislation is important, if applicable: Protection of Personal Information Act, no 4 of 2013; Children's act no 38 of 2005 and the National Health Act, no 61 of 2003.
6. Only de-identified research data may be used for secondary research purposes in future on condition that the research objectives are similar to those of the original research. Secondary use of identifiable human research data require additional ethics clearance.
7. No field work activities may continue after the expiry date. Submission of a completed research ethics progress report will constitute an application for renewal of Ethics Research Committee approval.

Note:
*The reference number **2017/CAES/044** should be clearly indicated on all forms of communication with the intended research participants, as well as with the Committee.*

Yours sincerely,

Prof MA Antwi
Chair of UNISA-CAES Health REC
E-mail: antwima@unisa.ac.za
Tel: (011) 670-9391

Prof SR Magano
Acting Executive Dean : CAES
E-mail: magansr@unisa.ac.za
Tel: (011) 471-3649

A2. INFORMED CONSENT AND ETHICS CLEARANCE FROM THE KZN DEPARTMENT OF AGRICULTURE AND OTHER CONSENTS TO PARTICIPATE IN THIS STUDY

CONSENT FROM THE DEPARTMENT OF AGRICULTURE AND FORESTRY PERMITTING UNISA STUDENT RESEARCHER TO CARRY OUT STUDY RESEARCH ONTHEIR SUGARCANEFARMS

I, SIZA VICTOR MTHETHWA (Department's representative), confirm that the student researcher, Fayez Mbamuku-Nduku, Tembon has told me about the nature, procedure, potential benefits and anticipated inconvenience of participation.

I have read and understood the study as explained in the information sheet.

I have had sufficient opportunity to ask questions and am prepared to participate in the study.

I understand that my participation is voluntary and that I am free to withdraw at any time without penalty (if applicable).

I am aware that the findings of this study will be processed into a research report, journal publications and/or conference proceedings, but that my participation will be kept confidential unless otherwise specified. I am aware that the data supplied by me may be shared for future research in instances where it becomes too expensive or impossible to get the same primary data.

I agree to the recording of the interview session(s).

I have received a signed copy of the informed consent agreement.

Department's Representative : Name & Surname...SIZA VICTOR MTHETHWA

Department's Representative : Signature.................Date 23 FEBRUARY 2018

Researcher's Name & Surname: Fayez Mbamuku-Nduku, Tembon

Researcher's signature:________________ Date...30th April 2017

University of South Africa
Preller Street, Muckleneuk Ridge, City of Tshwane
PO Box 392 UNISA 0003 South Africa
Telephone: +27 12 429 3111 Facsimile: +27 12 429 4150
www.unisa.ac.za

A3. SAMPLE CONSENT FORM SENT OUT TO POTENTIAL PARTICIPANTS

PARTICIPANT INFORMATION SHEET

Ethics clearance reference number:
Research permission reference number:

8th Nov. 2017

Title: Life Cycle Assessment Modelling of Biofuel: Environmental Issues in South Africa.

Dear Prospective Participant

My name is Mbamuku-Nduku Fayez, Tembon. I am researching with Prof Memory Tekere, a senior lecturer and professor in the Department of Environmental Sciences, UNISA, and Dr. M. Mujuru, Doctor at the University of Limpopo. This is towards a Doctorate Degree at the University of South Africa. We invite you to participate in a study entitled *'Life Cycle Assessment Modelling of Biofuel: Environmental Issues in South Africa'.*

WHAT IS THE PURPOSE OF THE STUDY?

This research aims to find out the impact of bioethanol on the environment. This study is expected to collect important information that could minimize the negative impact of this biofuel, bioethanol, on the different environmental dimensions throughout its value chain.

WHY AM I BEING INVITED TO PARTICIPATE?

[redacted] of the Ethanol Producers Association of Southern Africa, is well equipped to assist with this study. [redacted] was sourced as one of the main focus points of reference concerning data collection for this study. I was linked to [redacted] through an internet search as I researched for bioethanol producing companies.
Being the [redacted] in such a renowned industry relates to the fact that you are versed with the policy that governs the production and use of biofuel. Therefore, it will be our pleasure to gain your assistance with data linked to policy design, implementation, and monitoring concerning waste generation and waste management in the bioethanol production section.
We will gladly also welcome any available secondary data that can be useful for this study.

WHAT IS THE NATURE OF MY PARTICIPATION IN THIS STUDY?

The study involves audiotaping, questionnaires and a semi-structured interview. The questions that will be asked during the interview session are related to a policy with respect to land used for agricultural practice for the benefits of bioethanol's raw material cultivation and the impact thereof—the bioethanol production and use and waste management policy related to the bioethanol production and use sector.

Overall the data collection sessions will last about 5 hours, where one 1hour will be allocated for the questionnaire. After analyzing the questionnaires, back 4hours will be earmarked for the semi-structured interview, including the time for familiarizing/socializing and setting up the recording device before the interview and the actual interview session.

It is important to note that any information received during this interview will be used and kept confidential. Prof. Tekere will save the recorded data.

CAN I WITHDRAW FROM THIS STUDY EVEN AFTER HAVING AGREED TO PARTICIPATE?

Participating in this study is voluntary, and you are under no obligation to consent to participation. Also, note that there is no penalty or loss of benefit for non-participation. If you decide to take part, you will be given this information sheet to keep and be asked to sign a written consent form. You are free to withdraw at any time. However, if the questionnaire has been submitted already, you may not be able to start at that stage. Also, note that the questionnaire may ask for personal details like the participant's names; you may decide to keep it anonymous.

WHAT ARE THE POTENTIAL BENEFITS OF TAKING PART IN THIS STUDY?

The participant as an individual will add to the wealth of knowledge in the biofuel industry as a whole and particularly bioethanol. Your responses and suggestions are going to educate the farmers, the farm policymakers, the agriculture sector, the bioethanol manufacturers, the consumers of bioethanol, and the waste managers along the value chain of bioethanol, to be able to consider more sustainable methods that do not only cater for the production of biofuel but also for the social and economic needs of the inhabitants of South Africa and the environment as a whole.

Through your responses, bioethanol production companies will have to re-design their manufacturing system to suit more sustainable methods, especially with the management of waste throughout the value chain of biofuels. Both bioethanol raw material farmers and bioethanol production companies will be able to analyze potential risks of their activities and plan for mitigation steps and implementation strategies, respectively.

ARE THERE ANY NEGATIVE CONSEQUENCES FOR ME IF I PARTICIPATE IN THE RESEARCH PROJECT?

They are no negative consequences that you may encounter during or after you participate in this research. However, you will have to take time off your personal or work schedule. Therefore, the student will accommodate you at your best convenient time, however not compromising the moral and ethics for which this study is aimed.

There is no potential risk factor that may cause harm to you as a participant, although displacing oneself and driving to the interview venue is a risk on its own.

Your contribution to this study will be independent of the other contributors. Thus there is neither interference nor conflict of ideas.

WILL THE INFORMATION THAT I CONVEY TO THE RESEARCHER AND MY IDENTITY BE KEPT CONFIDENTIAL?

Although your identity may be found on the questionnaire, your identity will not be recorded anywhere, and that no one, apart from the researcher and her supervisors (Prof. Tekere and Dr. Mujuru), will know about your involvement in this research. However, your answers will be given a code number or a pseudonym. In this way, you will be referred to in the data, any publications, or other research reporting methods such as journal articles and conference proceedings.

Your answers may be reviewed by people responsible for ensuring that research is done correctly, including the transcriber, external coder, and the Research Ethics Review Committee members. Otherwise, records identifying you will be available only to people working on the study unless you permit other people to see the documents.

If necessary, your identity will also be exposed to the data analyst, UNISA's certified statistician. However, he will maintain confidentiality by signing a confidentiality agreement. Please note that confidentiality agreements will be submitted to the Research Ethics Review Committee for consideration.

HOW WILL THE RESEARCHER(S) PROTECT THE SECURITY OF DATA?

The researcher will store hard copies of your answers for five years in a locked cupboard/filing cabinet in a location that my supervisors will advise. For future research or academic purposes, electronic information will be stored on a password-protected computer. Future use of the stored data will be subject to further Research Ethics Review and approval if applicable. After the set period of keeping the information, as deemed necessary, information will be destroyed. For example, hard copies will be shredded, and electronic documents will be permanently deleted using a relevant software program from the computer's hard drive.

WILL I RECEIVE PAYMENT OR ANY INCENTIVES FOR PARTICIPATING IN THIS STUDY?

Although the researcher may not be capable of paying for your participation, a token will be made to compensate for your time and transport cost to and fro the venue of data collection. Any other expenses you incur should kindly be explained and justified in adherence to the principle of fair procedures (justice).

HAS THE STUDY RECEIVED ETHICS APPROVAL

This study has not yet received written approval from the Research Ethics Review Committee of the College of Agriculture and Environmental Science, UNISA. However, the application for ethical clearance has been submitted for approval.

HOW WILL I BE INFORMED OF THE FINDINGS/RESULTS OF THE RESEARCH?

If you want to be informed of the final research findings, please contact the student researcher on 0114712270 or tekerm@unisa.ac.za. The results are accessible for two years after the completion of the studies

Should you require any further information or want to contact the researcher about any aspect of this study, please get in touch with Fayez on 083 295 7635 or fakanah@gmail.com.

Should you have concerns about how the research has been conducted, you may contact Prof M. Tekere on 0114712270 or tekerm@unisa.ac.za. Also, get the research ethics chairperson of the College of Agriculture and Environmental Science General Ethics Research Committee chairperson, Prof. E.L. Kempen, on kempeel@unisa.ac.za if you have any ethical concerns.

Thank you for taking the time to read this information sheet and for participating in this study.

Thank you.

____

Fayez Mbamuku-Nduku, Tembon

Would you please continue on the next page

CONSENT TO PARTICIPATE IN THIS STUDY

I, __________________ (participant name), confirm that the person asking my consent to take part in this research has told me about the nature, procedure, potential benefits, and anticipated inconvenience of participation.

I have read (or had explained to me) and understood the study as described in the information sheet.

I have had sufficient opportunity to ask questions and am prepared to participate in the study.

I understand that my participation is voluntary and that I am free to withdraw at any time without penalty (if applicable).

I am aware that the findings of this study will be processed into a research report, journal publications, and conference proceedings, but that my participation will be kept confidential unless otherwise specified. Furthermore, I am aware that my contributions may be shared for future research when it becomes too expensive or impossible to get the same primary data.

I agree to the recording of the <insert specific data collection method>.

I have received a signed copy of the informed consent agreement.

Participant Name & Surname………………………………………… (please print)

Participant Signature…………………………………………..Date…………………

Researcher's Name & Surname: FayezMbamuku-Nduku, Tembon

Researcher's signature:___________________ Date…8th Nov. 2017

B. QUESTIONNAIRES DIRECTED TOWARDS SUGARCANE FARMING

B1. QUESTIONNAIRES TO SPECIALIST TO GAIN BACKGROUND KNOWLEDGE ABOUT THE SUGARCANE INDUSTRY IN SOUTH AFRICA

UNIVERSITY OF SOUTH AFRICA – UNISA

COLLEGE OF AGRICULTURE AND ENVIRONMENTAL SCIENCES

NAME AND SURNAME: MBAMUKU-NDUKU FAYEZ, TEMBON

STUDENT NUMBER: 45900655

SUPERVISORS: Prof. M. Tekere & Dr. Mujuru

DATA COLLECTION TOOL FOR STUDENT RESEARCH: QUESTIONNAIRE

TITLE: LIFE CYCLE ASSESSMENT MODELLING OF BIO-ETHANOL: ENVIRONMENTAL ISSUES IN SOUTH AFRICA.

INSTRUCTIONS: Below is a set of questions to be responded to by the experts in the various areas along the value chain of bioethanol.

In most cases a check box is provided. Use a tick (✓) to indicate your response.

In other cases, lines are provided for short explanations. Feel free to add the number of lines as deemed necessary. Also kindly use a different colour other than black if responses are typed.

Thank you once more for your consent and time taken to add value to this study.

QUESTIONS BASED ON AGRICULTURAL PRODUCE OF SUGAR CANE TOWARDS SUGAR AND BIOETHANOL PRODUCTION

1. What farm are you representing? ____
2. In which province is this farm located? ____
3. How big is this farm (In hectares)? ____
4. Are you (Your farming industry) the pioneer users of the land?

Yes		No	

5. If no, who are the pioneer users of that piece of land? ____

6. What was previously found on this piece of land before you converted it into a sugarcane farm?

____

7. What type of farming method do you practice there?

monoculture		Crop rotation	

8. Do you plough and make beds for planting, or do you just dig to make the soil soft for planting?

Plough and make beds		Dig to make soil soft	

9. For how long have you been using this same piece of land for agricultural practices?

____

10. Are there any rivers, streams in the proximity of your farm?

Yes		No	

11. Do you enhance the fertility of the farm with fertilizers?

Yes		No	

12. If yes, what is the chemical composition of your preferred fertilizer?

____

13. If no, briefly explain how you ensure the fertility of the soil

____

____

____

14. Are there any waste generated during the farming process? If yes list them.

	Waste generated during the farming process
1	
2	
3	

15. How far is the farm from residential areas? (Estimates are fine)

Direction of residential areas from farms	Distance in Km
Northern side	
Southern side	
Eastern side	
Western side	

16. What type of waste is generated during the harvesting of sugar cane?

____

17. How do you transport the sugarcane to the sugar producing plant?

____

18. How is waste generated during the farming, harvesting, and transporting of sugarcane, managed?

Waste generated during the process	**Waste management process**
Farming of sugarcane	
Harvesting of sugarcane	
Transporting of sugarcane	

19. Is there a policy document which provides some guiding principles for the various activities in the farm?

Yes		No	

20. Does this policy document guide on waste management strategies?

Yes		No	

21. Do you think the generated waste has an impact on the residents living in the proximity of the farms?

yes		No	

22. If yes, briefly describe the type of impact.

____

____

____

23. Are there any mitigation strategies in your policy to prevent such impacts mentioned above?

Yes		No	

24. If Yes, List some of these mitigation strategies.

Type of impact	**Mitigation strategy**

25. Do you have external monitors who come to monitor your farming practice strategy and methods?

Yes		No	

26. If yes, where do these external monitors usually come from? (Who authorizes their monitoring process)?

____

27. Do you have internal monitoring and evaluation personnel who ensure your strategies are implemented according to the required standards?

Yes		No	

28. Generally what soil type is your farm based on?

loam	
sand	
clay	
Others (Specify)	

29. What is the pH range of your soil?

Acidic (indicate level)	
Basic (indicate level)	

Neutral	

30. According to the natural soil type and pH range of the soil, do you think that is the preferred soil type for the growth of sugarcane?

Yes		No	

31. If no, what do you do to render the best soil quality for the growth of the sugarcane plants?

____

____

32. Do you think it will be possible for me to get a soil sample to get a laboratory analysis on it?

Yes		No	

Thank you so much for your time and I hope to see you during the interview session.

B2. QUESTIONNAIRES USED TO GAIN BACKGROUND KNOWLEDGE ABOUT THE SUGARCANE INDUSTRY FROM KZN SUGARCANE FARMERS TO BE ANALYSED USING THE Cool Farm Tool.

Sustainability Parameters	Sugarcane farms		
	EMERGING Non-Pivotal Sugarcane farms	COMMERCIAL Non-Pivotal sugarcane farm	COMMERCIAL Pivotal irrigated farm
Year of data / harvest			
Farm area or location			
Farm size (hectares)			
Climate (Temperate or tropical)			
Annual Temp (degrees C)			
Annual rainfall (mm)			
Land use change management (From………………. To sugarcane farm)			
YIELD			
Crop yield (tonnes)			
Seed amounts (tonnes)			
Net yield (tonnes)			
Assessment name			
SOIL TYPE AND FERTILIZER USAGE			
Soil texture			
(loam / sand / clay)			
Soil organic matter % - choose an option			
1. SOM > 10.32			
2. 1.72 < SOM < = 5.16			
3. 5.16 < SOM < += 10.32			

4. SOM > 10.32			
5. Custom value			
Soil moisture average (Moist or Dry)			
Soil Drainage (Good or poor)			
Soil pH - choose an option			
1. < = 5.5			
2. 5.5 < pH <= 7.3			
3. 7.3 < pH <= 8.3			
4. pH > 8.3			
FERTILIZER INPUTS			
Fertilizer Type- choose an option			
1. Compose your own			
2. Ammonium nitrate (33.5% N granulate)			
3. Ammonium nitrate (33.5% N prilled)			
4. Ammonium sulphate (21% N)			
5. Ammonium Sulphate Nitrate (26% N)			
6. Anhydrous ammonia (82 % N)			
7. Calcium Nitrate (15.5% N)			
8. Calcium NPK (15% N / 15%K_2O / 15% P_2O_5 – Mixed acid process)			
9. Calcium NPK (15% N / 15%K_2O / 15% P_2O_5 – Nitro phosphate process)			
10. Diammonium Phosphate (18%N / 46% P_2O_5)			
11. Monoammonium Phosphate (11%N / 52% P_2O_5)			
12. Muriate of potash / Potassium Chloride (60% K_2O)			
13. Phosphate /Rock phosphate (32% K_2O)			
14. Potassium Sulphate (50% P_2O_5 / 45% SO_3)			
15. Super Phosphate (21% P_2O_5)			
16. Triple Super Phosphate (48% P_2O_5)			
17. Urea (46% N)			
18. Urea Ammonium nitrate Solution (32% N)			
Fertilizer manufactured in -----			
Specify Country and			
Specify year			
E.g South Africa 2018			
Fertilizer application rate (Please calculate rate of fertilizer application per unit area)			
1. …….kg fertilizer /hectare farmland			

2. ……. tonnes fertilizer / hectare farmland			
Fertilizer weight or unit - choose an option			
1. ……. units of Phosphorus (P)			
2. ……. units of Potassium (K)			
3. ……. units of P_2O_5			
4. ……. units of K_2O			
5. ……. units of Nitrogen (N)			
Fertilizer application method - choose an option			
1. Apply in solution			
2. Broadcast			
3. Incorporate			
4. Fertigation – Surface drip			
Emissions inhibitors applied			
(Yes / No)			
CROP PROTECTION APPLICATION			
Category - choose an option			
1. Seed treatment			
2. Soil Treatment			
3. post-emergence			
Application doses			
FUEL CONSUMPTION			
Fuel usage (yes / No)			
Energy Source - choose an option			
1. Diesel			
2. Petrol			
3. Bioethanol			
4. Biodiesel			
5. Gas			
6. Other (specify)			
Energy used - Specify quantity			
1. --------Kg			
2. --------litres			
3. ----------tonnes			
4. ------------Other units (specify)			
What is this energy used for?			
e.g.: Ploughing, irrigation, transportation of cane etc			
MACHINES USED ON THE FARM			

List all machines used			
1. Name of farm Tillage machine			
2. Name of Fertilizer sprayer			
3. Name of Herbicide sprayer			
4. Name of harvester			
Name the Fuel type used in each machine mentioned above			
1. Name of farm Tillage machine (Diesel or petrol)			
2. Name of Fertilizer sprayer (Diesel or petrol)			
3. Name of Herbicide sprayer (Diesel or petrol)			
4. Name of harvester (Diesel or petrol)			
How many times do you use the specific machine during the entire growing cycle of the sugarcane agriculture?			
Specify number of times on each machine listed above			
IRRIGATION			
Farm irrigation (yes / No)			
Irrigation system (yes / No)			
Type of irrigation system			
Source of irrigation water			
How many times do you irrigate during a farm cycle			
How much water do you use during each irrigation intervention?			
FARM USE MANAGEMENT			
Have you have changed your tillage practices in this field during the last 20 years?			
Have you started or stopped growing cover or catch crops in the last 20 years?			
Has any part of this field been converted between arable land, grassland, or forest in the last 20 years?			
Since when did this conversion take place?			
How old was the previous land condition before the conversion?			
SUGARCANE HARVESTING			
Method (Burnt /Green)			
Method (manual / mechanized)			
Others Specify			

CROP TRANSPORTATION			
Distance from farm to sugar factory			
Mode of transport			
Type of fuel used			
Quantity of cane transported per trip			
Total number of trips made			

C. QUESTIONNAIRES DIRECTED TOWARDS SUGAR MILLING AND BIOETHANOL PRODUCTION

C1. QUESTIONS BASED ON THE MANUFACTURE OF SUGAR USING SUGAR CANE, TOWARDS BIOETHANOL PRODUCTION

QUESTIONS BASED ON THE MANUFACTURE OF SUGAR USING SUGAR CANE.

1. Where is your sugar producing plant based?

   ____

2. What is the size (total square area) of the plant?

   ____

3. Do you own your own sugar cane farm?

Yes		No	

4. If no, who how do you get supplies of sugar cane for the sugar production process?

   ____

5. Take us through the process of sugar production in point form:
   - ____
   - ____
   - ____

6. Do you have any by-products generated from any stage of sugar production?

Yes		No	

7. If yes, list some examples:
   - ____________________________________
   - ____________________________________
   - ____________________________________

8. Are all the by-products used by the company or transferred to other companies?

Used by our company		Transferred to other companies	

9. If used by your company, briefly describe some of the uses.

Type of by-products	**Uses by our company**

10. If given away / sold to other companies, briefly describe what you think they use it for.

Type of by-products sold / given away	Uses by other company

11. Is there any waste generated during any of the stages mentioned above? If yes list them per stage.

Stage of sugar production	Type of waste generated

12. How do you dispose of waste? Respond with respect to specific type waste.

Type of waste	Disposal method

13. What quantity of waste is likely generated annually? Please respond with respect to the specific type of waste.

Waste toxicity (Toxic/General waste)	Type of waste	Average annual quantity generated

14. Do you know the chemical composition of the wastes mentioned above? If yes list them.

Type of waste	Chemical composition

15. Do you think any of the type of wastes mentioned above has an impact on any aspect of the environment?

Yes		No	

16. If yes, list the impact with respect to the type of waste and the type of impact.

Type of waste	Type of impact (social, economic, political, environmental)	Impact description

17. What other impact other than the waste generation impact do you think is felt by the community (environment) because of the presence of your sugar producing plant and its activities? Briefly describe them.

Impact type	**Impact description**

18. Have there been any complaints from members of the community around your plant against your activities.

Yes		No	

19. Briefly describe some of their complaints.____
____
____

20. Do you think these complaints are genuine or the community members are only being uncooperative?

Genuine complaints		Community members are uncooperative	

21. Do you as a company, in any way try to prevent such impacts mentioned above? If yes, List some of the strategies that your company uses in mitigating the risk of such impacts.

Type of impact	**Mitigation strategy**

22. Does your company have a company policy that binds the strategic plans and implementation of your activities?

Yes		No	

23. Is this policy open to the public?

Yes		No	

24. Will I be allowed to have a copy for further studies as I prepare for the interview session with you or any one appointed to represent the company?

Yes		No	

Thank you greatly for your time in completing this questionnaire and for adding value to the sustainability of our environment. I will see you during the interview.

C2. QUESTIONS BASED ON THE MANUFACTURE OF BIOETHANOL USING MOLASSES FROM SUGARCANE

25. Where is your bio ethanol producing plant based?
    ____
26. What is the size (total square area) of the plant?
    ____
27. What raw material do you use in producing bioethanol?
    ____
28. Do you own your own sugar cane farm?

Yes		No	

29. If no, how do you get supplies of sugarcane or other raw material you may require for bioethanol raw production?
    ____
    ____
30. Take us through the process of bio ethanol production in point form:
    - ____
    - ____
31. Do you have any by-products generated from any stage of bio ethanol production?

Yes		No	

32. If yes, list some examples:
    - __________________________________
    - __________________________________
33. Are all the by-products used by the company or transferred to other companies?

Used by our company		Transferred to other companies	

34. If used by your company, briefly describe some of the uses.

Type of by-products	**Uses by our company**

35. If given away / sold to other companies, briefly describe what you think they use it for.

Type of by-products sold / given away	**Uses by other company**

36. Is there any waste generated during any of the stages mentioned above? If yes list them per stage.

Stage of bio ethanol production	**Type of waste generated**

37. Are any of these wastes' toxic?

Yes		No	

38. If yes, List the toxic wastes and the stage from which it is generated.

Stage of bio ethanol production	**Type of toxic waste**

39. How do you dispose of the waste? Respond with respect to specific type of waste.

Type of waste	**Disposal method**

40. What quantity of waste is likely generated annually from your bio ethanol plant? Please respond with respect to the specific type of waste.

Type of waste	**Average annual quantity generated**

41. Do you know the chemical composition of the wastes mentioned above? If yes list them.

Type of waste	**Chemical composition**

42. Do you think any of the type of wastes mentioned above has an impact on any aspect of the environment?

Yes		No	

43. Have there been any complaints from members of the community around your plant against your activities.

Yes		No	

44. Briefly describe some of their complaints.____

____

____

45. Do you think these complaints are genuine or the community members are only being uncooperative?

Genuine complaints		Community members are uncooperative	

46. Do you as a company, in any way try to prevent such impacts mentioned above? If yes, List some of the strategies that your company uses in mitigating the risk of such impacts.

Type of impact	Mitigation strategy

47. Does your company have a company policy that binds the strategic plans and implementation of your activities?

Yes		No	

48. Is this policy open to the public?

Yes		No	

49. Will I be allowed to have a copy for further studies as I prepare for the interview session with you or any one appointed to represent the company?

Yes		No	

50. What are the different things that bioethanol is used for?

Uses of bio ethanol
•
•

51. Do you think there is any type of waste generated during the use of bioethanol or the use of its product?

Yes		No	

52. If yes, provide a list of some of the wastes.

____

____

Thank you greatly for your time in completing this questionnaire and for adding value to the sustainability of our environment. I will see you during the interview.