WASTE MANAGEMENT
EVALUATION OF GREEN ENERGY GENERATION FROM SELECTED FACILITIES OWNED BY A CHICKEN PRODUCER IN SOUTH AFRICA

By

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ABSTRACT

Poultry production is among the fastest-growing livestock sector in the world, growing at an average of 3% per year (FAO, 2020). In South Africa, this sub-sector is the largest agricultural sector in the country contributing 20 % of all agricultural production in terms of rand value (SAPA, 2019). This subsector was projected to increase by 4 %, reaching 1.57 million tonnes in 2021. However, this huge increase in poultry production has also come at a cost to the environment due to an increase waste production related to poultry processing. The most problematic waste noted was the generation of about 100 tonnes daily of high COD wastewater sludge (~100000 mg/l) obtained from treatment of wastewater. This waste is highly polluted, and without the correct disposal, it poses serious risks for public health and the environment.

For one of the major poultry meat producing companies in the country, this challenge initiated construction of two waste to value (W2V) plants aimed at converting this waste into bioenergy. However, the performance assessment of these W2V plants in terms of their technical, economic, and environmental benefits has never been performed. The objective of the study was therefore to evaluate the waste generation and disposal at the processing plants and the performance of the W2V plants in terms of their bioenergy generation based on the feed used. A mixed method research approach involving interviews and document collection of performance data was used to address the objectives of the study.

The results of the study showed that the W2V projects have had positive impact on the environment in terms of water and air quality, reduced reliance on coal and external power for heating, and reduction of landfilling. The bioenergy plant produced enough electricity to power 20-30 % of the processing plant’s energy needs. In addition, the W2V plants resulted in economic benefits of up to 10 % on the carbon tax due to the offsets as a result of bioenergy production, as we all as profits from export of electricity to the grid of about R4.9 million annually. The study observed that on technical performance of the plants, the two plants are not yet running at optimum levels, producing about 50 % of the capacity currently.

Keywords: Bioenergy, waste management, wastewater sludge, economic benefits, environmental impact, biomass

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AD	Anaerobic digestion
CSR	Corporate Social Responsibility
DSW	Durban Solid Waste
DAF	Dissolved Air Flotation
EPA	Environmental Protection Agency, USA
EIA	Environmental Impact Assessment
GHG	Greenhouse Gas
ICAO	International Civil Aviation Organization
IRENA	International Renewable Energy Agency
NWMS	National Waste Management Strategy
NEMA	National Environmental Management: Waste Act
RSA	Republic of South Africa
SW	Solid Waste
WW	Wastewater
W2V	Waste to Value
ZWIA	Zero Waste International Alliance

CHAPTER 1: INTRODUCTION

1.1. Background

Waste management has become a major challenge and has been gaining so much attention globally because of the devastating impacts that wastes have on public health and the environment (Vergara & Tchobanoglous, 2012); (Liu, et al., 2015). Globally, the generation of wastes has been rising due to a combination of factors such as urbanization, increased production, and rising consumption. The composition of these wastes has been getting more complex than ever before as varying technological substances and equipment find their way into the markets (Vergara & Tchobanoglous, 2012); (Liu, et al., 2015). In 2016 alone, cities throughout the world generated over two billion tonnes of solid waste, amounting to an average of about 0.74 kilograms per person per day (Chan, 2016). At the current rate of population growth and urbanization, waste generation is expected to increase by 70 % from the 2016 levels to approximately 3.40 billion tonnes in 2050 (World Bank, 2019).

While millions of tonnes of both solids and liquid wastes are produced every year, solid wastes such as medical wastes, plastics, electronics, food waste and brines are of particularly special interest because of their disposal challenges. In many developing countries, solid waste management remains a great challenge. The World Bank raised concern about the increasing costs of municipal waste management which are currently making up to about 20-50 % of the budgets of the municipal services. The costs of solid waste management involve the collection, storage, transportation, and final disposal (Abdel-Sharfy & Mansour, 2018). Waste that is not disposed of properly is associated with numerous consequential implications for public health, the environment, the circular economy, and sustainability.

South Africa, like many other emerging countries, faces numerous challenges with solid waste management that harm the environment. The government has been under intense pressure to come up with efficient strategies to handle surging amounts of solid waste especially in the urban areas and the industry where there has been drastic growth because of the growing economy and growing urban population. Traditionally, various conventional methods such as landfilling, incineration, and composting have been the preferred ways for handling solid wastes (Abdel-Sharfy & Mansour, 2018). In South Africa where the average per capita waste generation is around 0.8 kg/person/day (0.4 kg in low-income households to 1.3 kg in high-income households), 90 % of that solid waste ends up in the landfill (SDCEA, 2000). In developing and poor countries, solid waste management is a major issue due to the limited resources and the competing priorities over those limited resources (Abdel-Sharfy & Mansour, 2018). While landfilling remains the favourable option for waste disposal in developing countries because of the low operational costs and low-technical requirements, the developed nations have been reducing wastes disposal to landfilling because of several environmental issues (Vergara & Tchobanoglous, 2012). Landfilling is not a sustainable way of disposing of wastes because of serious environmental concerns, especially contamination of groundwater resources by the leachate, and the release of greenhouse house gases (GHG) and other obnoxious gases (Vergara & Tchobanoglous, 2012); (Sun, et al., 2019)).

Landfilling, in particular, is of concern in South Africa given the amount and type of solid wastes going to the landfills, and the state of the country's landfill sites. According to the report by the Department of Environmental Affairs Report (2018) on the state of waste, the majority of the landfill sites in South Africa are operating without licences (about 56%) because of the failure to fulfil the minimum environmental regulation requirements. According to Chivandire (2021), these landfills took up to 48.5 million tonnes of waste in 2020 (64 % hazardous waste and 36 % general waste), with 34% of it being recycled. In addition to the several environmental issues, the scarcity of land for construction of landfills coupled with population growth has resulted in the residential areas encroaching closer and closer to landfill sites, a major concern for public health due to the air, water, and noise pollution (Vergara & Tchobanoglous, 2012); (Sun, et al., 2019).

For this reason, there has been a push for the development and adoption of other waste management methods that are efficient, effective and are environmentally sustainable. The quantity and the type of solids wastes produced are of the essence when developing proper waste management systems to handle and dispose of the excreted wastes (Abdel-Sharfy & Mansour, 2018). This information is very crucial for engineers and scientists as they decide on whether the waste has any intrinsic value that could be harnessed as well as predicting the makeup of gaseous emissions (Abdel-Sharfy & Mansour, 2018). Of the several types of wastes produced in the various industries, the interest in this study is on solid organic wastes. The growing population has had major implications on the amounts of solid organic wastes which have been growing every year (Abdel-Sharfy & Mansour, 2018). The composition of solid organic wastes varies from one place to another, with most dominated by agricultural waste, household food waste, human and animal wastes, food processing wastes and others. This type of waste is generally reusable with some used as fertiliser, animal feed, or it is incinerated or disposed to landfill sites (Abdel-Sharfy & Mansour, 2018). With growing calls for a reduction in landfilling because of sustainability issues, huge amounts of the organic wastes which are composed of materials rich in proteins, minerals, and sugars are being used in several processes as substrates or raw materials (Abdel-Sharfy & Mansour, 2018). For instance, a growing number of studies and projects have demonstrated the possibilities of converting various forms of organic waste into bioenergy and electricity (Owamah, Alfa, & Dahunsi, 2014); (Koop & Leeuwen, 2017); (Abdel-Sharfy & Mansour, 2018); (Moreno-G´omez, et al., 2021). A study conducted by Moreno-Gomez, et al. (2021) revealed that a renewable aviation fuel can be produced from all types of biomasses, including edibles and non-edibles. As a result of this development, waste management has started to focus more on the identification of the types of solids wastes produced, waste classification and development of technologies for waste reuse.

Energy is considered as the primary significant factor towards socio-economic growth (Barnes, Khandker, & Samad, 2011). The world energy production, which was 14 421 mega tonnes in 2018, showed an increased demand for crude oil and other natural gases within organizations and production plants around the world. It was mostly driven by fossil fuels: natural gas, coal, and oil, whose combined usage increased by more than 370 mega tonnes in 2018 (IEA, 2021). Coal supplies over one-third of global electricity and plays a vital role in industries such as iron and steel, making up 38.5% of the global mix (IEA, 2021). However, the continuing processing and consumption of energy derived from fossil fuels is exacerbating the environmental impacts of fossil fuels and is forcing countries to rethink alternative energy sources (Owamah, Alfa, & Dahunsi, 2014). Bioenergy production from solid organic waste is one of the alternatives that has been considered as sustainable strategy to deal with worldwide energy and global climate change challenges (Koop & Leeuwen, 2017).

The interest in the generation of bioenergy and electricity from waste organic matter has been growing because of the need to develop alternative sources of energy as fossil energy sources get depleted. The strong link between economic growth and energy demands in modern civilization has driven the energy use and the demand in every society around the world to elevated levels, resulting in severe environmental damage (World Bank, 2019). Therefore, the need for sustainable energy development with fewer impacts on public health and the environment has been the driver for related research work (Koop & Leeuwen, 2017); (Abdel-Sharfy & Mansour, 2018); (Moreno-G´omez, et al., 2021). The production of energy from solid organic waste has become a vital issue around the world and is now the generally preferred option for waste management. It has become integrated into many industrial projects as a way of reusing the wastes produced and also reducing the demand for energy from the grid. However, decisions on the reuse and recycling of wastes by several companies are impacted by several factors. According to Abdel-Sharfy & Mansour (2018), the waste management practices of choice should be financially sustainable, technically feasible, socially, and legally acceptable as well as environmentally friendly. Nonetheless, the current trends in waste management practices show growing interest by the global powers as well as private institutions towards a reduction in the use of fossil energy.

International Renewable Energy Agency (IRENA) statistics on global electricity generation from waste materials shows that it has had a 90 % growth from 46,108 GWh in 2010 to 87,500 GWh in 2016 (IRENA, 2020). Bioenergy production has accounted for about 10 % of total final energy consumption and 1.9 % of global power generation in 2015 (IRENA, 2020). South Africa has seen growth in this sector as well, evidenced by the commissioning of a bioenergy plant in 2017 in Cape Town at a landfill site in Athlone, capable of processing 500-600 tonnes of general waste per day (Chivandire, 2021). Together with bioenergy projects focused on the production of bioethanol and biodiesel, the country is moving in the right direction in terms of addressing the challenges posed by solid waste and reducing reliance on fossils energy sources.

1.2. Motivation

Energy is the fuel that drives the economy. The energy sector is a vital force that drives businesses, manufacturing, transportation of goods and the delivery of services to the nation. In South Africa, the energy supply is dominated by coal which constitutes 69 % of the primary energy supply in 2016, followed by crude oil with 14 % and renewables with 11 % (Ratshomo & Nembahe, 2019). South Africa has, however, been facing challenges on multiple fronts. On one side, the COVID-19 pandemic has caused untold economic damage to the country, while on the side, the country has been facing serious energy shortages that have been compounded by load shedding (Chivandire, 2021). According to Chivandire (2021), South Africa has a power deficit of about 21 000 megawatts (MW) because of the demand, which is exceeding supply, and was estimated to have cost the country at least R59-billion in 2019. Given that the country is currently in a COVID-19 pandemic is driven recession, sustainable economic recovery would be possible when there is enough energy to drive the economy while simultaneously minimising environmental impact.

The post-COVID-19 pandemic recovery of South Africa may need to tap into various other energy sources that are available in the country to address the energy needs needed to drive the economy. The country has a significant potential for the generation of power from renewable energy sources like wind, biomass and solar energy and these sources offer viable options to address the energy security concerns in the country. While there has been some progress concerning other renewable sources of energy, the huge amounts of waste produced in the country have not yet been fully utilised. The millions of tonnes of waste produced in South Africa are evidence of the potential for conversion of biomass into electricity, as well as limiting the environmental impacts associated with landfilling.

Current statistics highlight that South Africa generates about 108 million tonnes of waste per annum, which equates to about R25.2 billion worth of waste dumped with 90 % disposed to landfill sites and continues to increase annually (Stats SA, 2016). With the increase in urban population, scarcity of land for expansion of the landfill sites which are fast approaching full capacity, and the poor state of more than 50 % of the landfill sites, the risk for environmental and public health crisis due to landfilling is inevitable (BizTrends, 2017). Considering that South Africa is a water-scarce country, the landfill sites, some of them constructed long before the current regulations by the Department of Environmental Affairs, are a major risk to the environment. Generation of electricity from these huge amounts of biomass will help the government in addressing the solid waste management challenge in South Africa, and therefore save the country millions in costs related to the remediation of groundwater resources, and therefore sustainable development. The generation of electricity from waste materials is facilitated by anaerobic digestion of organic wastes which leads to the generation of biogas, which contains approximately 60 % of methane and 38 % carbon dioxide (Baby, et al., 2011); (Matheri, et al., 2017). Organic wastes primarily have high carbon content biomass, and this contributes to the energy content of wastes.

The most popular forms of biomass are agriculture wastes, manure, municipal wastes, plant material, food waste and other waste types. Wastes generated by agriculture e.g., bagasse in the sugar industry and municipal solid wastes are the main feed currently used in bioenergy projects (Oliveira, et al., 2012). In South Africa, additional sources of biomass that could be used directly for the generation of electricity or other forms of bioenergy include the animal production and processing industry wastes. Biogas produced from animal waste is widely used as a renewable energy source. This source of energy is thought to be cheap (Thu, et al., 2012). Biogas from treating livestock waste in an anaerobic digester has the potential to offset 930 to 1260 Mt CO_2 eq. per year of greenhouse gas emissions or 13 to 18 % of the current livestock-related emissions, while producing energy (WBA, 2019).

Of interest in this study is the poultry waste. According to Tanczuk et al. (2019), poultry litter is a problematic biomass waste that needs to be taken care of because of several impacts. Chicken litter is very rich in major phosphates, potassium, and nitrogen, and has traditionally been used for soil fertility. However, with the expansion of the industry, poultry litter is produced in large quantities more than can be used for fertilisation, which has resulted in the accumulation of these wastes. Additionally, overfertilization of agricultural land using poultry waste is reported to have impacts on surface and groundwater resources as nutrients not picked up by the plants get washed into the river bodies (Oliveira, et al., 2012); (Tanczuk, et al., 2019); (Pedroza, et al., 2021). As a result of its associated environmental problems, alternative uses of chicken waste have been extensively studied, with growth in its use as feedstock for biogas production and electricity generation where it has shown great potential (Dickens, 2008); (Chastain, et al., 2012); (Pedroza, et al., 2021).

According to the literature, chicken processing wastes can also be converted into useable products. Chicken fat has been used as a substrate for graphene synthesis, as well as raw material to produce biodiesel (Hanafi, et al., 2014). Biodiesel is one of the more hopeful renewable sources to fulfil the increasing energy demand of the world. Chicken fat is an encouraging product for biodiesel production. The waste chicken fat is commonly converted to biodiesel via catalysed transesterification (Mohiddin, et al., 2018). There are also a few studies that have been conducted in the processing of chicken fat to produce bio-jet fuel (Hanafi, et al., 2014). To overcome the listed waste management challenges, industries need to embrace innovation and technology that is driving waste management change globally and within South Africa.

1.3. Statement of Problem

Poultry production is the largest agricultural sector in South Africa, contributing 20 % of all agricultural production in terms of rand value in 2017, well ahead of all other animal sectors as well as a field crop and horticultural sectors (SAPA, 2019); (Makgopa & Bonsu, 2020). This industry has been growing and continues to grow in terms of production and contributions to the country's GDP. According to Makgopa and Bonsu (2020), chicken meat production is projected to increase by 4 percent reaching 1.57 million tonnes in 2021 from 1.51 million tonnes in 2020 and having grown by 43 percent from 1.1 million tonnes in 2019. This huge increase in poultry production is very positive for the country's economy. However, it also comes at a cost as it is associated with an increase waste production related to both poultry production and processing. Of all poultry production in the country, 75 % of the birds in the South African poultry industry are used for meat production, which is a huge number of birds that go through the meat processing plants every day in South Africa (SAPA, 2019). Poultry production waste consists mainly of large volumes of chicken litter and carcasses, while chicken processing waste is a bit complicated, consisting of many different components such as feathers, blood, heads, feet, viscera, bone, meat trim and the slaughterhouse wastewater. Without the correct treatment or disposal, poultry production and processing wastes that are produced in huge amounts may pose serious health risks, odour, and environmental pollution. While much of the poultry production wastes are generally composted and used for the production of organic fertilisers, the most problematic waste produced in this industry is the huge volumes of high COD wastewater sludge obtained from treatment of slaughterhouse wastewater which is a major environmental and public health risk. Production of slaughterhouse wastewater is a major problem because of the potential for severe impacts on the freshwater resources, and the cost of remediation.

In this study, focus was on the production of poultry processing waste at one of the major chicken production and processing companies in South Africa. The company produces huge volumes of processing wastes from its processing plants, especially its major plants in Rustenburg, Worcester and Durban. Poultry processing wastes consists of organic matter and are a valuable feedstock for biogas production, and therefore are a useful raw material for electricity production (Ashard et al., 2018). The company-initiated waste to energy (also referred to as waste-to-value W2V) projects at two of its chicken processing plants in Worcester and Rustenburg as a way of addressing the build-up of huge volumes of slaughterhouse wastewater sludge that the company has been struggling to dispose of. The projects use slaughterhouse wastewater sludge to produce bioenergy. These projects were the first of their kind in South Africa utilising this highly problematic waste in the chicken industry, and therefore offer a platform for other players in the industry to learn from. However, both plants have been reported to be currently not running to full capacity in some instances, sending some of their excess wastes to landfill sites.

Unlike the other two sites in Rustenburg and Worcester, the plant in Durban is currently not equipped with a waste to energy generation plant. Consequently, this site has waste management challenges with respect to the slaughterhouse wastewater sludge, sending considerably large amounts of its chicken processing wastes to Mariannhill landfill site and only converting about 20% of its wastes into chicken feeds. Chicken waste is a renewable protein resource, inexpensive, and is an abundantly available biomass. The company has set its goals on sustainable waste management, with a goal to have no waste going to the landfill site by 2025. The goal of sustainable waste management is to recycle as much waste as possible. However, because of the tonnes of waste produced every year by the company, only a small portion is converted into chicken feed and production of organic fuels, and the rest is taken to the landfill sites. Part of the of the company's vision is to expand investment in bioenergy production to other processing plants to increase capacity for self-generation of energy as well integrating bioenergy generation as a part of its waste management projects within the company's poultry processes.

The generation of bioenergy by integrating production processes with waste to energy onsite self-generation projects as a way of managing production and processing wastes makes waste a lucrative business. Onsite self-generation of electricity within the companies in South Africa was given a huge boost by the government through numerous measures that have been taken to increase generation capacity without a license rapidly and significantly outside Eskom as a way of dealing with challenges related to load shedding (Business News, 2020). One such measure was the enactment of the carbon offset standard which was proposed in the Carbon Tax Act of 2019. Additionally, the President of the Republic of South Africa announced in June 2021 that the government would increase the threshold for electricity self-generation in companies without requiring a licence from 1 MW to 100 MW, therefore allowing increased output from the self-generating projects within the companies (Kuhudzai, 2021) (Whyte, 2021). The new threshold which has been implemented in the Amended Schedule 2 of the Electricity Regulation Act (ERA) 4 of 2006 have opened up opportunities for investment into electricity production in the private sector (Kuhudzai, 2021). This move allows the private companies to increase electricity self-generation capacity, and therefore has become an important component of management solid waste through the minimisation of solid wastes that end up on the landfills.

The issues discussed above lead to the main objective of interest for this project, focused on investigating how much the W2V projects constructed at the Worcester and Rustenburg processing plants have impacted on the waste management discourse at those plants. This study described the current waste practices used in the South African chicken meat processing and discussed the risks and challenges these practices have on public and the environment. The investigation further evaluated the performance of the of electricity generation by the two plants by considering the technical, environmental, and cost savings. The research question that this project sought to answer was whether the implemented W2V projects are positively impacting waste management challenges in the company and whether results from the two plants can motivate investment into the building of a third waste to energy generation plant as a waste management strategy at the Hammarsdale branch and also other players in the poultry industry in South Africa. In order to answer the questions, waste management practices at the three processing plants were investigated by considering the generational outputs from each of the two plants, the environmental impact of the plants and financial impact associated with such a method of disposal on the company.

1.4. Aim and Objectives

1.4.1 Aim

The study aimed to evaluate the bioenergy production from poultry production and processing wastes at selected factories by a chicken meat producer in South Africa.

1.4.2. Objectives

I. Exploration of poultry waste production and characterisation at the poultry processing plants of a chicken meat producing firm in South Africa.
II. Assessment of bioenergy production of the poultry processing plants in Worcester and Rustenburg by considering the available infrastructure capacity, the current generation statistics of biogas and bioenergy.
III. To investigate the organic waste fraction and energy production from poultry waste by selected facilities of a chicken producing enterprise in South Africa.
IV. To assess the impacts of poultry processing wastes by selected facilities of a chicken producing enterprise in South Africa on the water quality.
V. Determination of carbon credits and cost savings due to green energy generation by selected facilities of a chicken producing firm in South Africa.

1.4.3. Research Questions

I. How much chicken waste is produced at the three main poultry processing for the chicken producer, and what fraction of the waste is shipped to the landfill sites?

II. How much waste is currently used in electricity generation at the sites in Worcester and Rustenburg, and how much is shipped to the landfill sites?

III. Is there a difference in the fraction of wastes shipped to the landfill sites for the plants with W2V plants constructed and those without?

IV. Are the plants at the sites in Worcester and Rustenburg producing electricity to their planned capacity?

V. What conclusions can be drawn from the two plants, and how they can influence the decisions of building a plant in Hammarsdale?

VI. What are the cost savings based on the current energy production?

1.5. Significance of Study

This work is focused on the waste management processes for large poultry producing and processing enterprises in South Africa. While the study is focused on a specific company, the practices in this company exemplify what is typical for chicken producing and processing plants in South Africa. The problem of slaughtering wastes in the processing plants are typical for other chicken meat producing firms as well. Except for bioenergy generation in the poultry industry, which is in its infancy, the other waste management practices observed for the company under study are the most common approaches used by other players. This research adds value to the chicken meat producing firms by providing a picture of waste production from the poultry industry and insight into possible trends as the industry grows from a South African perspective.

Possible environmental impacts of ineffective and inefficient waste management of poultry wastes are discussed in this work. The chicken producer has a KPI set to become a waste-free business by minimising waste going to landfills and exploring ways to turn waste into value and to achieve zero waste to landfill by 2025 (RCL

Foods, 2018). The company has the following key performance indicators that it is aiming to achieve:

- 50 % electricity self- sufficiency by 2025 and 50 % coal reduction by 2025
- 50 % water reduction in chicken processing by 2025
- Zero waste to landfill by 2025

Bioenergy production from the conversion of solid wastes from poultry processing into energy, is one of the main strategies that can lead the company to achieve its objectives. Lesson from the company's W2V projects in Rustenburg and Worcester, the first of their kind in South Africa, will therefore present a good opportunity from which other major chicken producers can learn about the viability of such projects as a way of addressing poultry waste.

The information from other studies have shown that waste management has rapidly increased in South Africa over the years (Acevedo et al, 2019). There are numerous potential benefits of organic waste utilization, including environmental protection, investment, and job creation. Changing the way, we think about waste will unlock opportunities for revolution. The government has already opened opportunities for increased self-generation of electricity by the private sector, and therefore promotes more investment in the waste industry.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Over the last 50 years, there has been a rapid change in how animal products are processed, produced, marketed, and consumed with an increase in meat production. Chickens are abundant because they are small, easy to raise and a highly popular food source of meat and egg production. The chicken industry has been the leading industry in chicken production in both emerging and established countries. There is a positive expectation for growth in the consumption of proteins and an open international marketplace. The chicken industry has been growing at an average of 3% per year (FAO, 2020). It is estimated that there are more than 50 billion chickens in the world, that is nearly seven chickens for every one person worldwide (FAO, 2020). Chicken meat production is among the fastest-growing livestock sector in the world. The consumption shares of developing countries accounted for 36 % of the world's production (FAO, 2020). Over the last 20 years, there has been a rapid growth in the proportion of the world's poultry consumption and production in developing countries from 43 to 54 % (Compassion for World Farming, 2017). The largest number by region is in America, followed by Asia, Europe, Africa, and Oceania as seen in Figure 2.1 (FAO, 2020).

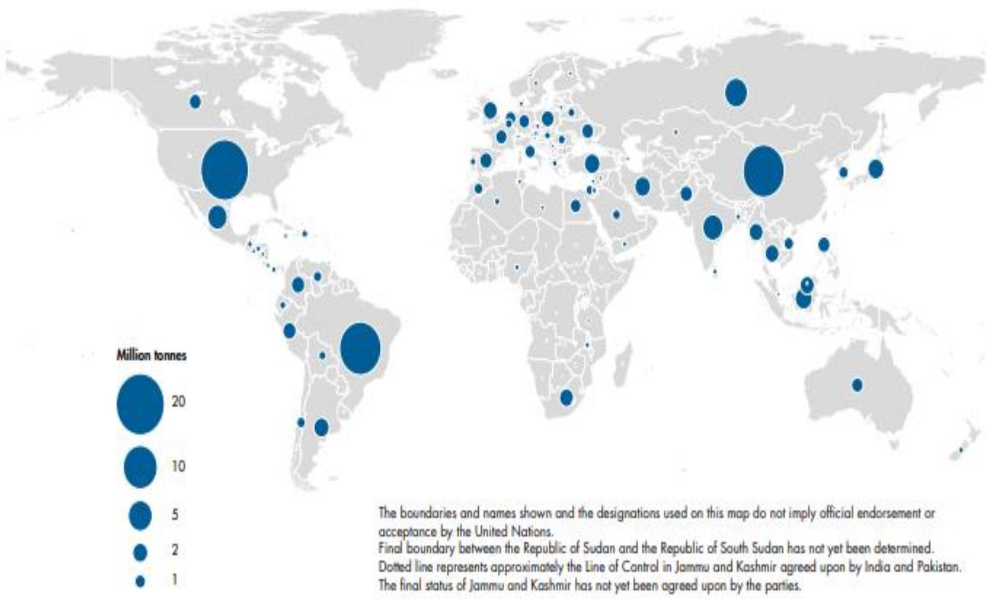

Figure 2.1: Production of Chicken Meat (Source: FAOSTAT,2020)

There has been an increase in per capita consumption of proteins with the world population increasing indicating a positive expectation for the growth in the chicken industry. According to statistics on broiler chickens provided by Compassion in World Farming, around $58x10^9$ chickens are slaughtered yearly, for meat in the world (Compassion for World Farming, 2017). World poultry production can generally be divided into broiler chicken, ducks, geese, turkey, and others. Broiler chickens account for 89.46 % of global poultry production (FAO, 2020). The annual projected consumption and production of chicken meat in developing countries in 2030 will increase by 3.5 % (FAO, 2020). Within Europe, Poland is a leading chicken producer, with a chicken population assessed at over 176 million animals per year generating a total volume of chicken waste assessed as 4.49 million tons per year (Tanczuk, et al., 2019).

However, the growth in the poultry industry has had a negative effect on the environment due to waste production. The growth of this industry has been accompanied by a growth in poultry wastes from the poultry production and processing which have raised alarm bells because of the disposal challenges of the large waste quantities produced. For large poultry farms, huge amounts of poultry waste such as chicken waste, bedding materials, furthers, spilled water and waste feed accumulated during the production cycles form the bulk of the litter production from chicken production generation (Dickens, 2008); (Chastain, et al., 2012); (Pedroza, et al., 2021). This chicken waste builds up causes environmental problems, such as insects, and can also indirectly affect groundwater pollution and eliminate some types of plants (Yılmaz & Sahan, 2020). Chicken litter is widely available as agricultural waste, which is renewable, biodegradable, and is free. This provides a potential for this agricultural waste to be converted into a variety of energy-rich products, such as biogas and fertiliser (Figure (Tamburini, et al., 2020).

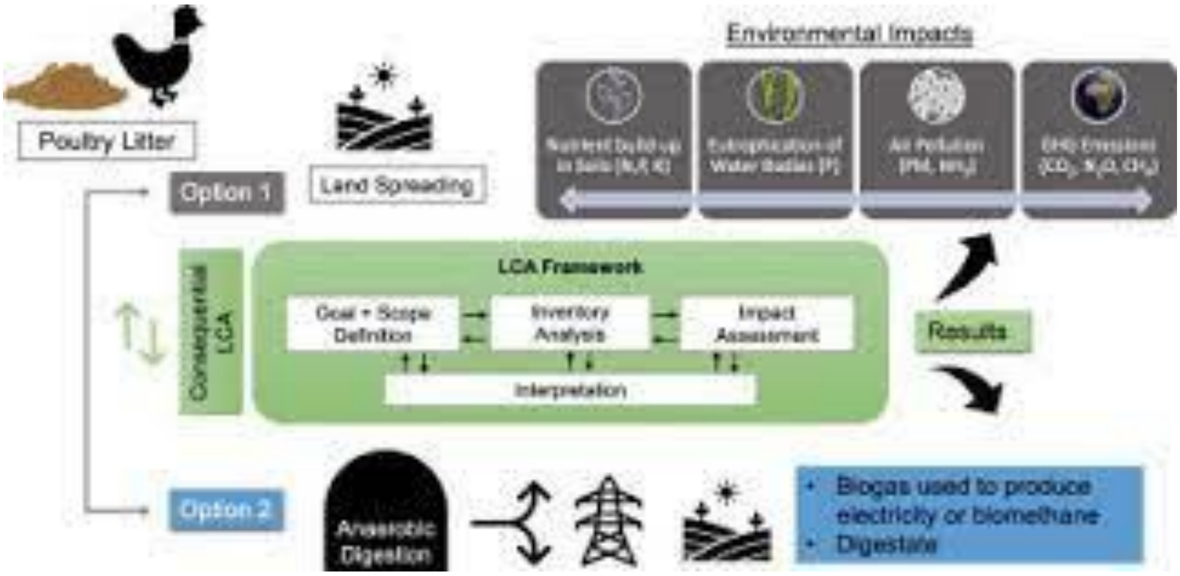

Figure 2.2:Pathways for potential uses for Poultry Waste (Beausang. C, McDonnell. K, Murphy. F, 2020)

According to the study conducted by Tanczuk et al, (2019), one of the solutions to prevent the environmental impact from chicken waste was to use it for energy production. Chicken waste can be changed into energy in such processes as fermentation (digestion), esterification, pyrolysis, gasification, co-gasification, combustion, and co-combustion (Tanczuk, et al., 2019). In Poland, the Pszczyna city, a raw chicken waste plant of 690 Mg/h supplies a biogas installation of 25–30 kW located directly on the farm (Tanczuk, et al., 2019).

In South Africa, the same problems of chicken production and processing waste disposal are slowly becoming a major issue that needs to be addressed. The chicken industry is the largest in terms of meat production in South Africa. Health-conscious consumers opt for healthier white meat instead of red meat, increasing the production of well-bred chickens. This is evident at one of the largest poultry enterprises in the country where there is intensive and large-scale production of poultry products which have been increasing over the years resulting in disposal problems of the wastes products. This company specialises in processing poultry meat for the local markets and imports. The company has a huge number of chicken farms around South Africa with a notably large number of farms in KwaZulu Natal (KZN), Western Cape and the North-West Province, the three provinces constituting 74 % of the company's poultry production, as well as major chicken processing plants in Durban, Worcester, and Rustenburg. The chicken enterprise has 20 million birds at any point on its chicken farms around the country. The company is currently producing huge amounts of waste from its farms and huge volumes of processing wastes from its processing plants, especially the major plants listed.

Landfilling, which has been used previously for disposing these wastes has become a major problem because of growing waste quantities. Landfilling of meat products has huge environmental impacts, and with increasing demand for chicken products, this presents a growing environmental challenge. Chicken waste is a renewable protein resource, inexpensive, and abundantly available biomass. The company has been developing strategies of converting most of its chicken production and processing wastes into useable products because poultry waste is considered a valued source of financial income if managed and processed properly. The company has initiated waste to value (W2V) projects aimed at tapping into the massive potential of the huge volumes of wastes produced and convert it into energy as a waste management strategy. The goal of sustainable waste management is to recycle as much waste as possible. Efficient and effective management of the edible and non-edible poultry by-products is very important not only for the profitability of the poultry industry but also for the environment. The recycling, reuse and reprocessing of animal waste where possible contributes to the maintenance of a healthy, sustainable agricultural environment that preserves resources while avoiding threats to human and environmental welfare (Sabiiti, 2011)

2.2. International experiences of bioenergy generation from poultry

The production of biogas from animal waste has become a common practice all over the world as different players explore other sources of energy which are sustainable and less harmful to the environment (Avcioğlu & Türker, 2012). The practice of harnessing biogas as an energy source from animal waste started long back around the 1940s (Avicenna et al., 2015). While the production of biogas has been increasing lately, its total production in developing countries remain relatively low (Gemechu, 2020). In most countries, the production of biogas has been mainly on a small scale with farm-based facilities being the most common with most developing energy production devices that use animal waste to produce biogas and profit from it (Krieg, et al., 2014).. India, the first country to build a digestion plant in Bombay in 1859 built the first successful biogas plant based on cow waste in 1941 (Avicenna, et al., 2015).

In the Arab world, Egypt, Morocco, Sudan, and Algeria adopted biogas as an energy source and started constructing biogas plants in the 1970s, while in other Arab Asian countries, such as Iraq, Jordan, and Yemen began using biogas plants in the 1980s (Jayyousi, 2015). Today, various animal wastes (chicken, pigs, and cow's wastes) from production and processing are common raw materials for renewable energy production in meat production industries. Globally, more than 50 countries have launched multiple biogas plant breeding programs, with China and India having the largest ones in terms of scale (Khoiyangbam, et al., 2011).

There are numerous environmental, economic, and social benefits of converting biomass to energy to aid the country. In a study by Trois (2019), environmental benefits highlighted are reduction of GHG and emissions, reduction of waste to landfill, reducing odour from waste resulting in an improvement in air quality. The offsetting of the purchase of energy from fossils, sale of by-products can be upgraded, a review of a possible reduction in municipal tax on waste and overall, a reduction of electricity loss are some economic benefits. The recently enacted carbon tax act of 2019 which is aimed at reviving the domestic carbon offset market offers huge economic and environmental benefits to the companies' efforts by reducing the amount of carbon tax in their books. Through this carbon crediting system as spelled in the carbon tax act, companies are rewarded for their mitigation efforts to reduce the amount of GHG emissions. Social benefits include examples such as an increase in jobs, increased capacity of electricity to the country, education and skill development and overall improvement of the quality of health (Trois, 2019).

As a result of the benefits of the use of biomass to produce biogas, world biogas production has increased rapidly since the turn of the century. Biogas is generally employed in industry as a gas substitute for heat production (Koop & Leeuwen, 2017). In 2018, global biogas production had an equivalent energy content of 1.36 exajoules in comparison to 0.28 exajoules in 2000 (IEA, 2021). Biogas technology also uses current resources and can balance the existing energy technology to generate heat and electricity for homes and companies (Omer, 2017). The process of formation of biogas involves the conversion of organic wastes into organic acids, which are then transformed into biogas by microorganisms. The biogas that is produced is upgraded to fuel and utilized in furnaces and stationary engines for heating and electricity generation (Omer, 2017). The slurry which remains after this process is rich in nutrients and can be used as biofertilizers and for soil alteration.

The most popular forms of biomass are agriculture wastes, manure, municipal wastes, plant material, food waste and other waste types. Wastes generated by agriculture e.g., bagasse in the sugar industry and municipal solid wastes are the main feed currently used in bioenergy projects (Oliveira, et al., 2012). In South Africa, additional sources of biomass that could be used directly for the generation of electricity or other forms of bioenergy include the animal production and processing industry wastes. Biogas produced from animal waste is widely used as a renewable energy source. This source of energy is thought to be cheap (Thu, et al., 2012). Biogas from treating livestock waste in an anaerobic digester has the potential to offset 930 to 1260 Mt CO_2 eq. per year of greenhouse gas emissions or 13 to 18 % of the current livestock-related emissions, while producing energy (WBA, 2019).

Various waste feeds from both the production of the cows, chickens and pigs, and meat processing have been used for production of bioenergy from biogas, and for most of the feeds, the technology is well developed. While cow waste has been one of the earliest waste sources for generation of biogas, according to history, the use of poultry manure has been a challenge and has generally been avoided. Over the years, growing interest has been shifting towards poultry waste as the fastest growing agricultural industry in the world. In China, the first combustion power plant and biogas power plant using chicken manure as raw materials were put into operation in 2009 (Li et al., 2021). In Europe, the first plant was constructed in Northern Ireland in less than 3 years back. As the interest in poultry waste grew, a number of studies have investigated its potential for production of biogas and compared with other waste types.

According to Shi (2014), some studies even investigated the potential of using a mixture of different waste types to improve the output. In India, a number of studies investigated the relative biogas performance of different animal wastes, and studies have found that chicken waste shows potential for higher biogas production yield

(Khoiyangbam, et al., 2011). In Italy, a laboratory anaerobic digester was designed and built to evaluate biogas production from different substrates (such as poultry and pig waste), and considering the higher methane production in poultry waste, this provides better performance (Fantozzi & Buratti, 2011).

In one study, dairy waste and chicken waste were observed to result in better yield for methane production using anaerobic digestion of multi-component substrates (Shi, 2014). In Turkey, biogas plants produce biogas by digesting two different types of chicken and cattle waste (Fantozzi & Buratti, 2011). In Africa, many studies have shown that chicken waste can be used for the production of biogas and biological fertilizers (Dai, et al., 2015). Biogas and methane are produced from starch and sugar-rich materials found in poultry waste and measured on a laboratory scale using simple digesters (Dai, et al., 2015).

2.3. Chicken industry in South Africa

The South African Chicken industry has undergone substantial growth over the past five decades. The chicken industry is an important sub-sector within the South African agriculture sector (Molapo, 2009). Chicken provides the most affordable source of animal protein, is the largest contributor to total gross agricultural production, and has a significant effect on the integrated value chain. More than 60 % of the total meat consumption in South Africa is from chicken meat. The chicken industry in South Africa processes more than $1x10^9$ broilers chickens per annum which contributes to 21 % of all agricultural production and 43 % of all animal products to the country’s GDP. Chicken meat only represents about 60 % of the weight of the chicken (Tesfaye, Sithole, & Ramjugernath, 2017).

South Africans eat 20-million chickens each week, or a third of a chicken each day. That’s nearly a billion chickens each year that are raised and slaughtered (Kings, 2018). About 40 g of waste is produced each day, from each broiler. That is 160 00 kg of waste from South African chickens each day, or 40-million kilograms a year (FAO, 2020). Usually, chicken slaughter facilities mostly produced whole birds, in contrast with slaughter plants today in South African and globally, generating a product composed of whole birds, cut-up parts, deboned meat and other further processed products (Blom, 2006).

The chicken industry has changed from basic farm-based operations to large commercial producers where economies of scale in processing have led to a high grade of operational productivity (Blom, 2006). The Republic of South Africa (RSA) is ranked the top in Africa and among the top 20 chicken producers in the world (FAO, 2020). In 2019, the per capita consumption of chicken meat and eggs was 39.3 kg and 8.90 kg respectively, and the total per capita consumption was 48.2 kg (including backyard consumption). Over the last ten years, the gap between the total consumption of poultry and eggs and the total consumption of other meats (Figure 2.2) has widened (SAPA, 2019).

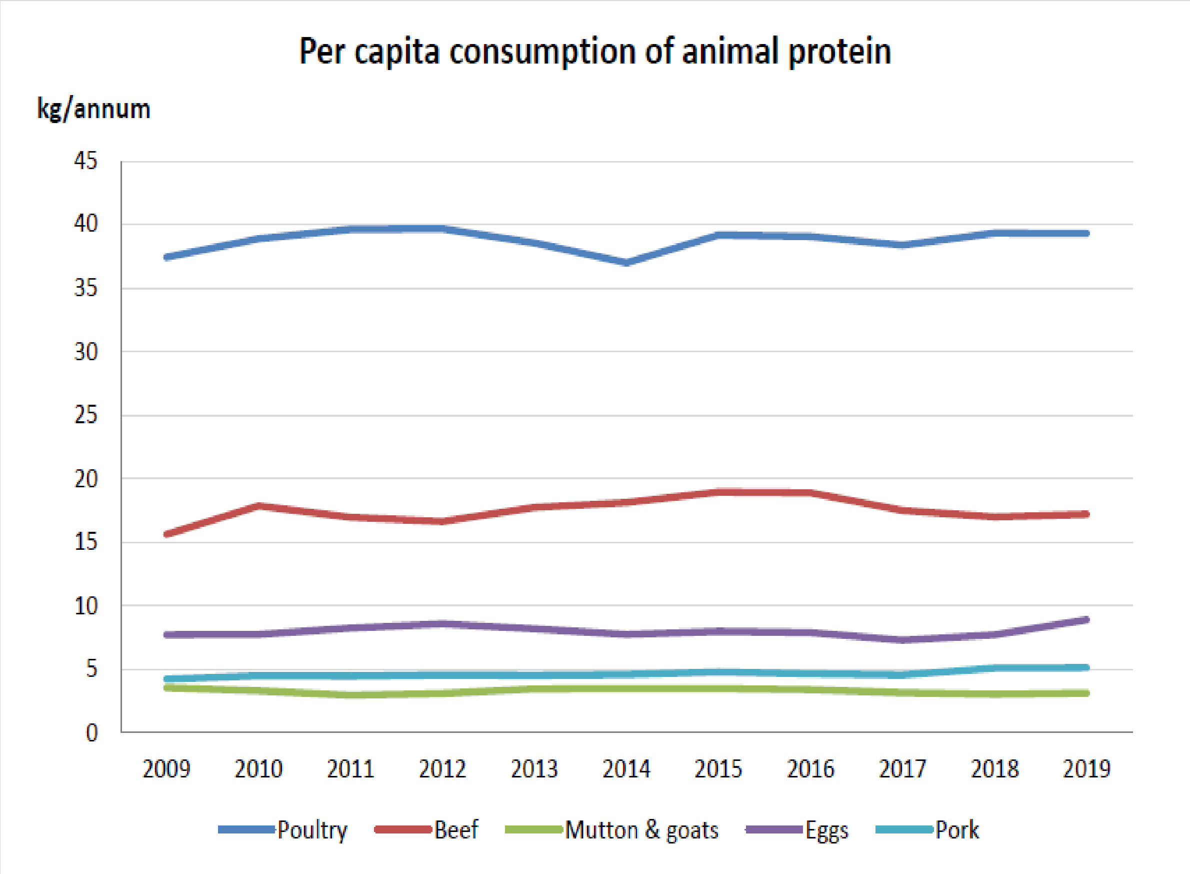

Figure 2.3: Per capita consumption of protein sources from 2009 to 2019 (DALRRD)

In 2019, the total consumption of poultry meat and eggs (according to DALRRD) was 2,879 million tons; 90.5 % more than the total consumption of beef, pork, lamb and goats of 1,511 million tons in the same period. Among them, poultry products (including imports) were 2,328 million tonnes and eggs and egg products were 551,000 tonnes (SAPA, 2019).

With the development of industries in neighbouring countries, South Africa's market share in the region has been declining. However, South Africa still dominated regional chicken production in 2018, accounting for 72.9% of the total production of the SADC Group (FAO stats) seen in Table 2.1. Malawi and Tanzania are the next largest producers, but each accounts for less than 8% of total regional broiler production (SAPA, 2019) In the ten years from 2008 to 2018, Botswana, the Democratic Republic of the Congo, Namibia and Seychelles experienced an industry contraction (SAPA, 2019).

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Table 2.1: The production of chicken meat in the SADC member countries in 2018 (FAO stats)

	Production		% Growth	% Total production		Population
SADC Country	**2008**	**2018**	**(10 yr)**	**2008**	**2018**	**2018**
Unit	Tonnes	Tonnes	%			M
Angola	13 140	27 208	+ 107	0.8	1.1	30.81
Botswana	6 609	4 247	- 35.7	0.4	0.2	2.25
Dem. Republic Congo	10 737	10 355	- 3.6	0.6	0.4	84.07
Lesotho	1 520	1 840	+ 21.1	0.1	<0.1	2.11
Madagascar	36 800	48 698	+ 32.3	2.2	2.0	26.26
Malawi	19 060	190 617	+ 900	1.1	7.9	18.14
Mauritius	42 200	49 000	+ 16.1	2.5	2.0	1.27
Mozambique	18 823	86 363	+ 359	1.1	3.6	29.50
Namibia	11 040	10 228	- 7.4	0.7	0.4	2.45
Seychelles	768	559	- 27.2	0.1	<0.1	<0.10
South Africa	1 327 564	1 754 562	+ 32.2	79.5	72.9	57.79
eSwatini (Swaziland)	5 200	6 048	+ 16.3	0.3	0.3	1.14
United Rep. of Tanzania	77250	100 991	+ 30.7	4.6	4.2	56.31
Zambia	38 500	49 487	+ 28.5	2.3	2.1	17.35
Zimbabwe	60 950	65 837	+ 8.0	3.6	2.7	14.44
Total for SADC	**1 670 161**	**2 406 040**				**343.99**

Due to limited production and trade statistics, it is difficult to calculate the per capita chicken consumption in the SADC region. However, according to FAO's production and trade statistics in 2017 (the latest trade estimate), the total production of “chicken” in the region at that time was 2,249,572 tons, total imports were 932,113 tons, and total exports were 71,080 tons. Using an estimated population of 335.05 million in 2017, the per capita consumption of chicken meat is approximately 9.28 kg (2017) (SAPA, 2019).

2.4. Potential pollutants and environmental impacts of chicken production

With the fast-growing chicken industry due to the population increase and rising demand for chicken, meat, and egg, one of the problems confronting the chicken industry is the build-up of waste within the chicken farms and surroundings resulting in many environmental problems such as fly breeding, odour, and greenhouse gas emissions (GHG) (Adeoye, et al., 2014). Additionally, the associated wastes produced from the slaughterhouses are reported to be even more worrying because of the water content of the waste due to the cleaning processes in the processing plants and organic solid by-products (Sari et al., 2016). The production of chicken results in hatchery wastes, bird excrement, litter (bedding materials such as sawdust, straw or rice hulls and on-farm mortalities (FAO, 2020). Animal wastes exist in the solid, liquid, and gaseous phases. The build-up of chicken waste causes air pollution as well as soil and water pollution.

Gerber et al. (2005) summarize some of the major potential impacts of intensive chicken production on land and water resources. Chicken waste is the source of odour and attraction of flies that can carry disease (Gerber, et al., 2005). Odour emissions, soil, and water contamination, caused by a large number of compounds including ammonia, carbon sulphide and phosphorus (Szogi A. A., et al., 2015). Poultry production is associated with a variety of pollutants, including oxygen-demanding substances, ammonia, solids, nutrients (specifically nitrogen and phosphorus), pathogens, trace elements, antibiotics, pesticides, hormones, and odour and other airborne emissions (Gerber, et al., 2005). Chicken production has a huge impact on ground and surface water quality. Surface and groundwater have a high risk of impacts related to waste spills, as well as surface runoff. These are related to the liquid waste from the processing of chickens as well as the leaching of nutrients from fertilisers derived from chicken litter. Human and animal health impacts are associated with drinking contaminated water (pathogens and nitrates (Harrison, et al., 2017).

A variety of products are produced from chicken meat, from boneless and skinless meat to chicken nuggets; all these processing steps require high energy and water input of chicken production (FAO, 2020). Anaerobic treatment of chicken waste is more problematic than anaerobic digestion of waste from other farm animals since chicken wastes contain high amounts of nitrogen which can result in ammonia and is later converted into nitrates in the water (Belostotskiy, et al., 2015). Pathogens and nitrates found in drinking water may be caused by underlying groundwater contamination, making the water unsuitable for human and animal consumption. Excess from chicken farms can carry contaminants such as toxic chemicals from pesticides, as well as pathogens and diseases from animal waste. Chicken farming concentrates large numbers of chickens in small areas resulting in the production of faeces and waste, sick and dead animals, microbial pathogens, and feed additives that adds to the strain to the environment (Ardebili, 2020).

Greenhouse gases trap heat in the atmosphere and contribute to global warming.
Carbon dioxide, nitrous oxide, methane, and fluorinated gases are categorised as GHGs. Greenhouse gases emission increased from the chicken facilities because of the decomposition of the wastes produced in the production of the chicken (Adeoye, et al., 2014). If the waste is not managed properly, all these gases are released into the atmosphere where they cause environmental degradation. Waste such as carbon dioxide and methane can become hazardous to the environment as well as be damaging to the health and safety of both humans and animals. More than 60% of greenhouse gases are yielded from these wastes (Seadi, et al., 2013).

Chicken production is also associated with soil and land impacts. Nutrients and trace elements in animal waste can accumulate in the soil and become toxic to plants. On the other hand, the use of biogas will decrease the dependency on fuelwood among rural communities. This will directly have an impact on deforestation which will decrease as the people use alternative energy sources. The reduced demand for fuelwood will decrease the environmental impact on the land, deforestation, and soil erosion. Biofuels could play an important role in decarbonizing the transportation and manufacturing sectors and mitigating global climate change (Riazi, Mosby, Millet, & Spatari, 2020).

2.5. The challenges related to solid waste in poultry production and production of bioenergy

Solid waste management has become a very challenging issue that has drawn global interest because of the several environmental impacts associated with solid waste disposal that are affecting all people. The continued increase in the volume of the waste generation that is triggered by the global population growth, changes in consumption patterns and uncontrolled urbanisation mean that new ways of converting wastes into useable products have become a necessity (Kolekar, et al., 2016). The overall goal of solid waste management is to collect, sort, treat and dispose of solid wastes generated in an environmentally and socially satisfactory manner using the most economical means available. Unfortunately, the most economical means available is not the most environmentally friendly.

Much of the worry is on the chicken industry which is fast-growing with an average of 3% per year (FAO, 2020). This is due to the increase in globalisation and rising demand for chicken meat and egg. Chicken is one of the only meat products that is generally accepted by all religions in the world. The chicken industry has been highlighted as causing numerous environmental problems related to waste management such as fly breeding, odour, nuisance, and greenhouse gas emission (Adeoye, et al., 2014). Chicken waste is the key source of environmental contamination with microorganisms, leading to an increase in soil and air pollution (Trawińsk, et al., 2016). Odour emissions, soil, and water contamination, caused by a large number of contributing compounds including ammonia, carbon sulphide and phosphorus sulphide (Szogi & Vanotti, 2009). More than 60% of greenhouse gases such as Carbon Dioxide (CO_2), and Methane (CH_4) is released into the environment from chicken facilities. The emitted gases can be damaging to the health and safety of both humans and animals, as well as the environment (Seadi, et al., 2013). The emission of greenhouse gases is mainly responsible for global warming.

In addition to the problem of waste management, another challenge facing the world is the continued reliance on fossil fuels as a source of energy. Excessive consumption of fossil fuels for energy production is highlighted as a threat due to the quick depletion of these fuels, and the environmental impacts related to climate change and global due to the excessive release of carbon dioxide. These energy sources are also used extensively in the chicken industry. For this reason, finding alternative energy resources is necessary to resolve this issue (Chowdhury, et al., 2020).

The conversion of waste products to form higher products such as energy is therefore very important in addressing the highlighted challenges related to the use of cleaner energy forms, while also providing a way of dealing with the waste. The production of biogas from organic waste is becoming a trend and is a common practice worldwide (Avcioğlu & Türker, 2012). In the 1940s, India started the production of biogas as an energy source with the use of cow dung (Avicenna, et al., 2015). Livestock waste and plant residue have the highest energy generation potential (WBA, 2019). Biogas is produced after organic materials (plant and animal products) are broken down by bacteria in an oxygen-free environment, a process called anaerobic digestion (AD). Stored biogas can provide a clean, renewable, and reliable source of baseload power instead of coal or natural gases. Based on a waste-to-wheels assessment, a compressed natural gas derived from biogas reduces greenhouse gas emissions by up to 91% relative to petroleum gasoline (EESI, 2017). AD can lower costs associated with waste remediation as well as benefit local economies. Chicken waste has a high biogas potential. It is hardly utilized for biogas production because it contains large amounts of ammonia. Its effective utilization as a biodigester feedstock requires that it go through an ammonia stripping process. AD also reduces odours, pathogens, and the risk of water pollution from livestock waste. Digestate, the material remaining after the digestion process, can be used, or sold as fertilizer, reducing the need for chemical fertilizer (EESI, 2017).

Currently, a huge amount of the waste is recyclable and could therefore be used for the generation of energy which would result in major savings in terms of carbon footprint and other related environmental impacts. The potential to generate energy from currently available major feedstocks in the world is 10,100 to 14,000TWh. This energy can meet 6-9% of the world's primary energy consumption or 23-32% of the world's coal consumption. This energy can be used in the form of heat and electricity or upgraded to biomethane to be used as heat or vehicle fuel. When used as electricity, it has the potential to meet 16-22% of the electricity consumed in the world (WBA, 2019). The benefit of displacing fossil fuel-based energy with low carbon, renewable energy, and reduction of greenhouse gas emissions.

2.6. Technological framework for generation of biogas from biomass

Chicken waste is made up of cellulosic bedding material and waste generated in the processing plants. These wastes can be converted into heat and/or electric energy and/or liquid fuel. Every kilogram of organic matter can give a yield of 0.5 m^3 of biogas. Biogas contains between 60-70 % of CH_4 and has a heating value of 5 to 6 kW (Musvoto, et al., 2018). There are different conversion technologies to produce green energy from biomass. The different conversion technologies along with their energy efficiencies are presented in Figure 2.3. The highest efficiency is seen from the anaerobic digestion of biomass whilst the lowest is from direct conversion (Shafie, et al., 2012). A variety of technologies, including thermochemical conversion, biomass production with subsequent combustion and gasification, biogas production, bioethanol production and microbial fuel cells, could contribute to energy products (SL Harrison, et al., 2017).

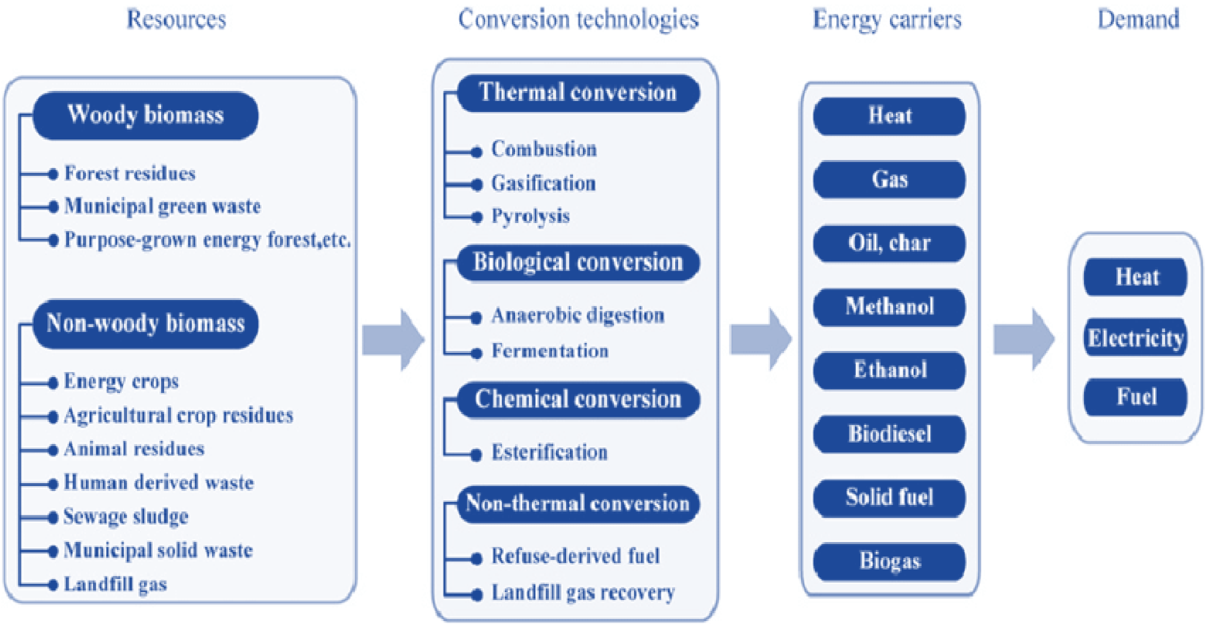

Figure 2.4: Biomass and waste energy sources and conversion technologies (Nakata et al., 2011)

2.6.1. Thermochemical conversion

Thermochemical conversion includes processes such as incineration, pyrolysis and gasification. It is an efficient method that is used to convert biomass into biofuels. It is a commonly used technique for transforming biomass into fuels of higher heating value (Chowdhury, et al., 2020). These primary processes for thermochemical conversion are discussed in the sections below.

2.6.1.1. Gasification process

Gasification is similar to combustion, whereby carbon-based material is converted into synthetic gas in a reactor (Musvoto, et al., 2018). Partial oxidation of biomass is carried out at higher temperatures, 800-900 ^{o}C to convert biomass into a gaseous mixture enriched biofuel product (Chowdhury, et al., 2020). Gasification technology which is established for coal and wood biomass conversion in the 1900s. This process was applied for processing biomass such as sewage sludge deriving mixed results (Musvoto, et al., 2018). Sludge gasification produces syngas (synthetic gas). Syngas consists mainly of hydrogen (H_2), carbon monoxide (CO), nitrogen (N_2), traces of methane (CH_4) and other hydrocarbons, as well as tar, particulates, and carbon dioxide (CO_2). Gasification occurs with deficient oxygen; thus, complete oxidation does not occur. Most full-scale installations are in Europe, mainly in Germany (Musvoto, et al., 2018).

Approximately 10.5% and 16.8% of the total world's oil and natural gas reserves are found in Iran, an oil-rich country. Despite the outstanding potential of sustainable energy sources, Iran's energy system depends almost entirely on fossil fuels to meet its energy requirements (Ardebili, 2020). Gasification is viewed as an intermediate process between combustion and pyrolysis (Musvoto, et al., 2018).

2.6.1.2 Incineration (Direct conversion)

Direct conversion is whereby biomass is utilized as fuel to produce hot flue gas. When hot flue gas is mixed with air in the combustion chamber, steam is produced. This mechanism was applied to bioethanol plants (Chowdhury, et al., 2020). Direct conversion is also explained as chemical energy converting to electrical energy by using bacteria to oxidise organics. This yields low energy outputs. The cost of material is high and most suitable for high-tech applications (Burton, et al., 2011). A study conducted by Oliveira et al, 2012, has contributed to the research of the evaluation of the mechanical and financial features of green energy generation using biomass obtained from chicken litter and to contribute to the research of chicken waste use in real-life applications. There is also the possibility of using the poultry litter as a direct fuel for generating electricity (Oliveira, et al., 2012).

2.6.1.3 Pyrolysis process

Pyrolysis is a process in that biomass is decomposed at a high temperature in the absence of oxygen (Lam, et al., 2021). Pyrolysis is characterized as a slow, fast, and flash process. While gasification and combustion are mature and recognized, pyrolysis is still considered an emerging technology (Musvoto, et al., 2018). In the absence of air, a volatile fraction of solids are transformed into a carbon-rich substance called "char" This takes place around 600 ^{o}C. The “char” is gasified in the presence of oxygen greater than 800 ^{o}C and is converted to syngas. The cleaned syngas can be as fuel to generate electricity and heat (Musvoto, et al., 2018). Gases react with the char at 800 to 1200°C, generating more CO and H_2 while being cooled to below 800°C. The unconverted char and ash are collected and sent for disposal (Musvoto, et al., 2018). A study by Ernsting, 2015, determined that of the 40 biomass and pyrolysis plants with a capacity of at least 1 MW, at least nine have been built. Out of the nine, eight of these gasifiers have failed and been shut down (Ernsting, 2015).

2.6.2. Biological Conversion

Biological conversion of biomass involves the use of biological materials to breakdown the biomass into gaseous or liquid fuels such as biogas and bioethanol. Biogas production is the most popular of the two methods especially for small scale producers. The processes involved are discussed below.

2.6.2.1. Anaerobic digestion

AD is the most effective route to convert waste into resources. It is a biological process to convert waste materials into biogas in the absence of oxygen (Li, et al., 2017). AD has received substantial importance within the last 20–30 years. Biogas as a representative of renewable energy sources can be obtained via biological degradation of various organic waste materials such as agricultural residues and municipal solid wastes, under anaerobic conditions (Belostotskiy, et al., 2015). Biogas is a clean and renewable form of energy. It is a mixture of gases produced during AD of biological matter. Different biological matters can be used during the AD process such as kitchen waste, animal, or human waste (EESI, 2017). Biogas is made up of 50-70% methane, 30-40% carbon dioxide, and traces of other gases such as hydrogen sulphide and ammonia. Biogas is an odourless and colourless gas that burns with a clear blue flame (Ghimire, 2013). Biogas can be used as a substitute for conventional sources of energy such as coal, wood, and paraffin. The conventional sources of energy cause ecological and environmental problems and are exhausted at a rapid rate (Belostotskiy, et al., 2015).

There are many advantages of anaerobic digestion which are the generation of "green energy", improved waste composition and less odour, no acidification of the soil as digestate has a pH of 8, higher availability of nutrients, higher crop yields, decrease in the emission of greenhouse gases and contribute to a sustainable agricultural sector. AD may be defined as the engineered anaerobic decomposition of organic matter (Razaviarani & Buchanan, 2015). AD is the technology of choice for the conversion of chicken litter and other wastes into bioenergy and other bioproducts such as biofertilizers. In biogas production in Shungqiao, China, AD was seen as an attractive method for treating chicken or livestock waste.

AD is a type of biological treatment that is carried out in the absence of free oxygen. The system is completely enclosed to prevent the entry of air. The involvement of the microorganisms enables the use of suitable organic substrates, and the system operates as a two-stage fermentation process with works simultaneously within the digester. Anaerobic co-digestion involves aggregated digestion of two or more waste types within or across industries. This can provide further opportunities by boosting biogas production (Tait, Harris, & McCabe, 2021). During the first stage bacteria breaks down complex organic substances into simpler compounds such as unstable fatty acids, carbon dioxide, water, hydrogen gas, hydrogen sulphide as well as ammonia while maintaining a suitable pH value (7.0 – 7.2) plays an important role in this process. Temperature also plays an important part in the economic production of methane (Michael Bjerg-Nielsen, et al., 2018). In the biogas plant, the AD process consists of three phases namely, enzymatic hydrolysis, acid formation, and gas production (Figure 2.4) (Khoiyangbam, et al., 2011). At the final stage of AD, gas production is the end-product. The gas released may contain hydrogen supplied, ammonia, and carbon dioxide besides methane (Michael Bjerg-Nielsen, et al., 2018).

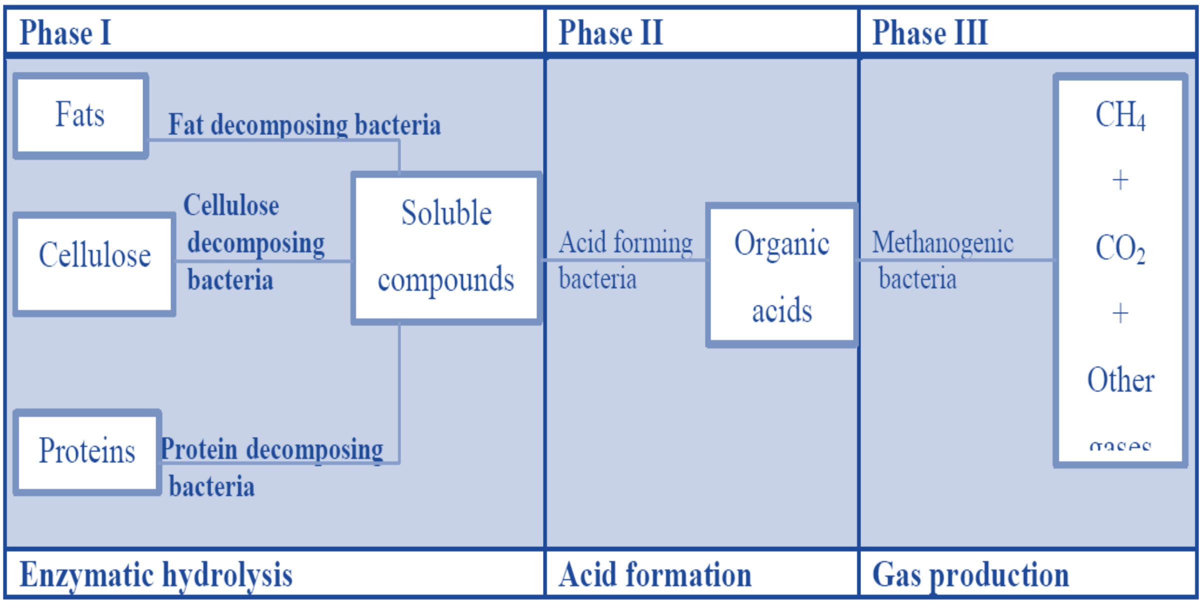

Figure 2.5: Phases of Anaerobic Decomposition in a Biogas Plan (Source: Biogas Technology, 2011)

2.6.2.2 Fermentation process

The fermentation process is used for the commercial production of bioethanol from sugar crops and starch crops. Fermentation is a well-established technology. Yeast is used to convert sugar into bioethanol, then the distillation process is used to purify bioethanol which can be used to generate green energy (Chowdhury, et al., 2020). The findings from the study conducted by Moreno-Gomez et al, (2021), indicated hydro-processing of oil derived from chicken fat, the resulting yield of bio-jet fuel is 47.46%, which is competitive and greater than those reported for castor and oils (Moreno-G´omez, et al., 2021). The effluents and solid wastes from the anaerobic fermentation process can be used as fertilizer for having a high content of protein, vitamins, and minerals (Oliveira, et al., 2012). Fermentation of wastewater produces low ethanol levels. The separation process also called distillation uses up to 30% of energy. The organics used during fermentation are not simple sugars and require pre-treatment for the process (Burton, et al., 2011).

2.7. Producing biogas from poultry waste

A biogas plant is a simple and low-cost process. The technology of biogas plants is to produce biogas from organic waste by bacterial degradation under anaerobic conditions as discussed earlier. The waste could be liquid, feed waste, harvest waste energy crops, waste from private households and municipalities and industrial waste (Gomez, 2013). Livestock and agriculture-based resources have been used in the generation of biogas because of their considerable potential for bio-power generation mainly due to their relatively low cost (Ardebili, 2020). In India, over 200 000 families per year switch from the traditional fireplace to biogas for heating and cooking (Burton, et al., 2011). It has become an important component of waste management around the world because of the potential it provides in converting waste into useable products. In Bangladesh, the demand for possible applications for waste management of large quantities of animal waste was encouraged (Chowdhury, et al., 2020). It was demonstrated that the highest amount of livestock waste, approximately 229 million tons were produced in 2016 and it accounted for a total biogas production potential of 16 988.97 million m^3 which could be converted into 16.68 x 10^7 MWh of electricity (Chowdhury, et al., 2020).

In recent years, biogas technology has gained the attention of many and was, described as an efficient and non-polluting energy source in which it can replace fossil fuel (Gomez, 2013). Some industrial systems currently are designed to tap into the biogas resources from treatment of municipal wastewater, industrial wastewater, municipal solid waste, and agricultural waste. Biogas can be used directly for heating and lighting or to generate electricity (Gomez, 2013). The effluent released from the biogas plants can be used as excellent biofertilizers, improve the physical, chemical, and biological traits of the soil such as aeration, nutrients, and microbial biomass

(Abubaker, et al., 2015). The current estimate of biogas generation from cattle is 86 % while the chicken is 7 % (Chowdhury, et al., 2020). The production of biogas has been expanding from family-size systems that are designed to digest food waste at home to small-scaled systems typical for digesting animal waste, and into much larger systems used by big plants on a large scale. In Sweden, hundreds of cars and buses run on refined biogas derived from biogas generating systems (Home Biogas, 2021). Numerous biogas plant programmes are being launched around the world, with China and India being of the largest scale (Avicenna, et al., 2015).

While the statistics show that the use of poultry waste in biogas is still much low compared to other wastes, comparative studies conducted in India have however showed that biogas yield from chicken waste yields a higher gas compared to other livestock waste such as pigs and cattle (Khoiyangbam, et al., 2011). AD of chicken waste is theoretically seen to be the most sustainable way to stabilize chicken waste (Chaump, et al., 2019). Another study conducted by Chaump et al. (2019) also recommended that chicken waste had greater bio-methane potential than dairy waste. Chicken operations are periodic and thus large amounts of litter are disposed of in short periods creating a challenge (Chaump, et al., 2019). In Higashi-Hiroshima. Japan, a study conducted by Abouelenien et al, 2010, determined that the energy released by the combustion of methane produced by this system (157- and 195-ml g-VS1) are 5638 and 6994 kJ kg^{-1} VS CM. This energy could be used in the form of natural gas directly in the day-to-day operations of chicken farms, essentially for heating the homes and for the generation of electric power (Abouelenien, et al., 2010).

While chicken production waste (chicken manure) has been generally used as a feedstock for on farm generation of biogas, slaughterhouse wastes applications are still on the rise. According to Ardebili (2020), about 53.43 million tons of wastes from the slaughterhouses produced about 16,026 million m^3 $year^{-1}$ of biogas. For poultry slaughterhouse wastes, one of the problematic wastes that has been challenging to reuse is the feathers. Feathers are a high protein content waste and have been investigated into their use feathers as a source of biogas in a study by Forg, et al, 2011. The feathers were treated biologically with a recombinant Bacillus megaterium to break down the keratin content which presents challenges in digesting. After the treatments, the feathers showed potential for biogas production (Forg, et al., 2011).

The use of animal wastes for production of biogas which is a renewable energy source, provides some efforts and solutions to counter global warming problems by minimizing fossil fuel consumption (Khoiyangbam, et al., 2011). Biogas technology helps in improving the environment by providing means for the safe disposal of animals, agricultural and human's waste. If massive amounts of waste can be utilized correctly, it will not only reduce the reliance on fossil fuels but also can contribute to building the fuel economy and help deal with the waste management catastrophe that is currently building up in the poultry industry (Chowdhury, et al., 2020).

2.8. Factors affecting biogas production

In a study by El-Nahhal, et al, 2020, the environmental battery has a life of 40–65 days of sustainable electricity production (El-Nahhal, et al., 2020). Moreover, the study reveals the effects of pH, sunlight, temperature, and waste sterilization on electricity generation and demonstrates the influence of the electricity generation process on animal waste (El-Nahhal, et al., 2020).

2.8.1. pH

The ideal biogas production is achieved when the pH value is with the digestor is between 6 or 7. If the pH is found below 5, the digestion or fermentation process is inhibited. Methanogenic bacteria are very sensitive to the pH and do not flourish below a pH of 6.5. In a study in Indonesia, wastewater was collected from an alcohol production site to study the effect of added nitrogen source and pH control on biogas production (Budiyono, Syaichurrozi, & Sumardiono, 2013). pH condition is an important parameter, in the anaerobic digester. The affects bacteria activity to destroy organic matter to biogas. pH optimum has a range of 6.5 – 8.2 (Budiyono, Syaichurrozi, & Sumardiono, 2013). At pH 6, the biogas production rate was lowest whereas, at pH 8, biogas production was increased (Budiyono, Syaichurrozi, & Sumardiono, 2013).

2.8.2. Temperature and Sunlight

The production of biogas generally operates in complete darkness (Abendroth, et al., 2020). Exposure to sunlight during the generation of electricity results in the photochemical degradation of organic molecules to produce ionic species and free radicals. Sunlight can also cause photosynthetic activity of some microbial communities in animal waste such as cyanobacteria are being activated due to exposure (El-Nahhal, et al., 2020).

The temperature has a major effect on biogas production as it impacts the growth of methane-producing bacteria. There are temperature ranges during anaerobic fermentation that can be conducted: psychrophilic (<30 ^{o}C), mesophilic (30-40 ^{o}C) and thermophilic (50-60 ^{o}C) (Yadvika, et al., 2004). Mesophilic temperatures are used in further studies to examine the scaling up of the process (Wang, et al., 2018). A study in China used cow waste and corn straw in biogas production. During the methanogenic phase, it was identified that the methanogens were more sensitive to temperature changes. Temperature significantly influences the growth and metabolic activity of methanogens. This indicated that it is important to regulate the temperature to improve biogas production in the methanogenic phase (Wang, et al., 2018).

2.9. Biogas plant models

A biogas plant is a closed system in which the anaerobic fermentation parameters are optimized to produce and supply usable gas (Bachmann, 2013). Biogas plants can be built of concrete, steel, brick or plastic and placed underground or on the surface (Bachmann, 2013). All designs have the same two basic components, namely the digester and the gas collection chamber; The biogas plant can be classified in many ways according to the design and the way of working. Depending on the feeding method, the biogas digester can be batch or containment type (Shi, 2014).

Biogas plants can also adopt vertical or horizontal travel modes, depending on the location of the digester (Bacenetti, Negri, Fiala, & González-García, 2013). There are many ways to design the biogas plant (Bojesen, Birkin, & Clarke, 2014). The anaerobic digester can be a multiphase or single chamber, or floating drum or a fixed dome. Both types have their characteristics (Bojesen, Birkin, & Clarke, 2014). Various designs and structures of biogas plants have been developed; biogas digesters with simple structures used as household biogas digesters are used to provide energy for households or farmers all over the world due to their high cost-effectiveness and simple operation. In India, more than 30 designs have been developed in the country (Khoiyangbam, et al., 2011).

In China, more than 30 million household biogas digesters have received government support (Teng, et al., 2014). Several developing countries in Asia and Africa, such as Nepal, Bangladesh, Cambodia, Vietnam, Kenya, Rwanda and Tanzania, are using biogas technology. These developing countries are using three main types of biogas plant models, namely fixed dome biogas digesters, pontoon biogas digesters, and plug flow biogas digesters (Cheng, et al., 2014). The most popular simple biogas digester model is shown in Figure 2.5, which illustrates the widely used simple household biogas digester model.

2.9.1. Fixed Dome Type

The first development of a fixed dome biogas digester was in China (Khoiyangbam, et al., 2011). They consist of fermentation chambers, can be constructed of various materials, such as concrete, brick, stone, and even steel or plastic, and can be placed underground (Cheng, et al., 2014). In the dome type, the biogas produced by the fermentation process is collected in the upper part of the dome-shaped digester; as the biogas accumulates, it squeezes the mud in the digester and moves it to the displacement chamber (Cheng, et al., 2014). The fixed dome type is relatively cost-effective, with fewer problems and less maintenance than other types (Wilawan, Pholchan, & Aggarangsi, 2014).

2.9.2. Floating Drum Digester

The floating-type digester is similar to the fixed dome-type digester, but the floating-type digester has a drum usually made of steel on the top of the digester, which is used to separate the production and collection of gas and provide a constant gas pressure. Gas reservoirs can move up and down. However, floating drum digesters are very costly and require annual maintenance, so floating drum digesters are not popular (Teng, et al., 2014).

2.9.3. Plug-flow Digester

The plug flow digester consists of grooves that do not allow mixing, and the digester is covered with plastic balloons (Chanakya & Sreesha, 2012). The length of the digester must be greater than the width and depth to ensure proper plug flow conditions (Teng, et al., 2014). The inlet and outlet of the digester have opposite ended to help semi-continuous feeding mode. The design is very simple and cost-effective, with low capital cost and low water consumption (Cheng, et al., 2014).

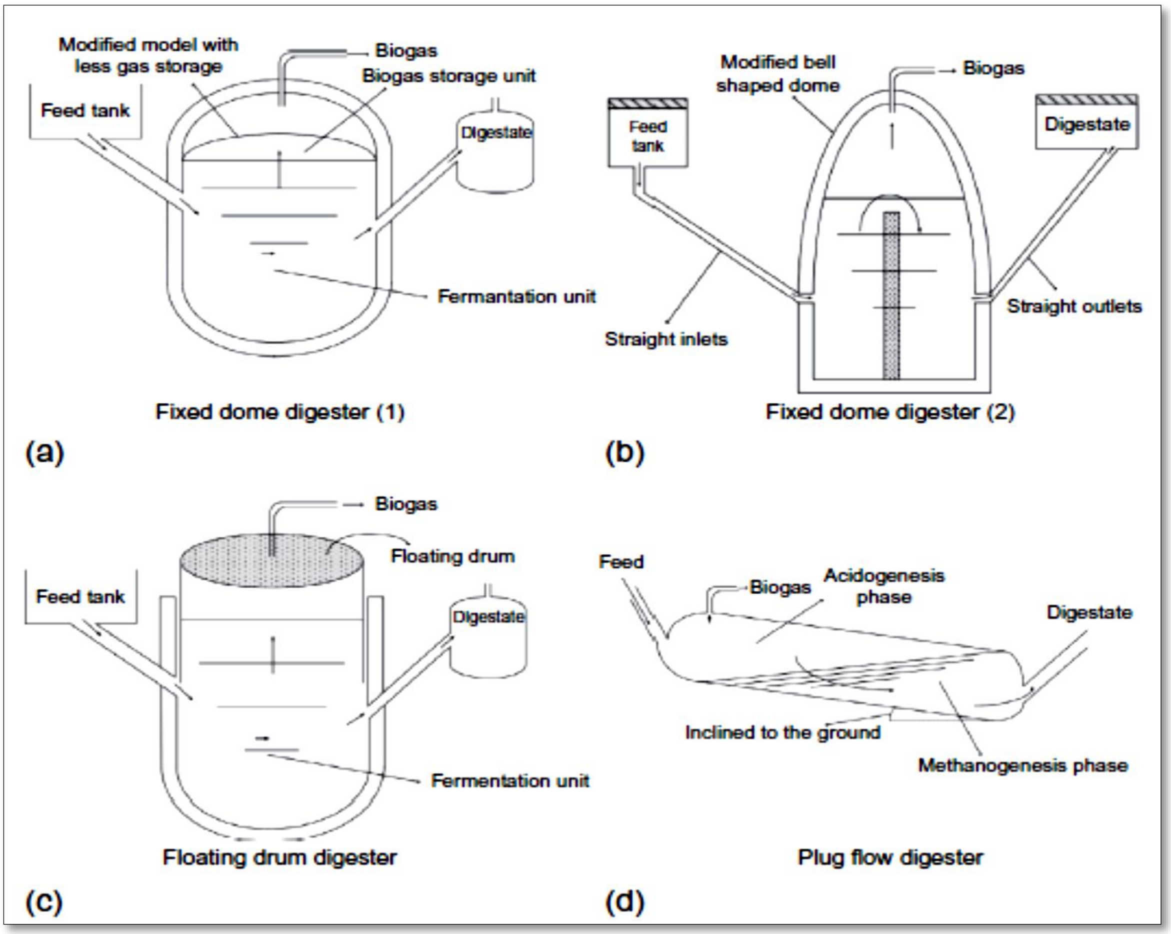

Figure 2.6: Different household digester models (Source: Design and optimization principles of biogas reactors in large scale applications, 2014

2.10. Biogas technology benefits

In addition to producing free, clean, and renewable energy for developing countries through anaerobic digestion of ready-made household biomass (such as kitchen waste, animal waste, and human waste), biogas technology also provides subsequent benefits.

2.10.1. Health benefits

Burning solid fuels, such as firewood, animal manure, agricultural residues, and charcoal, releases smoke that contains toxic pollutants (such as carbon monoxide, hydrocarbons, and particulates). Cooking is usually done indoors without adequate ventilation, resulting in serious health effects related to indoor smoke. Additionally, research has linked exposure to indoor air pollution (IAP) with several other health effects, including asthma, cataracts, tuberculosis, and high blood pressure (Surendra, et al., 2014). Biogas improves the health of low-income rural households by providing fuel for cleaner cooking, thus avoiding these health problems (Surendra, et al., 2014). In 2012, the global death toll due to PAR increased to 4.3 million, almost all of which occurred in low- and middle-income countries (LMI). Southeast Asia and the Western Pacific region bear most of the burden, with 1.69 million and 1.62 million deaths respectively. Nearly 600,000 people died in Africa, 200,000 people died in the eastern Mediterranean, 99,000 people died in Europe, and 81,000 people died in the Americas. The remaining 19,000 deaths occurred in high-income countries (WHO, 2012). Another health benefit is related to the relief of abdominal pain, which is attributed to the reduced workload of women and children collecting and transporting firewood for cooking over long distances (Amigun, et al., 2012).

2.10.2. Biogas Slurry Used as Organic Fertilizer

In addition to fuel in the form of biogas, AD produces organic fertilizers in the form of a bio-slurry or digestive agent as a by-product of nitrogen, potassium, and phosphorus-rich phosphorus. The suspension of the digestion of the expenditure that leaves the biogas, the digester increases the physical, chemical, and biological attributes of the soil and improves the productivity of crops when applied to Earth. To improve flow characteristics, digestibility can penetrate quickly, which reduces the risk of nitrogen loss in the form of ammonia (Surendra et al, 2014). It is also known that digestion suppresses pathogens mediated by soil by stimulating the radiation of the soil that produces antibiotics (Surendra, et al., 2014). In general, bio-slurry contains N_2 (1.8 %), P_2O_5 (1.0 %), K_2O (0.9 %), Mn (188 ppm), Fe (3 550 ppm), Zn (144 ppm) and Cu (28 ppm), seen in Table 2.2 (Surendra, et al., 2014).

Table 2.2: Nutrient content of important organic manure (Surendra et al, 2014)

Organic Manure	Organic Matter (%)	C: N	N_2 (%)	P_2O_5 (%)	K_2O (%)
Farmyard manure	25-55	15-20	0.40-0.80	0.60-0.82	0.50-0.65
Biogas slurry	60-73	17-23	1.50-2.25	0.90-1.20	0.80-1.20
Vermicompost	9.80-13.40	-	0.51-1.61	0.19-1.02	0.15-0.73

The slurry can be used as a complete fertilizer for agriculture (Surendra, et al., 2014). DA can also significantly reduce the odour of crude oil feedstock (up to 80%), resulting in an odourless biological suspension that does not attract flies (Surendra, et al., 2014).

2.10.3. Economic Benefits

The economic benefits of biogas are the jobs created by the biogas sector and the funds that can be obtained through carbon credits. In Nepal, around 11,000 people are employed in the biogas sector. By installing biogas digesters, Nepal reduces the use of imported paraffin by 7.7 million litres each year, resulting in annual savings of approximately US $ 2.1 million (Gautam, Baral, & Herat, 2009). Organic fertilizers can be used on agricultural land as a substitute for chemical fertilizers. Fertilizers are generally imported from Nepal (Gautam, Baral, & Herat, 2009). It is estimated that the installation of biogas digesters in Nepal can save 4 329 tonnes of nitrogen, 2 109 tonnes of phosphorus and 4 329 kg of potassium each year (Gautam, Baral, & Herat, 2009). This means annual savings of almost US $ 300,000 (Gautam, Baral, & Herat, 2009). Economic benefits of biogas generation are also realised through the carbon crediting system. Carbon credits are emission units that are issued by a crediting program to represent emission reduction or removal of GHGs from the environment. In South Africa, all companies emitting GHGs above the thresholds are supposed to pay a carbon tax system in accordance with the Carbon Tax Act that came into effect June 2019. Carbon tax is a pollution tax and a form of carbon pricing for energy sources that emit carbon dioxide. Its purpose is to reduce harmful emissions of carbon dioxide and to slow global warming. Research by Cova Advisory estimates that R2.5-billion was raised in the 2020/21 tax year by taxing direct emissions at R127 per CO_2 equivalent emitted. This tax rises to R134 this year and escalates at a rate of 10% per year over the next five years (Planting, 2021). In South Africa, the government set up a carbon crediting which has resulted in further economic benefits for companies as a result of their reduction in emitting GHGs or investment in green energy projects. The carbon credits in South Africa are evaluated as carbon offsets allowances for the emitters or carbon taxpayers that can be sold to reduce their carbon tax liability by 5 % to 10 % of their total GHG emissions through investments in GHG-reducing projects. One ton of carbon offset represents the reduction of one ton of carbon dioxide or another greenhouse gas equivalent. A carbon offset is used to compensate for or compensate for an emission made somewhere else. Whilst offsets have its advantages, businesses experience some disadvantages mainly due to costings (Table: 2.3).

Table 2.3: Advantages and Disadvantages of Carbon Offsets

Advantages	**Disadvantages**
Slow down global warming	Increase in product prices
Protection of species	Some companies may go out of business
Fairer distribution of the costs of emissions	Higher unemployment rates
Higher investments in R&D	Lower profits
Faster technological progress	Extensive knowledge is required
Efficiency improvements	High administration costs
Puts pressure on companies to go eco-friendly	Additional effort for companies
Profit maximization & eco-friendliness aligned	May not be enough to mitigate global warming
Simple and straightforward concept	Controls necessary
Promotes sustainable behaviour	May not be necessary for all industries

A common project type is renewable energy, such as wind farms, biomass energy, or hydroelectric dams. Other types of projects include energy efficiency, the destruction of industrial pollutants, or agricultural by-products, or the destruction of landfill gas. This tax was implemented to encourage companies to discover more efficient ways to manufacture their products or deliver their services and, in the process, reduce their carbon footprint. According to this tax system, 5—10 % of emissions can be rebated using carbon offsets. There are three types of the offset standards used (Table 2.4), these offsets have their own advantages and disadvantages.

Table 2.4: Table showing the carbon offset standards used around the world

Offset Standard	**Description**
Clean Development Mechanism (CDM)	By participating in the CDM, developing countries can earn certified emission reduction (CER) credits, each equal to one ton of CO_2. CERs can be traded and sold and used by industrialized countries to meet their carbon reduction targets. **Advantage**: effective in mobilizing thousands of mitigation projects in developing countries, and has also been able to reform itself continuously **Disadvantage**: weak environmental integrity, high transaction costs and complex governance.
Verified Carbon Standard (VCS)	The VCS Program is the world's most widely used voluntary GHG program. **Advantage**: The VCS is broadly supported by the carbon offset industry (project developers, large offset buyers, verifiers, and projects consultants) and is active globally. **Disadvantage**: VCS projects need to specify a monitoring plan consistent with an approved methodology
Gold Standard (GS)	The Gold Standard (GS) is an independent certification standard for carbon credits generated from Clean Development Mechanism (CDM) projects or Voluntary Emissions Reduction (VER) projects.

	Advantage: The GS can be applied to CDM projects and many other project types **Disadvantage**: GS does not recognize any other voluntary standards for generating GS-carbon credits.

One of the offset standards seen in table 2.3 is selected, registered, and maintained on the Carbon Offset Administration Systems facilitates for the listing, transfer, and retirement of carbon credits to offset carbon tax liabilities. In South Africa, carbon tax offsets are approved by the relevant standards for specific projects. All projects are subject to the mandatory processes involved in project registration and credits issuance as defined by the standard. Carbon Offset Administrator will monitor the listing and retirement of credits for compliance with the carbon tax after the South African government selects the standards.

2.10.4. Reduction In Greenhouse Gases

The use of traditional fossil fuels such as wood, coal, and paraffin in low-efficiency stoves in China to meet energy needs will lead to greenhouse gas emissions. Biogas helps reduce greenhouse gas emissions by replacing the consumption of wood and paraffin wax (Garfí, et al., 2012). Biogas technology not only helps control environmental pollution and nutrient recycling but also helps reduce dependence on imported fossil fuels. In South Africa, the use of biogas to meet the energy needs of low-income households can help reduce pressure on the national grid.

2.10.5. Reduction In Deforestation

Especially in developing countries, the most important impact of high dependence on firewood for fuel is its association with deforestation. Fuelwood accounts for 54% of forest losses in developing countries (Amigun, et al., 2012); (Garfí, et al., 2012); (Surendra, et al., 2014). Global deforestation accounts for 17-25% of all man-made greenhouse gas emissions, making it one of the main reasons for the increase in greenhouse gas emissions. Deforestation is a factor that leads to soil erosion, making it vulnerable to droughts and floods. With increasing deforestation, the time spent finding fuelwood has also increased due to fuelwood shortages. Therefore, the use of biogas reduces the dependence of rural communities on firewood, which reduces deforestation, soil erosion and the burden on women and children.

2.10.6. Social Development

Social development is closely related to reducing the workload of women and children and the supply of clean energy for the family. In most developing countries, women and children are responsible for collecting firewood and manure, which is time-consuming and laborious (Surendra, et al., 2014). For example, women and children in some places travel more than 4-5 kilometres and spend nearly 5-6 hours a day collecting biomass and cooking food. A survey reported by Surendra et al. (2014) showed that by installing biogas, one-third of the time to collect solid fuel can be saved (Surendra, et al., 2014).

In rural areas where there is no electricity supply, the use of biogas as a light source enables women to participate in night studies, promotes literacy classes and other family and community activities. Installing biogas plants at the household level can directly provide more and better opportunities for gender equality in rural areas in developing countries; its long-term social benefits may be significant (Surendra, et al., 2014).

2.11. Waste Hierarchy

According to the National Waste Management Strategy (NWMS), the most common method of waste disposal adopted internationally is to send waste directly to landfill however the appropriate waste management system (NWMS, 2011). Waste to be managed using the waste hierarchy, which is as follows: waste reduction; reuse for the original purpose; recycle and reuse of material; composting; biological treatment; incineration with energy recovery; incineration without energy recovery; and landfilling.

The 3 R’s (reduce, reuse, and recycle) in the waste management method hierarchy (Figure 2.6), are used as the basic principles for conducting waste management approaches. The waste management hierarchy aims to reach a zero-waste-based economy.

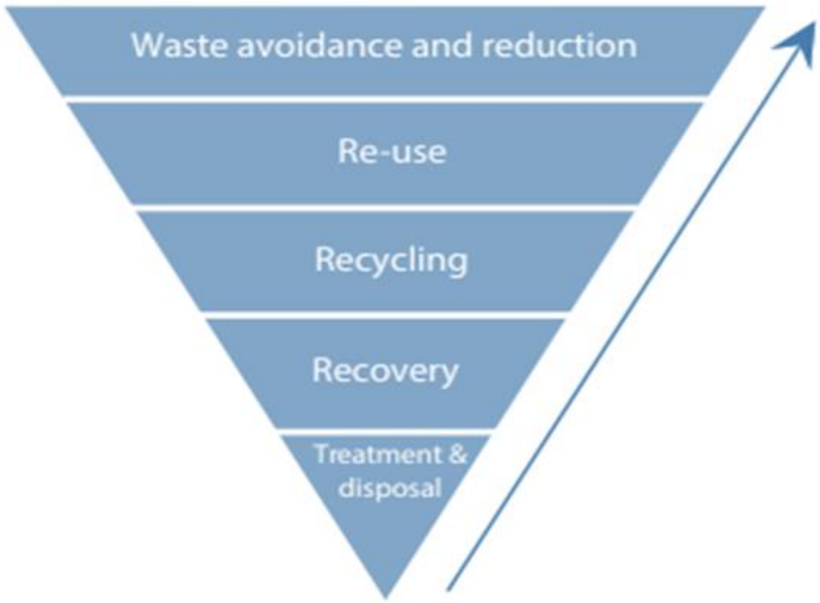

Figure 2.7: Waste Management Hierarchy (Source: NWMS, 2011)

Regardless of landfilling being the final step and last option in the waste management hierarchy, it is the most popular disposal method in South Africa (Acevedo et al, 2019). Over the past few years, the cost of landfilling has increased in South Africa due to land scarcity for landfill sites. This is due to the rapid increase in population and land being used for the building of houses and factories. In numerous countries, animal waste is not accepted at landfills to avoid water contamination and insects' infestations (EPA, 2019).

A study conducted in South Africa by Matheri et al, (2017), found that the waste produced in the city's landfills could be co-digested with animal waste to produce methane which can be used as a source of useful energy for the transport sector, industries and homes biofuel and electricity production (Matheri, et al., 2017). Municipal wastewater treatment plants have been highlighted as main energy and cost-intensive facilities.

In European countries, the average electric energy requirement of treated wastewater is around 0.5 kWh per cubic metre; however, values from 0.3 to 0.78 kW h are reported in the literature (Budych-Gorzna, Smoczynski, & Oleskowicz-Popiel, 2016).
Waste management can lead to the generation of new job opportunities and thus shrink the unemployment problem. Manpower will be essential for every stage of this process. Biogas will be used for power generation while selling biofertilizers will also add up to the income of the plants. Farmers will gain from this as it will reduce the harvesting cost which will ultimately lower the prices of food prices (Chowdhury, et al., 2020).

In South Africa under government notice GNR 634 of 2013: Waste Classification and Management Regulations, non-infectious animal carcasses are classified as general waste and are, therefore, according to GNR 636 of 2008: National Norms and standards for disposal of waste to landfill, eligible for disposal to landfill (DEA, 2013).

2.12. Renewable Energy Policy in South Africa: Biogas

In 2000, the estimated energy contribution of renewable energy was 115 278 GWh/year (mainly from firewood and waste), which was mainly due to poverty (e.g., firewood and animal waste for cooking and heating) (Department of Minerals and Energy, 2003). According to the White Paper on Renewable Energies of 2003, the government has set a medium-term goal (10 years), that is, by 2013, the contribution of renewable energies to final energy consumption will reach 10,000 GWh (that is, an increase of 1,000 GWh per year), which is mainly composed of biomass and wind energy. The major objectives of government energy policy were spelled out in the 1998 Energy White Paper as: increasing access to affordable energy services; improving energy governance; stimulating economic development; managing energy-related environmental impacts; and securing supply through diversity (DME, 1998). Small-scale solar and hydroelectric energy production (Department of Minerals and Energy, 2003). Renewable energy will be used for power generation and non-electric technologies such as solar water heating and biofuels (Department of Minerals and Energy, 2003).

This is approximately 3% (1,141 MW) of the estimated energy demand (41,539 MW) in 2013, which is almost equivalent to replacing the two units (2 x 600 MW) of the Eskom combined coal-fired power plant (Department of Minerals and Energy, 2003). In 2010, South Africa's total power generation was estimated at 46,993 MW, of which 17% came from renewable energy sources (hydro, wind and solar), and the estimated power generation capacity for 2030 was 89,532 MW, of which 30% came from renewable sources energy. According to the 2003 Renewable Energy White Paper, there is the possibility of using manure from cattle, pig, and poultry farms. The potential energy that can be harvested from animal manure on farms in South Africa is shown in Table 2.3 below. According to Nethengwe et al., (2018), the poultry production industry has potential to produce an annual electricity and thermal heat production of 829 GWh and 1066 GWh respectively. It can be concluded that the poultry industry has huge potential for energy production in South Africa.

Table 2.5: Potential energy from livestock manure and litter (Department of Minerals and Energy, 2003)

Type	Energy Production (GWh/year)
Cattle	3 889
Pigs	306
Poultry	1 417

2.13. Conclusion

This chapter has elaborated on the international experiences of bioenergy generation from poultry and looking at the challenges experienced globally and in South Africa. The literature review provided insights on the technological frameworks and factors affecting biogas production. Different biogas models and their benefits was highlighted along with the renewable energy policies practiced in South Africa. In the following the chapter the methodology for achieving the objectives set is explained.

CHAPTER 3: METHODOLOGY

3.1. Introduction

This chapter provides a description of the research methodology that underpins this study, carried out to investigate bioenergy projects for a major chicken producer in South Africa. The chapter provides a perspective about the research process carried to collect and analyse the data, the choices on the research design, the tools employed for data collection, as well as justification for the research methods employed. The limitations of the study are also presented.

3.2. Research Design

The research design used for this study employed the mixed-method approach, using both quantitative and qualitative methods. Quantitative methods use a larger and randomly selected group to test the hypotheses, look at cause and effect, and make forecasts. This approach identifies statistical relationships. The qualitative method is used to understand and interpret the social interactions with the use of interviews, participant measurements using structured and observations, field notes and reflections, and document review. The mixed-method approach combines both qualitative and quantitative methods to answer the research question reasonably and to demonstrate acceptable scientific standards for consistency (validity, reliability, and trustworthiness).

According to Creswell, (2003), the employment of both quantitative and qualitative methodologies minimises the limitation that each method has. The rationale for choosing this approach was because of the nature of the study which is diverse and required an analysis of qualitative and quantitative data to achieve its objectives. The use of mixed methods allowed the consideration of both statistical information collected as well as several perspectives of all stakeholders involved, and thus approached the objectives of the study in a holistic manner (Creswell, 2011).

The primary purpose of this research was to evaluate performance of green energy generation at a major chicken producing company in South Africa. The company has two major bioenergy projects running, both focused on reducing waste that is sent to landfill sites by the company. The first bioenergy project focuses on the conversion of sugarcane production waste, using bagasse to produce electricity while the second project is focused on converting chicken production and processing wastes into energy. This study is mainly focused on chicken production and processing waste, while the first one is discussed in the broader scheme of the bioenergy projects in the company. The company combines some of the data required for this work with that of sugar waste bioenergy projects, and because of privilege limitations, some of the primary data was not provided for the study. The research techniques used to collect data included interviews, questionnaires, field observations and document collection. All data were collected from the chicken producer’s sites in Worcester, Rustenburg as well as Hammarsdale processing plant in Durban. The data collected were used to evaluate the performance of the plants in converting chicken waste into green energy.

3.3. Study Area

The proposed research collected data for waste production and disposal, waste water analysis data to investigate the possible impacts of the wastewater on the environment, and bioenergy production data for major chicken producers’ processing sites in Worcester and Rustenburg. The chicken processing plant has been part of the food manufacturing company since 1963. The company is one of the largest processors and marketers of chicken in South Africa, and distributes and markets fresh, frozen, value-added, and further-processed chicken. An additional chicken site without a W2V plant situated in Hammarsdale was used in the analysis to compare waste production and disposal, and possible impacts of the W2V plants on waste management practices.

Hammarsdale is located in Durban, KwaZulu Natal. The town was the home of KwaZulu-Natal's textile industry from the 1950s, with Mpumalanga township having been set up by the apartheid government to house workers brought in to work in the factories. The chicken processing plant has been part of the food manufacturing company in this town since 1963. Worcester is a town in the Western Cape. It is located 120 km (75 mi) northeast of Cape Town on the N1 highway north of Johannesburg. The town also serves as the hub of the Western Cape's interior commercial, distribution and retail activity. Rustenburg is a town at the foot of the Magaliesberg mountain range, in the Northwest Province of South Africa. Rustenburg was established in 1851 as an administrative centre for an Afrikaner farming area that produced citrus fruit, tobacco, peanuts, sunflower seeds, maize, wheat, and cattle.

Figure 3.1: Study Area: South Africa with highlighted chicken processing plants and the landfill (Source: Maphill)

3.4. Research Methods and Data Collection Tools

To answer the research questions for this study, both quantitative and qualitative methods were used to collect both primary and secondary data for waste production, disposal, environmental impacts and the generation of electricity. Below are the descriptions of the data collection methods and the process of data collection.

3.4.1 Data Collection Tools

3.4.1.1. Primary Data Sources

Primary semi-structured key informant interviews, as well as a written questionnaire, were conducted with the chicken producer and landfill key informants. Across the two sites, a total of four SHEQ managers and two risk control managers were identified as key informants. Respondents were informed before the interview that their responses were going to be used only for the study and that their identities would be kept confidential. Key informant interviews were performed using either telephone or face-to-face techniques depending on the type of information that was required. Permission was granted to the researcher to record the interviews. Due to the COVID-19 pandemic, all interviews with key informants were conducted virtually through Microsoft Teams or Zoom to ensure privacy, avoid interruptions, and adhere to the social distancing protocols during the coronavirus pandemic. The key informants were identified as the key individual within each site with the ability to provide insights on waste handling, recycling methods, and strategies, and also with access to the data required to compile the reports. Interviews held with key informants of the chicken producer collected information on the environmental impacts of generating green energy (Appendix F). Based on their position within the company and closeness to activities of interest in this study, the researcher chose those specific people because they are knowledgeable, enforcers of legislation, and therefore good sources of information for the research objectives.

In addition to the questionnaires and interviews, observation was used as a tool to collect data from W2V factories and landfills. Observation is a process in which the researcher visits the research area many times to be able to observe without too much interference (Struwig & Stead, 2001). Observation was used for activities at the Hammarsdale plant. Restrictions due to COVID-19 made scheduled observations for activities in Rustenburg and Worcester to be postponed and eventually cancelled. However, some forms of observations were carried out by use of video conference and findings was recording in a table format (Appendix G). Observation allowed the researcher to have direct access to information and therefore corroborate data collected through interviews with key people (Matthews and Ross, 2010).

3.4.1.2. Secondary Data Sources

Secondary data sources used for the study included document collection. The documents collected included the company's annual sustainability reports, the business' integrated annual reports, financial reports, records from the various sites containing data on waste generation, waste utilisation and recycling, and energy generation. The literature of existing green energy generation was also consulted as part of the document collection. The information from the document review was used to cross-analyse the information provided in the interview and questionnaires.

3.4.2. Research Methods

The data collected for the research in question consisted of both being both qualitative and quantitative data. A combination of qualitative and quantitative methodologies was used to address the objectives of the study. Below is a summary of the data collected and the research methods choices for each of the research objectives.

3.4.2.1. Investigation of the waste management processes in place, and the waste quantities and types produced at the poultry processing plants of a chicken meat producing firm in South Africa.

The investigation of the waste management processes in place for the processing plants in Worcester and Rustenburg involved a quantitative assessment of waste generation for each plant, assessment of recycling and reuse of the wastes, and an assessment of waste disposal of those materials which cannot be used or converted into useable products. This objective was achieved through the use of interviews with key informants as well as reports from the company with information of chicken production, waste records and data on disposal processes. Across the two sites at Worcester and Rustenburg, a total of four SHEQ managers and two risk control managers were identified as key informants. The criteria for their selection were discussed earlier. The interview schedule was used to extract information on waste types, quantities, and interrogation of doubts in the provided documents. A questionnaire was used together with the interview (Appendix F), to capture information on the types of waste and quantities of waste produced within the chicken producer (Appendix E). The questionnaire was used for preliminary feedback, and the feedback was further interrogated during the interviews. The reports provided additional quantitative data on waste disposal and production. The waste data obtained was very limited, summarised for each month, and limited to one year.

3.4.2.2. Evaluation of the performance of bioenergy production of the plants in Worcester and Rustenburg by considering the available infrastructure capacity, the current generation statistics, and compatibility with national policy objectives.

The performance evaluation of bioenergy production of the processing plants in Worcester and Rustenburg involved a quantitative assessment of the energy generation and how it compared with the expected based on the available infrastructure, quantitative assessment of biogas generation and analysis of the methane content. The data for the evaluation of performance of the bioenergy production plants was collected from secondary data in the company records and reports on the operation of the two W2V plants. Data used for the calculations was limited to three months for Worcester (August to October 2021) and two months for Rustenburg (August-September 2021). However comprehensive data showing feeds, biogas production, digestate production, thermal and electricity production was available for Rustenburg for only and limited for only one week due to data privilege restrictions for Rustenburg. The mean data for the plant was used to calculate monthly and annual bioenergy generation for the plant and was compared with its maximum capacity to evaluate performance. Biogas analysis data and average yield for given mass of feed was used to evaluate performance of the digestors and electricity generation.

3.4.2.3. Investigation of the environmental impacts of generating green energy from chicken waste by selected facilities in South Africa.

Assessment of environmental impacts involved the assessment of the environmental consequences of the project on the water quality and air quality. The focus on this study was to look at the impacts of poultry slaughterhouse waste generation on the environment, and the impacts of the integrated W2V plants at the poultry processing plants located in Worcester and Rustenburg. The objective focused on the impact the bioenergy generation plants have had on waste management challenges of the processing plants, as well as water quality and air quality impacts of its operations. Water quality was approached from water statistics, and pollutant load related to slaughterhouse wastewater while air quality looked at the release of GHGs and other related pollutants into the atmosphere. The study looked at both possible and actual impacts of the processing waste from recorded or reported real data. A combination of qualitative and quantitative data, using both primary and secondary data sources was used to address this objective. Interviews with two third-party providers responsible for collecting of the wastes from the company (Appendix H) and the SHEQ managers, as well as document analysis was used to address the objective. Previous and current sustainability reports, actual data for generation, disposal and wastewater analysis data from the company documents and reports, as well as literature were collected and analysed to determine the environmental impacts.

Secondary data collected through a table format (Appendix I), for water analysis carried out by the company and the municipality was collected to address the objective. The data was limited for the years 2020 and 2021. However, the sampling frequency was limited for some sampling sites to perform adequate statistical analysis of the data. The data contains analysis results for COD, phosphate, total nitrogen content, total suspended solids, and the pH of wastewater from the drains at the company and water bodies in the surrounding areas. Table 3.1 below shows a summary of analysis details for the physicochemical parameters listed. Data on water recycling and recovery from the collected was also employed to address the issue of impacts of bioenergy on water usage.

Table 3.1: Table showing the key parameters analysed for wastewater monitoring for chicken processing wastewater.

Parameter	Instrument
pH	pH Probe
Chemical Oxygen Demand (COD)	Oxygen Probe
Phosphate	Reflectometric Analysis
Total Nitrogen	Reflectometric Analysis
Total Suspended Solids	Filtration and Gravimetric Analysis

3.4.2.4. Determination of carbon credits and cost savings due to green energy generation by selected facilities of a chicken producing firm

Carbon credits are emission units that are issued by a crediting program to represent emission reduction or removal of GHGs from the environment. The Carbon Tax Act in South Africa that came into effect June 2019 provided the approach used to calculate credits due the production of green energy in this study. The carbon credits in South Africa are evaluated as carbon offsets allowances for the emitters or carbon taxpayers that can be sold to reduce their carbon tax liability by 5% to 10% of their total GHG emissions through investments in GHG-reducing projects. Offsets are measured in tonnes of carbon dioxide-equivalent (CO2e). One ton of carbon offset represents the reduction of one ton of carbon dioxide or another greenhouse gas equivalent which is a 1:1 ratio (Promethium Carbon, 2015). The three offset standards are Clean Development Mechanism (CDM), Verified Carbon Standard (VCS) and Gold Standard (GS). One of three offset standards are selected and registered on the Carbon Offset Administration Systems facilitates for the listing, transfer, and retirement of carbon credits to offset carbon tax liabilities. Providing consistency and confidence in the voluntary carbon market is one of the goals of the National Carbon Offset Standard (NCOS). In order to achieve "carbon neutrality," it sets minimum requirements for measuring, auditing, and offsetting a company's carbon footprint In South Africa, carbon tax offsets are approved by the relevant standards for specific projects. All projects are subject to the mandatory processes involved in project registration and credits issuance as defined by the standard. In order to determine the carbon credits due to the generation of green energy, secondary data using document collection was employed. The documents used includes company reports, data and other documents showing energy usage and green energy generation for the W2V plants constructed. The amount of green energy produced from chicken waste was used to determine the value of carbon credits due to the South African chicken producer. Cost savings are calculated based on the amount of energy produced versus the actual cost if paid for from Eskom if the produced energy was purchased. With an ongoing yearly increase in tariffs between 18% - 25%, the most recent rate of 1.051 was used.

3.5. Sampling

3.5.1. Sampling for qualitative data (interviews and questionnaires).

The interviews collected part of the data required to address sections of the objectives 1-3. The study participants were limited to the SHEQ managers and from the chicken processing plants. The sampling plan employed was purposive sampling plan where a selection of study participants that fits specified criteria was employed. The participants for the interview and questionnaires included only those people with in-depth knowledge of the workings of the W2V plant and the related waste generation and management processes for the company.

3.5.2. Description of sampling points for the chemical analysis of wastewater samples.

Chemical analysis data for wastewater and surface water was obtained from secondary data collected by the company and the municipality and is recorded. Analysis of surface water and wastewater is carried periodically to monitor pollution. The samples are described as below.

3.5.2.1. Slaughterhouse Wastewater Feed

Wastewater from the slaughterhouses at the two processing plants is collected for recycling where it undergoes an initial settling process in the dissolved air flotation (DAF) system to remove much of the suspended organic matter and other solids. From the DAF system, a high COD wastewater sludge, and the untreated water are separated. The untreated water from this process enters the reverse osmosis system where samples are collected for the inlet and outlet points before and after water treatment. Grab samples are collected and logged on an hourly. The samples are analysed immediately for COD, pH, temperature and electrical conductivity.

3.5.2.2. Drain Discharge Monitoring

Wastewater monitoring for drain discharge within the processing plants, and those away from the plants at strategic location to detect effluent discharge from the plants is carried out periodically. Collection of drain samples is performed by both the company and the respective municipalities for monitoring of industrial effluents. The collected results for analysis in 2020 and 2021 showed that the municipality collects drains samples for analysis from the municipality drains once every month. The company collects samples each time the municipality collects. Company drain samples were collected and analysed twice in 2020 for the three processing plants.

Table 3.2 below lists the sampling sites. Sample collection method used is grab sampling at the municipal discharge point in 250 mL plastic bottles. The samples are collected in the morning at 06:00 hrs or in the evening at 18:00 hrs. After sample collection, parameters such as the COD and pH, that can be analysed on the field are analysed and recorded before transporting to the laboratory for analysis. The samples are transported in cooler box to the laboratory where they are analysed immediately on arrival. Separate samples for total suspended solids are collected in 1000mL plastic bottle (D) 24-hour maximum holding time.

3.5.2.3. Surface Water Monitoring

Chemical analysis of water samples from the reservoirs of surface water close to the processing plants is performed periodically to monitor water for pollution from the effluents from the processing plants. Water samples are collected from the dams presented in Table 3.2. as well as to monitor pollution. Dam water sampling involved multiple gab samples using standard procedure, in triplicates at 30 cm below surface, into a pre-washed and acetone rinsed 1.00 L amber bottles. Samples were collected in the morning at 06:00 hrs or in the evening at 18:00 hrs. After sample collection, parameters such as the COD and pH, that can be analysed on the field were analysed and recorded before transporting to the laboratory for analysis. The samples are transported in cooler box to the laboratory where they are analysed immediately on arrival. Separate samples for total suspended solids are collected in 1000mL plastic bottle (D) 24-hour maximum holding time.

Table 3.2: Table indicating the sampling points for wastewater

Sampling Point	**Sample Type**	**Sampling Point Description**
RTB Rainbow	Drain Discharge	Worcester, Western Cape, South Africa. 2.4km away from a nearby local river
W2V Rainbow	Drain Discharge	Rustenburg, North West, South Africa. Near the construction companies and feed mills which is 4.6km away from the W2V plant.
Municipal Drain	Drain Discharge	Rustenburg, North West, outside the construction sites. It is residential area about 4.6 km south from the city centre.
Clear Dam	Dam Water	Gravity/earth-fill type dam on the Hex River, a tributary of the Elands River, part of the Crocodile River (Limpopo) basin. It is located near Rustenburg, North West, South Africa. Its primary purpose is for irrigation. (25°33′45″S 27°21′14″E)
Mixture Dam	Dam Water	Dam is situated approximately 90 km northwest of Pretoria, on farm Bulkop 75 JQ. The dam completed in 1972, was built 300 m downstream of the merging rivers Hex and Elands. (25°37′45″S 28°11′22″E)
Dirty Dam	Dam Water	Kwaggaskloof Dam is a dam on the Wabooms River, near Worcester, Western Cape, South Africa. It was established in 1975. 2.4km to residential area and local malls. 107 km from the airport (33°46′6″S 19°26′4″E)

RTB (#1) Night	Drain Discharge	Processing Plant - 5.5km away from residential areas and 20.8km from Camperdown Rural Area (29°47'40.0"S 30°39'23.1"E)
RTB (#2) Night	Drain Discharge	Production Plant - 5.5km away from residential areas and 20.8km from Camperdown Rural Area (29°47'40.0"S 30°39'23.1"E)
Municipality (Morning)	Drain Discharge	Approx. 3km, outside the Processing and Production plants and 2.5km away from residential areas and schools.

3.6. Data Analysis

De Vos (2002) regards data analysis as the process that brings order, structure, and meaning to the collected data to extract important information that addresses the objectives of the study. The main purpose of this research was to evaluate performance of the bioenergy production using of chicken waste at a chicken producer in South Africa. The collected data comprised both qualitative and quantitative data. The collected data was analysed and verified by comparing consistency in the data collected from different sources. That was performed to ensure that the data used for further analysis was valid, especially data collected from tools that are deemed subjective. Document analysis for extraction of quantitative data from the reports and records collected with information regarding the waste generation from poultry processing for the company for the period between 2015-2021 was performed. All findings that were gathered during this process were documented and captured on Microsoft Excel. Statistical analysis was performed on the quantitative data collected from the reports and records for waste generation and utilisation, and bioenergy production for the three sites under investigation, covering the period between 2015 and 2021.

Primary data with records for the waste production and energy generation for the W2V plants was limited to 2-6 months periods of data recorded within the 2019 and 2021 timeframe due to data availability limitations from the company. For Rustenburg, limited data in 2021 was provided as the plant is only recently commissioned. Data obtained include amounts of poultry wastes produced by the processing plants, statistics on utilisation and disposal of the various waste types for various waste management processes within the company. The other data processed included biogas generation and compositional analysis for the W2V plants, electricity, steam and heat generation for waste plants. The data for waste generation at the Hammarsdale processing plant was corroborated with the data from the Mariannhill landfill site where most of the waste which cannot be reused or recycled is disposed of.

Qualitative data analysis in this study involved triangulation of data. Triangulation refers to a process where multiple methods or data sources are applied in qualitative research to develop a comprehensive understanding of the data. Qualitative data was collected through interviews, observational studies, and document review. Content analysis was used to interpret the information contained in the provided documents as well as records from observational reports by the researcher. The data analysis procedure involved organising the content, appraising, and synthesising the information from data contained in documents. The data from the documents was corroborated with that from the interviews and questionnaires. Interview data were analysed using framework analysis. This will involve summarization of the data and organized into themes or patterns.

3.7. Research Limitation

The study faced several limitations. The major challenge involved permission from the company to get access for some of the privileged data where clearance was not granted and therefore limited information was available to adequately address some objectives and facilities. In some instances, the primary records were with the third parties who also had clearance level permissions restrictions to such data. For instance, data for waste generation, generation of electricity and biogas generation was limited to between 2-12 months of data. Some of the data was available for some processing plants and limited for the others. Data on the wastes was not segregated and therefore the various types of wastes produced could not be separately quantified.

Due to limited time period for the provided data, seasonal variations could not be processes. The other challenge was that the primary data was not centralised, and therefore presenting challenges when requesting from the various plants. With the Covid-19 pandemic, strict measures were put into place, limiting direct access to specific sites. The availability of documents and poor document management were the other additional limitations encountered during the research, resulting in the researcher having only had access to a limited amount of data than expected. Plans were put into place to mitigate this limitation, allowing scheduled meetings via Skype and other communications methods. Visits to waste management sites was monitored due to staff limitations. All social distancing and best practices were adhered to during this COVID-19 pandemic.

3.8. Ethical Considerations

In this research study, the researcher observed all the ethical considerations such as informed consent to talk and interview respondents. Everyone who took part in the research was made aware of the conditions of the research. Participants were required to sign a consent form that indicates their willingness to participate in the research study. The respondents were provided consent to the questionnaire by answering the question, "I agree with the above and would like to give consent to complete the questionnaire." This question was at the start of the questionnaire. Participant's confidentiality was emphasized and maintained; it was expressly explained that the study is sorely for academic purposes. The basic information of the research was provided to the participants, including basic information such as the purpose and procedures of the research and the role and identity of the researcher. Confidentiality was maintained as much as possible by removing any identifying data from the final report and allowing participants the opportunity to agree or refuse to participate. No respondent personal data was captured in the study. All the information obtained from secondary sources during literature study and further research was referenced as a sign of acknowledgement of other people's academic work. The consent form explains the purpose and benefits of the study as well as which sections were going to be used in obtaining primary data. Findings would be made available to the respondents and the South African Chicken Producer and Landfill.

CHAPTER 4: RESULTS PRESENTATION AND DISCUSSION

4.1. Introduction

This study investigated the waste management processes and the performance of bioenergy production at the facilities of a large poultry producing and processing enterprise in South Africa. The study focused on the following key indicators to address the objective of this study:

- poultry waste generation and disposal processes at a major poultry processing company,
- environmental impacts related to the bioenergy generation,
- economic benefits related to the generation of bioenergy and,
- the performance of the bioenergy plants in terms of energy generation using the available infrastructure.

The study showed that the chicken industry in South Africa is a heavy waste producer, producing excessively huge amounts of wastewater and solids wastes from the slaughterhouses that pose grave dangers to the environment, especially the water resources. While the solids are generally disposed of through various disposal strategies such as landfilling, composting and rendering, disposal of wastewater sludge has been the main problem in the industry. For the facilities in this study, conversion of wastewater sludge into biogas and onsite electricity generation has become an integral part of the waste management practices. On the key objective of the study related to the performance of bioenergy in terms of electricity generation, this research observed that W2V plants are not operating to their optimum capacity. However, the study also observed that there were several economic and environmental benefits related to the construction of the W2V plants at the poultry processing plants under investigation. These findings are discussed in more detail in the sections below.

4.2. Waste Production and Disposal at a Large Chicken Firm in South Africa

4.2.1. Waste Production

The chicken producing and processing firm under investigation has farms and processing plants throughout all provinces in South Africa with large scale operations in at least three provinces: KZN, North West, and Western Cape provinces. The study mainly focused on the activities at the processing plants in Durban, Worcester, and Rustenburg. Large scale operations in the Western Cape and Northwest provinces necessitated the need for the development of W2V plants which are currently operating and converting the bulk of the wastes produced by the plants, therefore reducing pressure on the landfill sites. These projects have been driven by the chicken producer's vision as described in one of its KPI stating its ambition to become a waste-free business by minimising waste going to landfills and exploring ways to turn waste into value and to achieve zero waste to landfill by 2025 (RCL Foods, 2018).

The schematic diagram in Figure 4.1 below shows a summary of the processes involved at the three processing plants. Both Worcester and Rustenburg have W2V plants that are already running, converting large amounts of their processing wastes into value products. The plant in Worcester (a 1.5 MW electricity generator) only uses the energy-rich wastewater sludge from the slaughterhouses as feed for biogas production into the anaerobic digestors (wastewater feed-in Figure 4.1). The plant in Rustenburg (a 6 MW electricity generator) uses poultry manure from the production side (chicken farms) in addition to the energy-rich wastewater sludge from the processing unit as feed for biogas production. Both feeds are illustrated in Figure 4.1. The processing plant in Durban is without a W2V plant and therefore relies primarily on composting, rendering for animal feeds and landfilling as waste management practices for the disposal of their processing wastes. Its wastewater is treated on the DAF system and released into municipal effluent line without further treatment.

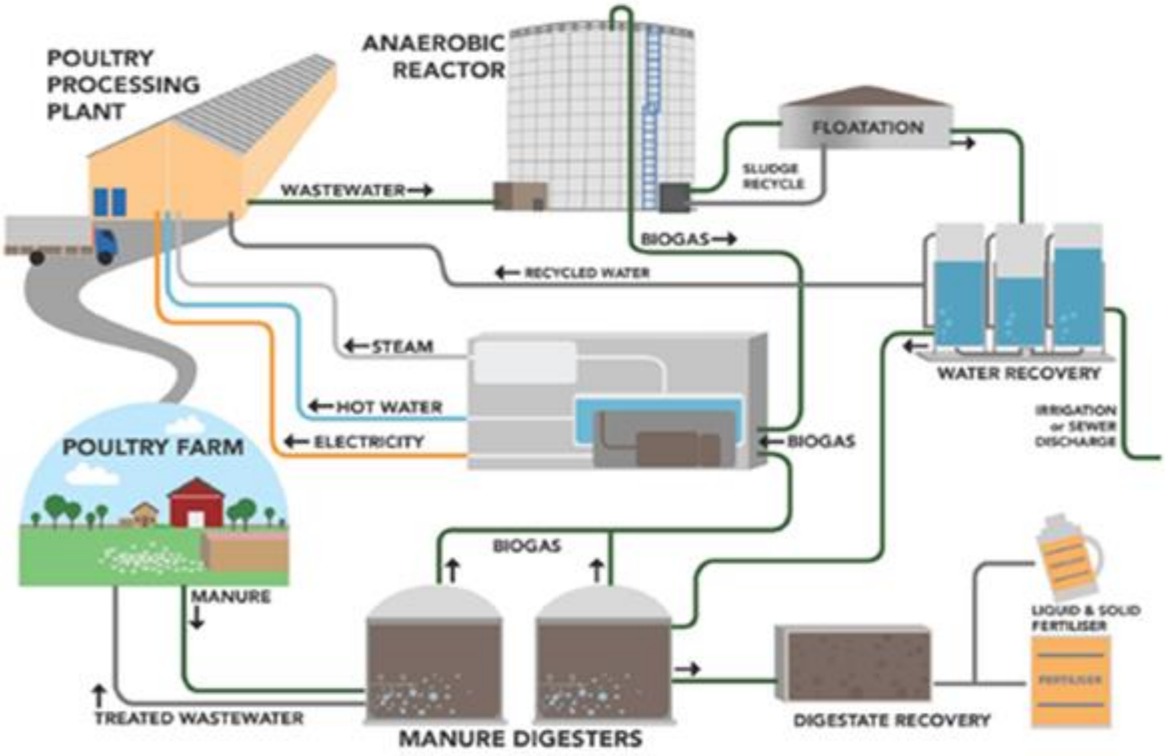

Figure 4.1: Figure showing the schematic presentation of bioenergy generation from poultry waste for the W2V plants in Worcester and Rustenburg

Data from an interview schedule carried out with the SHEQ managers of the W2V plants in Worcester and Rustenburg using questionnaires presented in Appendix E is presented in Table 4.1 below. The questionnaire was completed without the disposal method since the disposal methods were not documented per waste category (Table 4.1). These chicken processing wastes are separated into two main components: the first component being the wastewater which is collected and sent to the DAF system while the other mixture consists of much of the solid waste components from the dressing of the chickens (Table 4.1).

The solid waste components of poultry processing wastes consists of feathers, blood, meat trim, bones, necks, heads, and viscera (Table 4.1). This mixture is sent to the rendering plant to produce animal feeds. While much of this solid processing wastes is sent to the rendering plant for production of animal feeds, there are also secondary wastes related to poultry processing that were noted from the production of animal feed highlighted in Table 4.1. These waste components are discussed in more detail in sections below.

Table 4.1: Types of Waste and the estimated quantities produced daily from the data collected from interviews with the SHEQ managers from the two processing plants in Rustenburg and Worcester.

Waste Category	**Source**	**Daily Waste Production**	
		Rustenburg Processing Plant	**Worcester Processing Plant**
Energy-Rich Wastewater Sludge	By-Product of Wastewater Treatment	100-120 tons	
Chicken Processing Waste (Viscera, blood, feathers, fats, bones)	Chicken Processing	100-120 tons	90-100 tons
Poultry Manure	Production	80-100 tons	
Animal Feed	Rendering Plant	5-8 tons	3-5 tons
Wastewater	Chicken Processing	1500-2000	1500- 2200 kL

4.2.1.1. Solid Chicken Processing Waste

Results from the interviews presented in Table 4.1 above indicated that as much as 100-120 tonnes of chicken processing waste consisting of viscera, blood, feathers, fats, and bones was being produced daily in the chicken processing plants. This waste production data from the interview was corroborated with data collected from the literature, the company documents, and data from the production sites. There was no data showing total poultry waste or the segregation of the various solid waste types from company documents. However, data from the company's records reporting on the total monthly wastes send to the landfill sites, compositing and the rendering plant were used to approximate total poultry waste from each plant and to also investigate the waste situation in the company. The data is presented in Figure 4.2 below. The presented data from waste management records showed that between 13-28 tonnes of solids wastes are produced daily at Rustenburg processing plant while 8-11 tonnes are produced daily at the Worcester processing plant. These values for solid waste generation were much lower (about 4-8 times smaller) than the approximations by the SHEQ managers. Further analysis of the data was considered to develop a better picture of waste production and segregation at the processing plants. In order to achieve this, waste production data was approximated from slaughterhouse figures the two processing plants.

According to literature, approximately 20-30 % of the total weight of a poultry bird is converted into waste in the slaughtering process (Arshad, et al., 2018). This approximation includes the heads, feet, viscera, bone meat trim, feathers, and blood. According to Williams (2019), blood is approximately 2-3 % while feathers comprise approximately 4-7 % of the total live weight of the bird. According to Ashard et al., (2018), viscera and the heads each account to about 4-5 % while bone meat trim accounts 7-8 % of bird's live weight. The total amounts of waste produced however vary from place to place and related company processes. In South Africa, the chicken feet, necks, and some of the internal organs are processed and sold as food and the remaining viscera goes to waste.

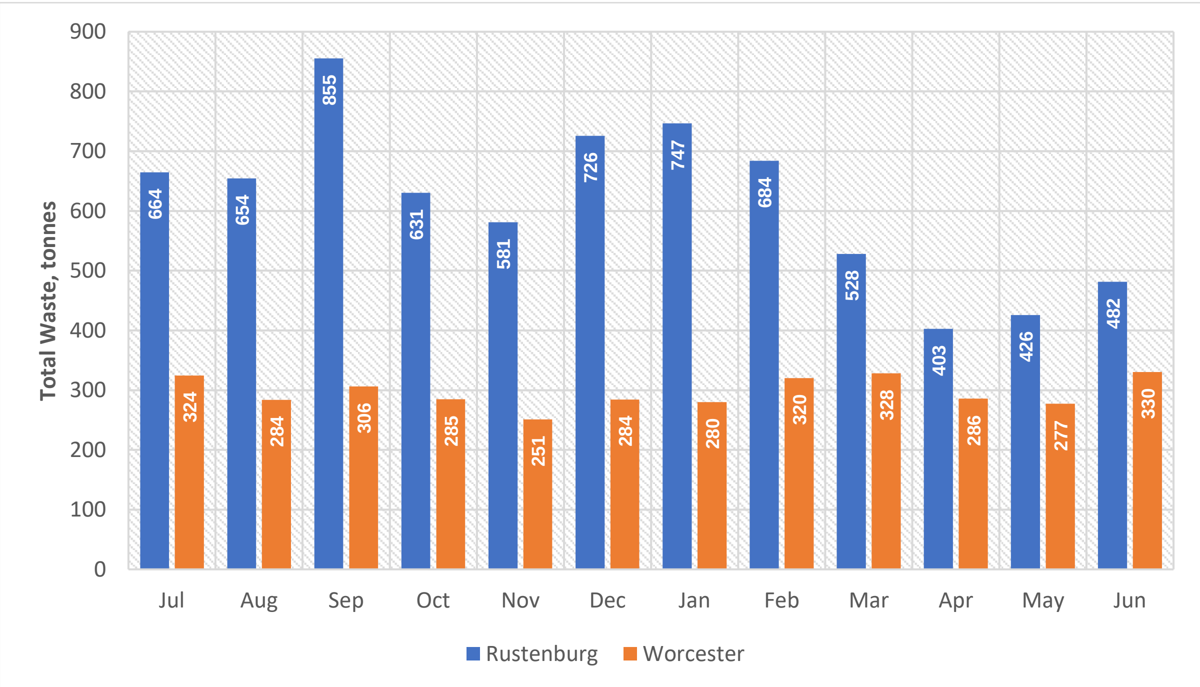

Figure 4.2: Total waste calculated from records on waste send to the landfill, composting site and the rendering plant for the Rustenburg and Worcester processing plants.

At the company involved in this study, only the chicken feet, hearts, livers, and gizzards are collected and sold as meat. Using the approximation from Arshad et al. (2018), it can be concluded that for this poultry processing plant in South Africa, the 20 % approximation may be a good estimate of the total poultry bird's live weight that is converted into waste. Figure 4.3 below shows typical statistics for the chickens slaughtered daily and the mean weight of the birds from the Worcester processing plant in the Western Cape. The mean chickens slaughtered daily over four months in 2021 shown in Figure 4.3 is 282 470, with a mean weight of 1.77 kg. From this data, it can be approximated that approximately 100 tonnes of poultry waste are produced daily from this plant, in agreement with the interview data.

Additional data for total dress weight for each plant which covered a much broader period (24 months) than what could be extracted from the presented data for the various waste management components (landfill, composting or rendering plant) were used to corroborate the collected data, draw conclusions for other plants without the recorded data and to provide a much broader view of the waste situation in the company and identify potential hotspots and problem areas regarding chicken waste production in the company.

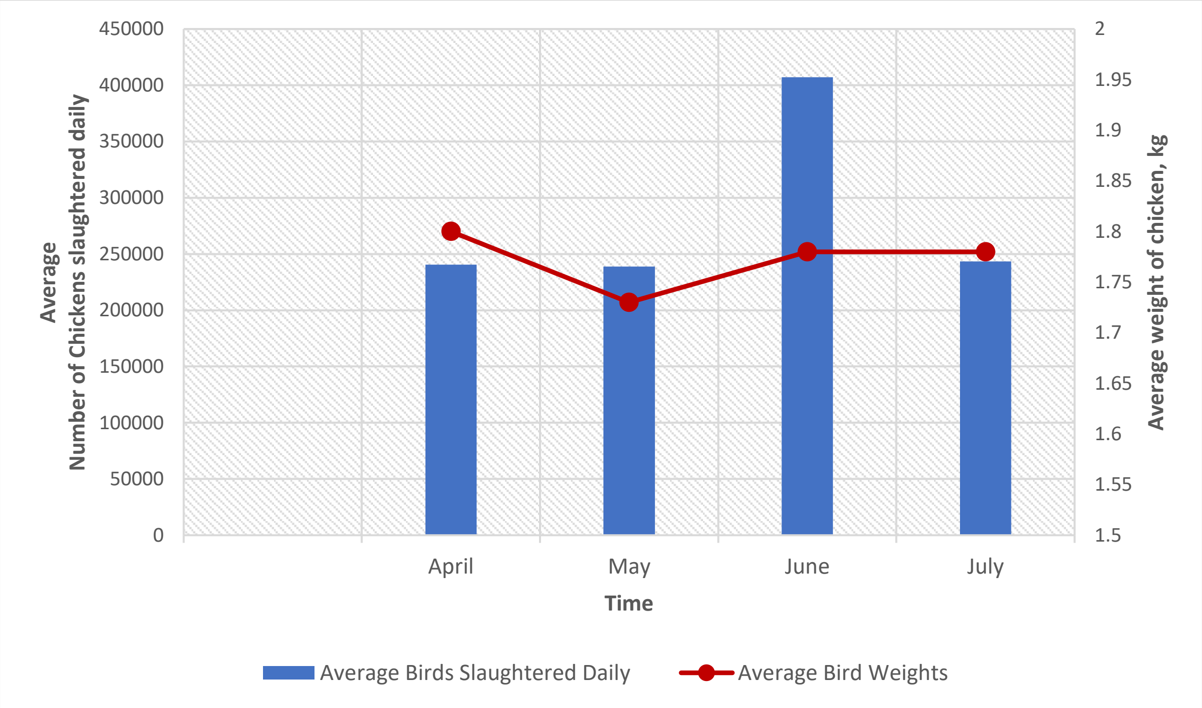

Figure 4.3: Average number of chickens slaughtered per day and the mean weight for the ***Worcester*** *poultry processing plant for the period between April and July 2021*

Figure 4.5 show the reported total dress weight per month for each of the Rustenburg and Worcester processing plants for the period between July 2020 and June 2021, which overlapped with data from Worcester for the months April, May, and June. The reported dress weight for this period was used to verify alignment of the data. The data for waste production was then evaluated from the projections using the approximation for waste production shown above by Ashard et al. (2018) using the dress weight.

Using the same data and approximations, waste segregation profiles were developed for the two plants (Table 4.2). The presented data shows that about 30-40 tonnes of feathers are produced daily at each of the two processing plants. Bone meat trim is bf far the largest of these listed waste types, with a daily production of around 50-60 tonnes. While the mass of bone meat trim and viscera produced daily considerably large (about 55 tonnes and 35 tonnes respectively), these two waste types are reused in the rendering plant and are not considered problematic for the environment. However, some of the viscera components are washed resulting in the high COD load of the wastewater. The feathers are however problematic, in most cases ending up on the landfill. The blood is also problematic because it washed by the water and becomes the one of major pollutants in the wastewater.

Table 4.2: Table showing the daily and annual waste production for chicken processing plants in Worcester and Rustenburg, evaluated using approximations by Ashard et al. (2018).

	Rustenburg Processing Plant (Tons)		Worcester Processing Plant (Tons)	
	Daily	Annually	Daily	Annually
Feathers	43,0	15484,7	32,4	11660,6
Blood	21,5	7742,3	16,2	5830,3
Viscera	38,7	13936,2	29,2	10494,5
Bone Meat Trim	64,5	23227,0	48,6	17490,9

The results were compared with data from records for waste management data reported earlier in Figure 4.2. The profiles of the waste generation are closely related, showing an increase in waste generation from around September to the period around January (Figure 4.2 vs. Figure 4.4). The December and February period seems to be the busiest in terms of chicken meat production and the period between March and July seemed to have the least poultry meat generation. The period between December to February should subsequently be the period with the highest waste production values. The data however shows that Rustenburg processing plant is by far the largest chicken processing plant in the company, producing a total of 267,8 kilo tonnes for the given period, which translates to a monthly average of 22,3 kilo tonnes per month of dressed chickens (Figure 4.5). Waste production for the Rustenburg plant is also much larger, averaging 5,58 kilo tonnes per month while the Worcester plant averaged 3,81 kilo tonnes per month evaluated from dress weight for a 2-year period.

The average daily waste data presented in Figure 4.5 projected from dress weight in Figure 4.5 agrees with earlier projection for generation of solid wastes above, as well as the data from interviews showing that approximately 100-120 tonnes of chicken waste was produced daily. However, data from these projections doesn't agree with data for waste generation using waste management data that seems to show much lower wastes than those projected from dress weight.

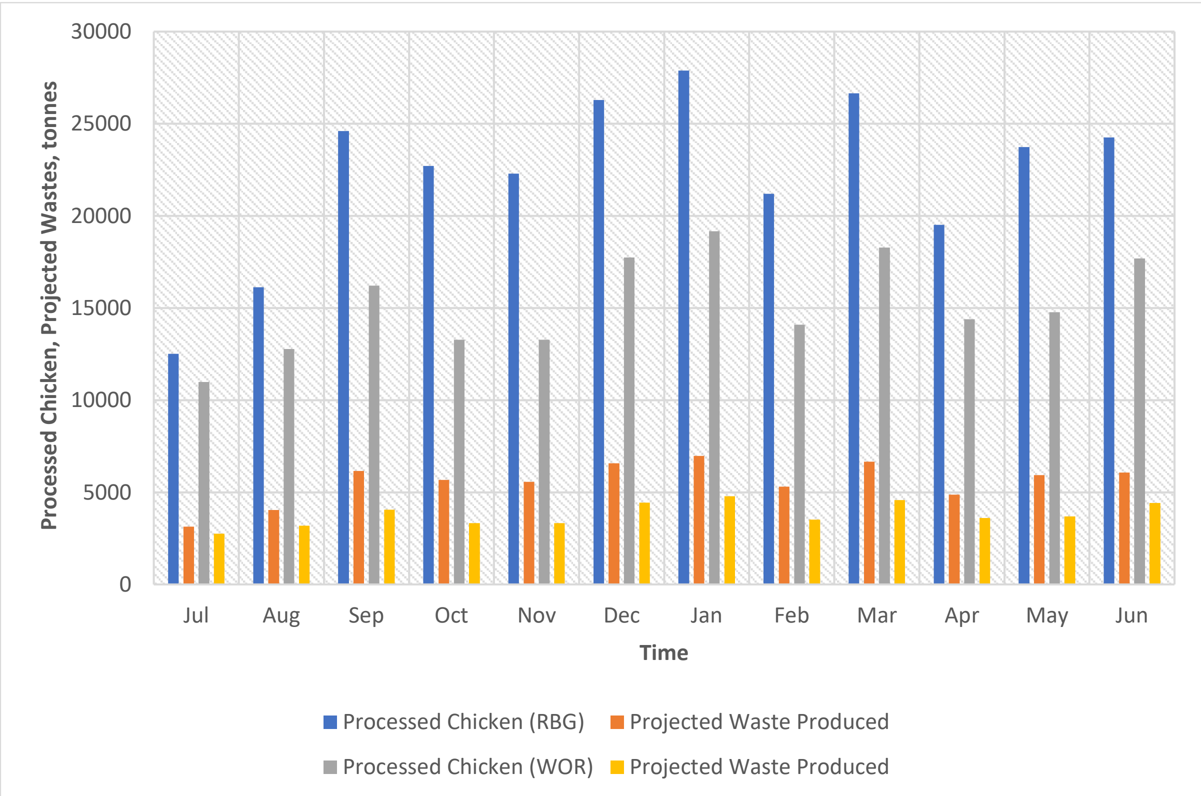

Figure 4.4: Total monthly dress weight of chickens and projected monthly waste production at the Rustenburg processing plant in North-West and the Worcester processing plant in Western Cape.

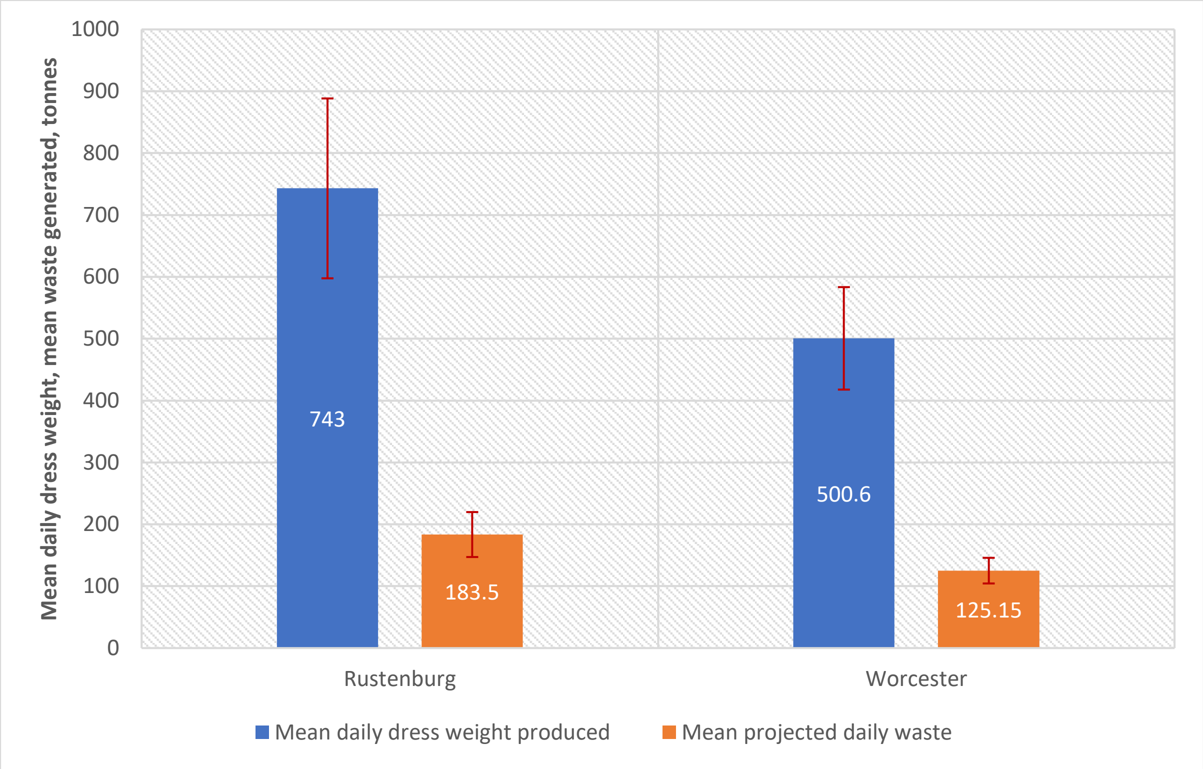

Figure 4.5: Data showing average annual processed chicken, and the calculated total poultry waste generated for each plant.

It was observed that much of the waste records were recorded and kept by the third parties that are involved in the collection and disposals of the wastes. The difference observed with records of waste management could be attributed to incomplete records in the presented data, or partial records because of multiple players taking part in the waste management. This could explain the disagreements between the provided data. These results show that not all the wastes are accounted for in the data from the records. Some of the wastes not accounted for in the calculation include the wastewater sludge, which is the most problematic in terms of disposal. The presented results show that chicken processing produces a huge amount of waste and therefore has huge potential for rendering by converting the wastes into useful materials.

However, it should also be noted that improper disposal of the wastes poses severe environmental impacts on the groundwater and the soil (Environment Protection Agency, 1999). While much of the project was focused on processing waste from the poultry slaughtering houses, the Rustenburg plant also uses manure as feed. Precise data could not be obtained on the population of the birds in the chicken farms affiliated to the chicken enterprise of interest in the study as well as the statistics of the birds in different phases of growth. However, according to the company data, the enterprise has 20 million chickens in its farms at any given moment (RCL integrated annual report, 2018). According to Tanczuk et al. (2019), adult birds produce about 150-160 g of droppings daily while the young ones produce 65-100g every day. According to a report by the South African Poultry Association report, at least 48 % of the chicken's farms in the country have a bird population of between 100000 – 400000. By approximating the mean of this range as the mean bird population for the chicken farms in the country and using a mean of 110 g for droppings from each bird every day, this approximates 27.5 tonnes of chicken waste production (litter) every day. Oliveira et al. (2012) estimate that a bed necessary for the production cycle (40-60 days) of a bird is about 2.19 kg, which was used to approximate the amount of litter in their study. Using the two approaches, and average populations for a single farm, it can be approximated that waste products from the chicken farms are between 9.1 - 13.7 tonnes every day. For the 55 farms around the processing plant in Rustenburg, they should produce enough manure to satisfy their current target of 90 tonnes of manure waste per day. Figure 4.6 below shows the trend of production of poultry wastes throughout the company's poultry farms in the country in the years between 2018 to 2021. While there was a decrease in total poultry production waste in 2019 and 2020 of 14 and 18 % respectively, the results for 2021 show an uptick in waste production in the company's farms (Figure 4.6).

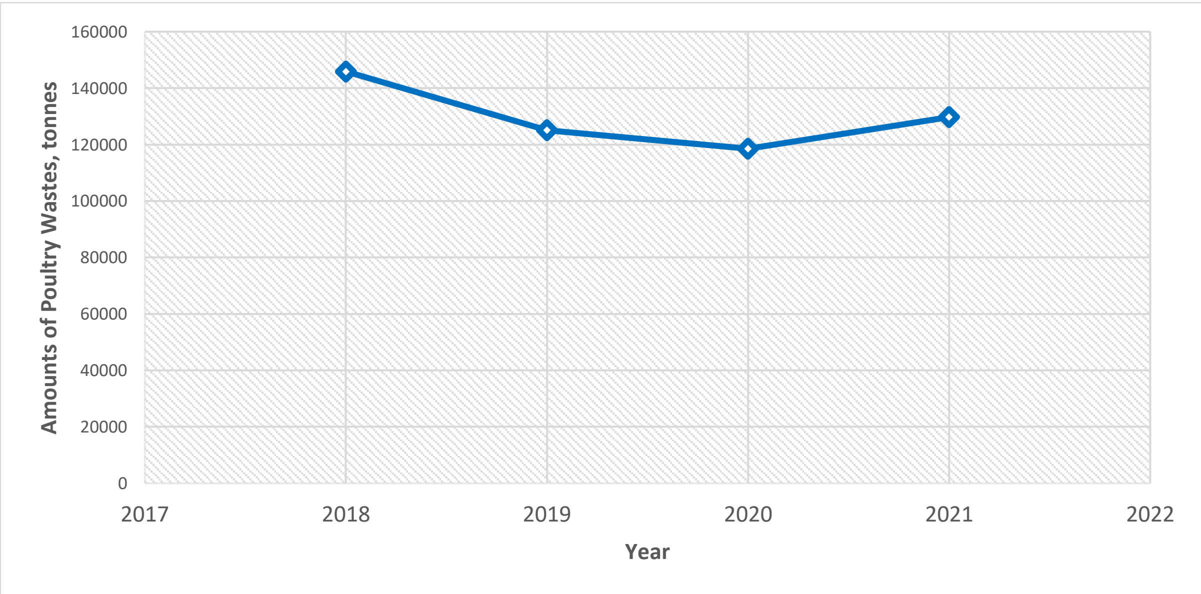

Figure 4.6: Figure showing total poultry waste production from the poultry farms for a major poultry company in South Africa

4.2.1.2. Wastewater and Wastewater Sludge

Wastewater and wastewater sludge were noted by the managers as the most potent and problematic of the waste volumes produced in the chicken production and processing industry. This waste results from significantly high amounts of water usage in the processing plants' slaughterhouses. According to literature, chicken processing uses between 10-30 L of water per bird (Chavez, Dendooven, & Escamilla-Silva, 2005); (Lujan, Morawicki, & Loo, 2016). For big poultry processing plants like Worcester and Rustenburg, this amounts to excessive water usage of around 1500-2500 kL on a daily basis. Water in the processing plants is "crucial" not only to maintain and clean the process areas, but also to enable many other basic operations such as stunning, scalding, chilling, carcass washing and cleaning and disinfection equipment" (Luján-Rhenals, et al., 2016). Slaughterhouse wastewater is a type of wastewater that is heavily polluted with organic matter (Yaakob, et al., 2018). Data collected from Worcester for three months (April to June in 2021) showed that on average, around 239000 were slaughtered every day, with an average water daily wastewater generation of 1871,6 kL (Table 4.2). This calculates to usage of about 7,83 L per bird, just below the values cited in literature (Chavez, Dendooven, & Escamilla-Silva, 2005). Limited data collected from Rustenburg and the Hammarsdale plants gave an average wastewater generation of 1495 and 237 kL respectively, translating to 7.8 and 8.2 L water usage per bird respectively (Figure 4.7). The wastewater generation for the three plants is summarised in the Table 4.2. It should be noted that the presented values were evaluated from limited data recorded as feed for the wastewater treatment systems for the various plants and may not indicate total wastewater generation for the respective plants.

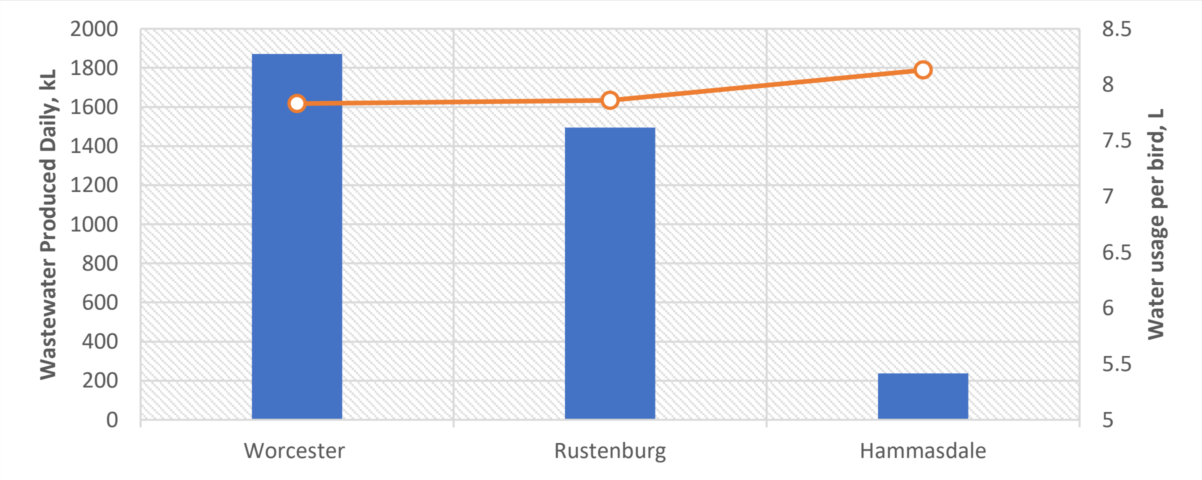

Figure 4.7: Figure showing waste generation and water usage per bird for the three processing plants

As a result of these slaughterhouse activities, water used for chicken processing picks up a huge amount of biodegradable organic matter, forming the wastewater. Table 4.3 shows the characteristics is this waster. The data recorded from the analysis of the wastewater from the three plants showed that it contained much higher degree of organic pollutants, with COD values of over 15000 mg/L average, which was higher than approximations by Bingo et al. (2019), and about 200 times higher the general guides for poultry effluent discharge. This could be explained by the amount of water used per bird (Fig 4.7) which is lower than those reported in literature (Chavez et al., 2005; Lujan et al., 2016).

According to Bingo et al. (2019), poultry wastewater contains high organic strength with COD values in the ranges 2000-10000 mg/L, BOD values of 4500-12000 mg/L and total suspended solids (300-5000 mg/L), as well as high content of phosphates and Total Kjeldahl Nitrogen. The wastewater produced from the processing plants had on average 255.4 mS/m of electrical conductivity, which is about 50 % above the general guidelines for poultry effluent discharge. Because of the high degree of pollution of the poultry wastewater, it is treated and disinfected onsite before it is released into the environment.

Table 4.3: Table showing wastewater generation for each of the three chicken processing plants and the characteristic parameters

<table>
<tr><th>Site</th><th>Raw Wastewater Treated Daily/ kL</th><th>Conductivity mS/m</th><th>pH</th><th>COD</th></tr>
<tr><td>Worcester</td><td>2560</td><td rowspan="3">255,4±50.0</td><td rowspan="3">5,8±0.3</td><td rowspan="3">15617±2754</td></tr>
<tr><td>Rustenburg</td><td>1495</td></tr>
<tr><td>Hammarsdale</td><td>237</td></tr>
<tr><td colspan="2">General Guidelines for Poultry Effluent Discharge</td><td>170</td><td>5.5-9.5</td><td>75</td></tr>
</table>

The treatment of the at company's processing involves an initial wastewater treatment in the DAF system for treatment to reduce its COD, BOD, total suspended solids, and other pollutants. Figure 4.8 below shows typical statistics of wastewater feed into the DAF system. On average 112.2 m^3 if fed into DAF system every hour for treatment. The water temperature is also monitored, the effluent for this day was on average 37.2 ^{o}C, 2.2 ^{o}C higher the target of 35 ^{o}C while the inlet was on average 31.4 ^{o}C. For a processing plant like Hammarsdale without a W2V plant, after the DAF process, the water is sent into the municipal discharge drains. The collected sludge discharge from the DAF process forms the energy rich wastewater sludge, which is used fed into the anaerobic digesters for biogas production. More details are provided in the section below on wastewater production.

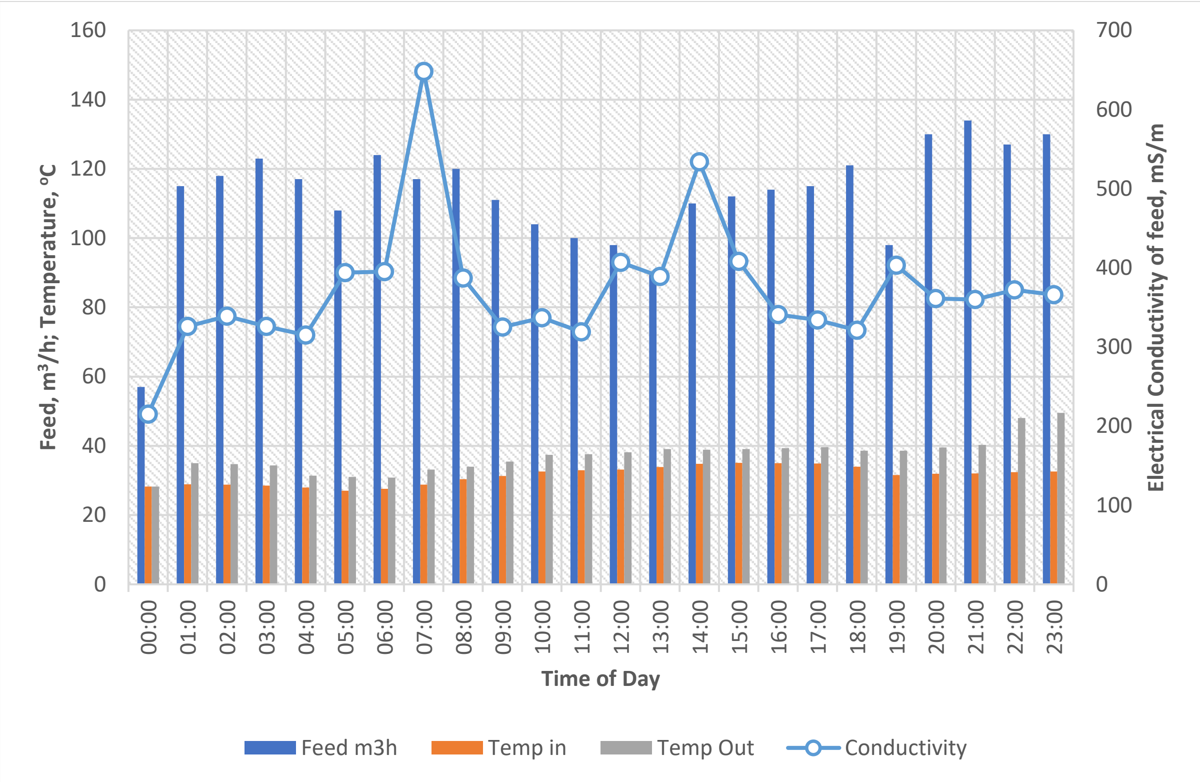

Figure 4.8: Figure showing wastewater feed in (m3/h) into the DAF system, the influent and effluent temperature and the electrical conductivity readings of the effluent stream from the Worcester plant.

Availability of wastewater treatment was a challenge for the two plants, with available data only restricted to limited time periods for the different plants to be able to develop seasonal trends. However, the Worcester processing plant data provided records for five months, which were for a much longer period compared to the data from the other processing plant and was therefore used for better clarification of wastewater generation. The results presented in Figure 4.9 below for wastewater generation for the month of April 2021 showed that much of the processing plant's activities are carried during the week and slowing down over the weekends. Average wastewater production during the weekend was between 500-750 kL per day, with Sunday recording no wastewater generation throughout (Figure 4.9). The same profile was observed for the other months. The average daily wastewater production calculated from a weekly profile shown in Figure 4.10 showed a similar trend reported for dress weight statistics for the Worcester plant (Figure 4.2), showing reduced production in the winter and increasing during the spring towards the summer period.

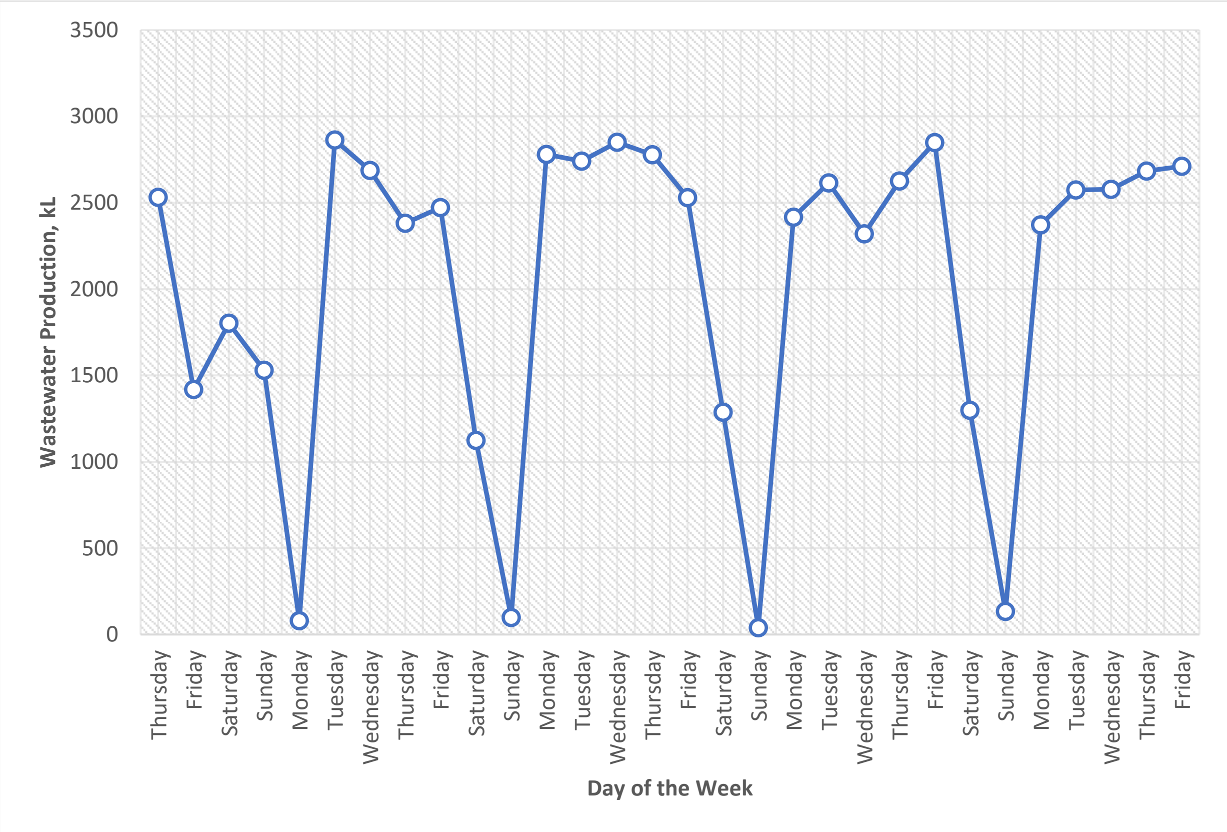

*Figure 4.9: Figure showing daily wastewater production for the **Worcester** plant for April 2021.*

Chemical analysis of the wastewater from the slaughterhouses is performed on an hourly basis when it's fed into the DAF system and on exit. The parameters recorded includes the COD, pH, electrical conductivity, and the temperature. Figures 4.11 and 4.12 below show the physicochemical parameters of the wastewater influent and the clarified water (effluent) from the DAF system. As was discussed earlier in Table 4.3, poultry slaughterhouse wastewater produced from the company's processing plants is highly polluted with average conductivities of around 260 mS/m, pH less than 6, and an average COD value greater than 15000 mg/L (Figures 4.11 and 4.12).

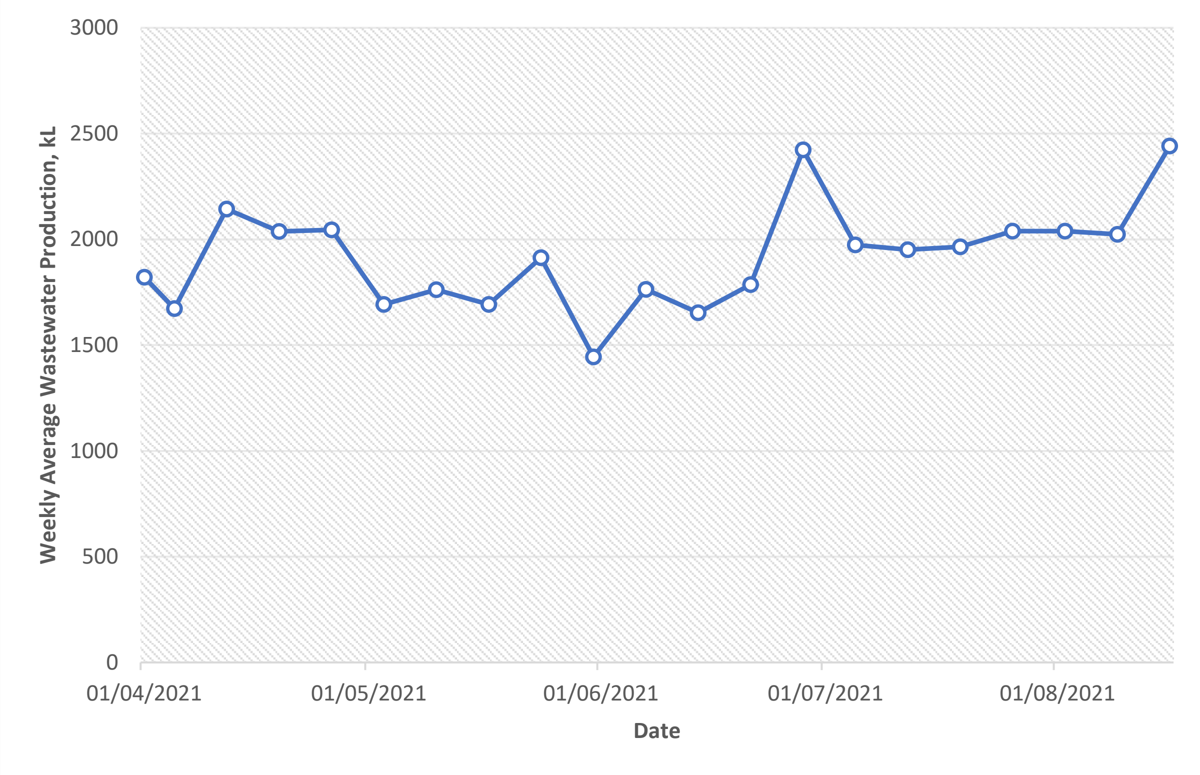

*Figure 4.10: The weekly profile for average daily wastewater production for **Worcester** processing plant for the period between April and June 2021.*

The chemical characteristics of the clarified (treated) water were compared with those of the raw wastewater from the slaughterhouses in Figure 4.11 and Figure 4.12 below. The daily average values calculated for each week show that an increase in the pH and conductivity of the effluent is observed (30 % and 49 % respectively) (Figure 4.12) while a decrease in COD of about 82 % is achieved by the DAF system (Figure 4.11). On average, up to 86 % of COD is removed in the DAF process based on daily data from 3 months. If the treated water has reused in the processing plant, it should be further treated because of the COD of 2200 mg/L and conductivity values of 373 mS/m that are over the quality guidelines (SANS 241, 2015). For the Worcester and Rustenburg plant, the treated water is transferred to the reverse osmosis for further purification and is collected as permeate which is reused in the processing plant. However, no data was available was available for the treatment or chemical analysis of the permeate from the RO system. Limited data was available from the Rustenburg plant for a week of analysis is shown in Figure 4.13 below.

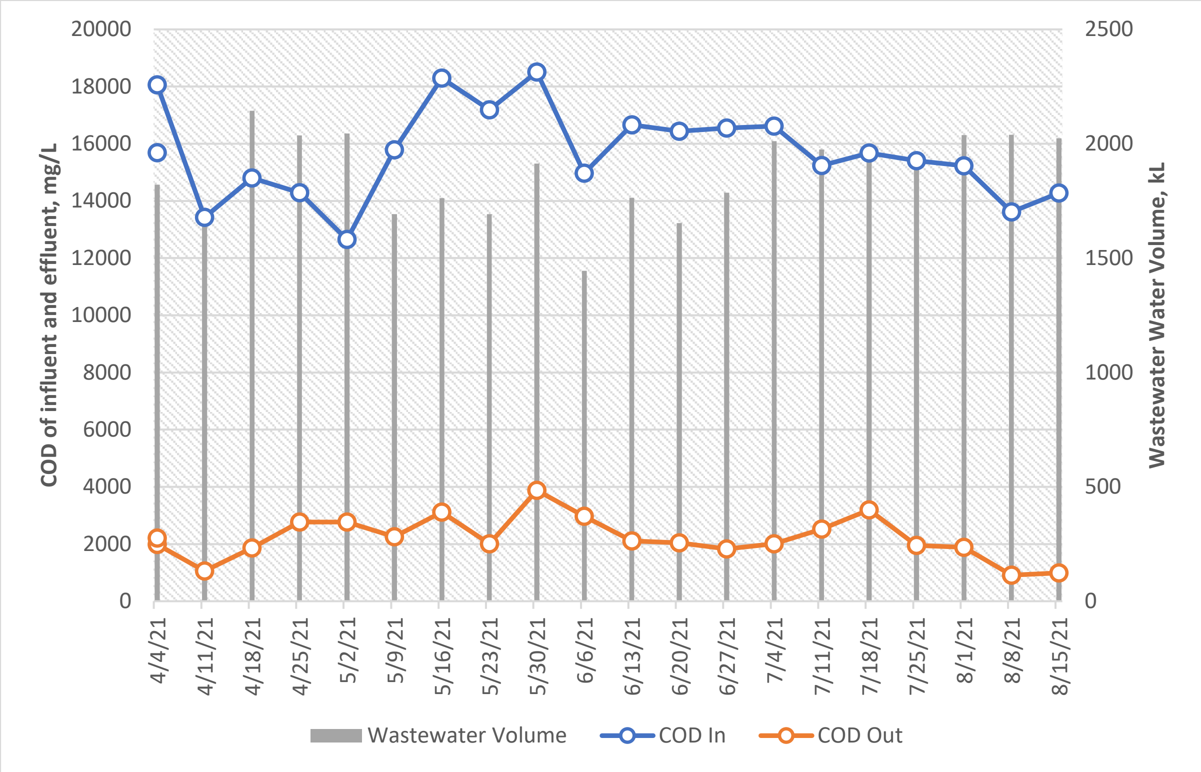

Figure 4.11: Figure showing the daily average COD values for the influent and effluent from the DAF system, and the average daily wastewater generation for the period between April and August 2021 for the ***Worcester*** *processing plant*

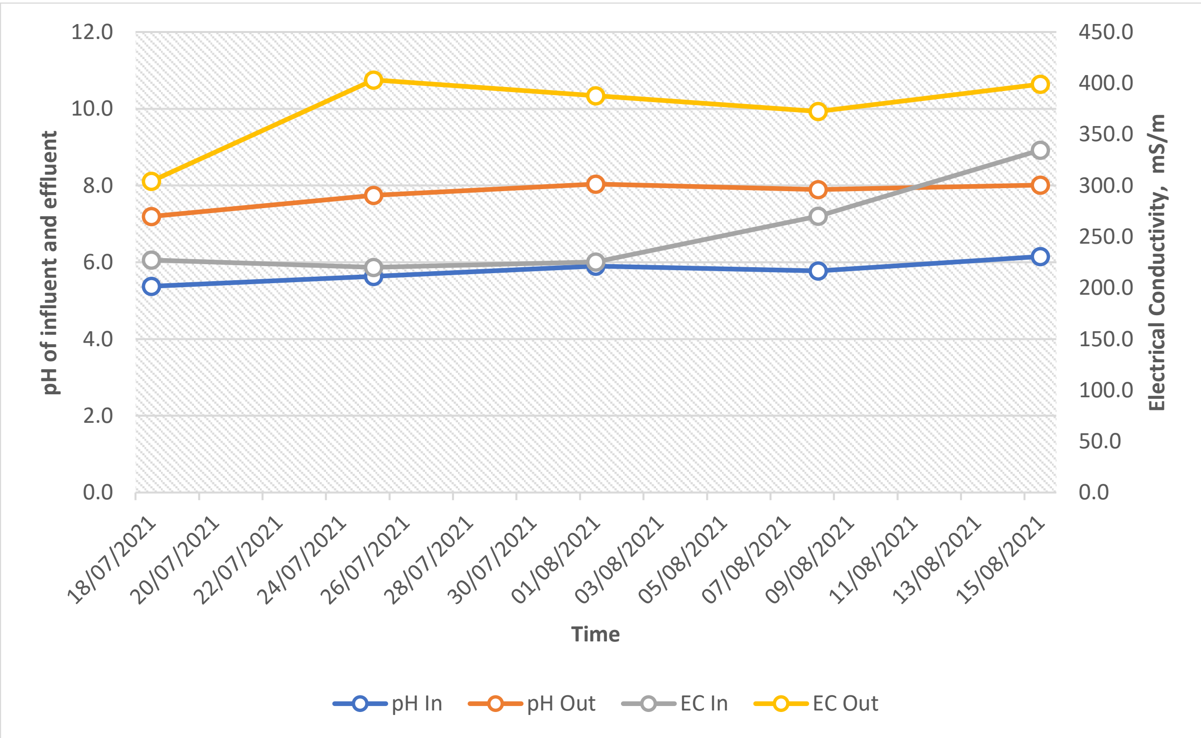

Figure 4.12: Figure showing the daily average pH and electrical conductivity values for the influent and effluent from the DAF system for the period between April and August 2021 for the ***Worcester*** *processing plant.*

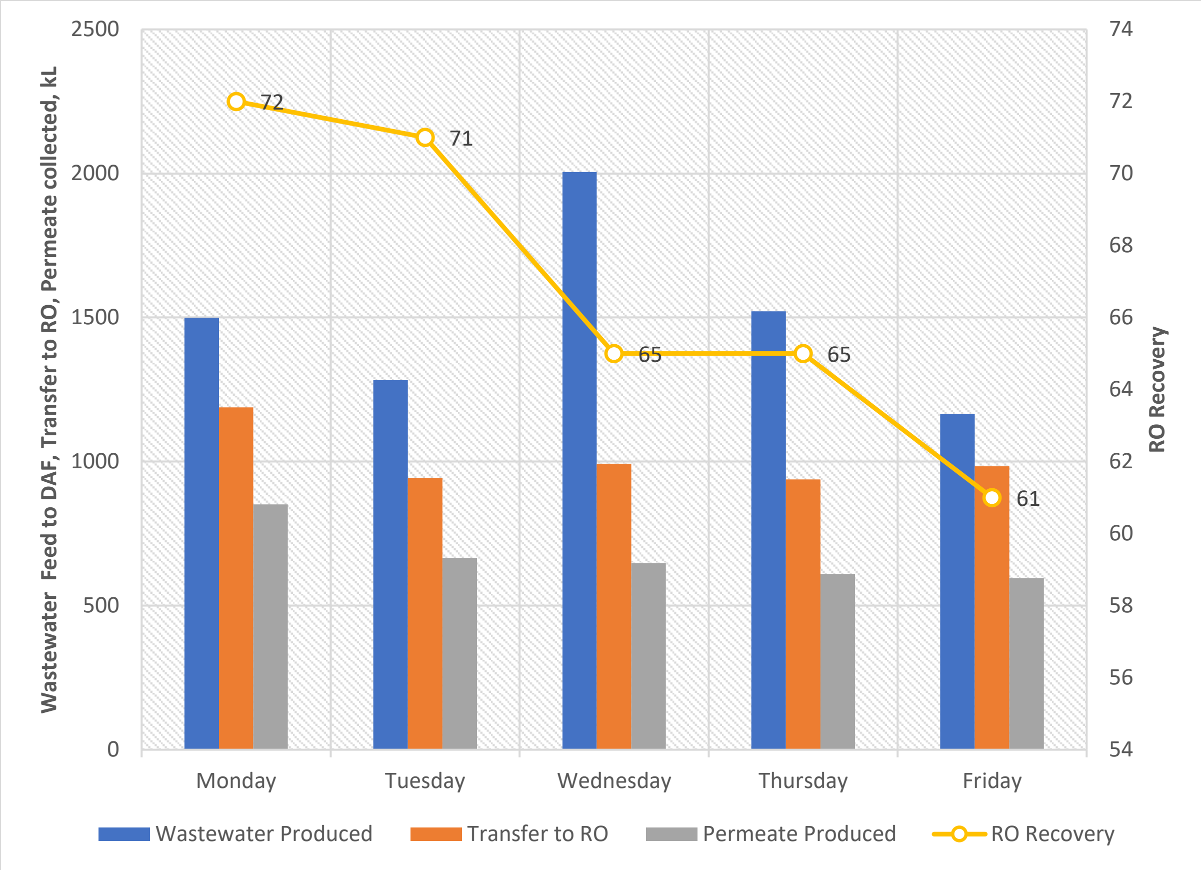

Figure 4.13: Figure showing statistics for wastewater feed into the DAF system, transfer to the RO system from the DAF system, and the permeate collected from the RO system for the Rustenburg plant.

Figure 4.13 shows the DAF feed, the feed into the RO system from the DAF effluent and the collected permeate after the RO process. According to the provided data, the design target feed into the DAF for the Rustenburg plant is 2050 kL every day, with a daily target of 1500 kL for the permeate. For the week in question however, the target were not met, achieving on average 73 % for the DAF feed, while the RO target scored a 45 %. RO recovery was evaluated from the feed into the RO and the collected permeate. Low percentage recovery indicate that more water is drained and wasted. The results showed a decrease in percentage RO recovery from Monday to Friday, with a recovery of 67 % on average. The change could be a explained by a number of factors such as the quality of the water feed, membrane performance and temperature among others. The reasons for that trend was not investigated. However, it should be noted that these results were recorded during the time the Rustenburg was still in its initial phase of normal operation after the commissioning of the W2V plant. The results therefore point to system that was still being optimised.

The DAF process also produces as by-product of the treatment process, a concentrate containing the removed organics and other solids. This concentrate is what is referred to as the wastewater sludge in Table 4.1. According to Aziz et al. (2018), the wastewater sludge has a high concentration of organics such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), phosphorous, and nitrogen. The SHEQ managers pointed out that the processing plants produced about 120 tons of the wastewater sludge every day. The organic matter load of this sludge water comes from different sources such as undigested food, blood, fat and lard, loose meat, paunch, colloidal particles, soluble proteins, and suspended materials (Aziz, et al., 2018). Figure 4.14 shows the typical COD composition of the wastewater sludge from the plant in Rustenburg. The analysis was performed for a week in July 2021. The wastewater sludge contains excessively high COD values averaging 126571 mg/L, which translates to about 12.4 tonnes of organic waste for every 100 tonnes of wastewater sludge. At such high COD values, this wastewater sludge from the slaughtering house is a major environmental risk and cannot be released into the environment. In the various poultry processing plants around the country, wastewater sludge has been reported to be the major problem. For this reason, the target of the W2V plants has been to convert this waste into value products while recovering the water for use within the plants. The Worcester plant is using almost all its wastewater sludge in the production of bioenergy, the W2V plant was receiving approximately 60 tons per day and slowly ramping it up to 100 tons per day. The Rustenburg W2V plant is in its early stages and is already using much of its wastewater sludge of about 110 tonnes of sludge every day for the generation of biogas for the W2V plants.

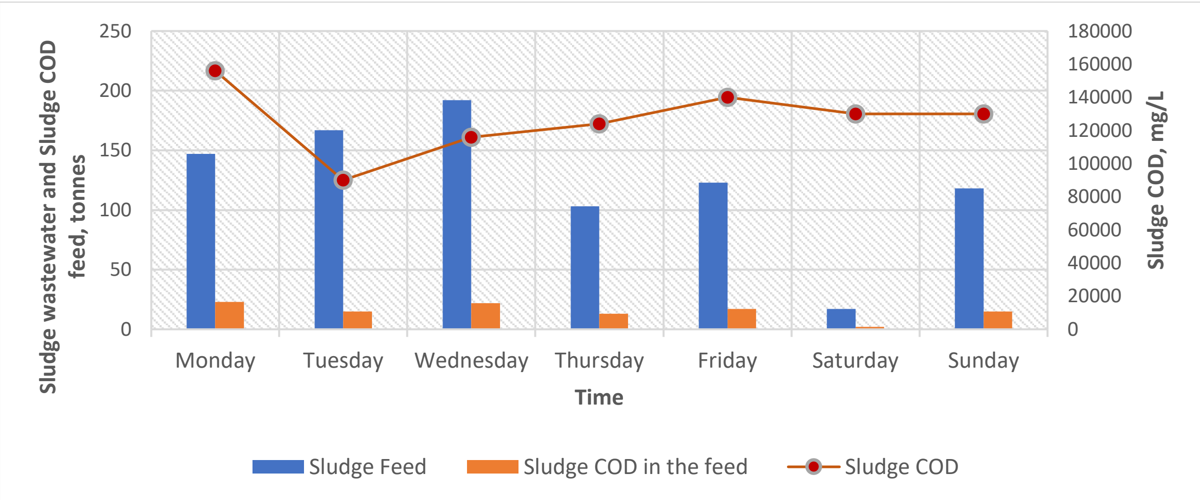

Figure 4.14: Figure showing the wastewater sludge and the organic load for the feed into the anaerobic digestor for biogas production for the ***Rustenburg*** *processing plant.*

4.2.2. Disposal of the poultry wastes

The discussion in the previous section showed that enormous amounts of wastes are produced in both poultry production and processing. Poultry waste is particularly a problematic biomass waste, with high content of plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Oliveira, et al., 2012). Proper management of the wastes is very crucial to mitigate its environmental impacts. One of the objectives of the study was to investigate the disposal processes used in the chicken industry. Results of the interviews were used to develop a waste inventory guideline for the waste classifications and the disposal processes involved for each type of waste as shown in Table 4.4 below.

The various waste management practices used in the poultry industry over the years include various recovery, reuse, recycling and disposal practices such as landfilling, composting (to produce organic fertilisers) and production of animal feeds as shown in Table 4.4. These methods remain the main disposal practices of choice for the processing plants without W2V plants like Hammarsdale. Chicken litter (manure) is the main waste from the poultry production side, mainly used for the production of organic fertilisers. All the other waste products are from the processing side and are sometimes very hazardous. The development of two W2V plants at the Worcester plant in Western Cape and the Rustenburg plant in North-West was necessitated by the growing wastewater sludge waste which the company struggled to deal with because of growing volumes of wastewater sludge. As highlighted earlier, these major plants are producing over 100 tonnes of wastewater sludge every day and an additional large amount solid processing.

The W2V plants have provided the company with additional options of dealing with increasing poultry waste and reducing amounts of wastes going to the landfill sites given the amounts of poultry waste from the plants in Worcester and Rustenburg as was highlighted above. Unlike the plant in Worcester, the plant in the Rustenburg province can process many diverse waste types and is used to process production wastes in addition to processing wastes. Animal feed production plays a very important role in waste reuse. The approximations used in the section above for the weight of the processing waste produced from poultry dressing is several hundreds of tonnes for the three plants (Table 4.4). According to interview results with the SHEQ managers, all the poultry bird dressing waste is reusable and is therefore harvested for use in the production of feeds or for composting. Rustenburg seemed to have had challenges with the volumes of feathers which they reported to have been landfilled several times. Composting has been one of the choices for poultry waste disposal and continues to grow because of its use as an organic fertiliser. The various disposal methods have been discussed in more detail in the sections below

Table 4.4: The types of wastes produced from the two plants

Type of Waste	Source	Disposal method
Energy rich wastewater Sludge	Chicken Processing	Production of biogas for the W2V plant
Wastewater/effluent water	W2V Plant	Treatment with the RO process
Feathers	Chicken Processing	Animal Feed, Excess is sent for Landfilling
Manure	Chicken Production	Composting (organic fertilisers) and Production of biogas for the W2V plant (Rustenburg Plant)
Viscera	Chicken Processing	Animal Feeds
Blood	Chicken Processing	Animal Feeds
Digestate	Biogas Production	Composting (organic fertilisers)

4.2.2.1. Production of Animal Feeds

The production of animal feeds is one of the waste management's practices that the poultry industry has been employed to deal with poultry processing waste and still plays an important role today. This method of waste management practices uses most of the poultry dressing by-products including blood, meat trim, the heads, feathers, and viscera to producing of animal feeds. This waste is harvested during the slaughtering process, it is collected in one container without segregation and is sent to the rendering plants. This rendering process involves heating these processing wastes from the slaughtering houses in large steam-operated batch cookers at a temperature of around 133 ^{o}C in order to extract useable ingredients, such as protein meals and fats. The product of the process is a thick soup which is then pumped into a tri-canter. The tri-canter splits the product into three, stick water, meat pulp and oil. The stick water goes to the waist to value plant, the meat pulp is sent to the drier to become poultry carcass meal and the oil is being sold, to be used in pet food factories. This process is very important as it ensures minimal waste ends up at the landfill site. Additionally, the process is facilitated by steam from the W2V plant, thus doesn't add additional energy requirements to the process. The statistics for poultry processing wastes going to the rendering plants obtained from the collected data for waste management from the two plants showed that an average of 431.4 and 105.4 tonnes of slaughtering waste is send to the rendering plant every month for the Rustenburg and Worcester processing plants respectively (Figure 4.15).

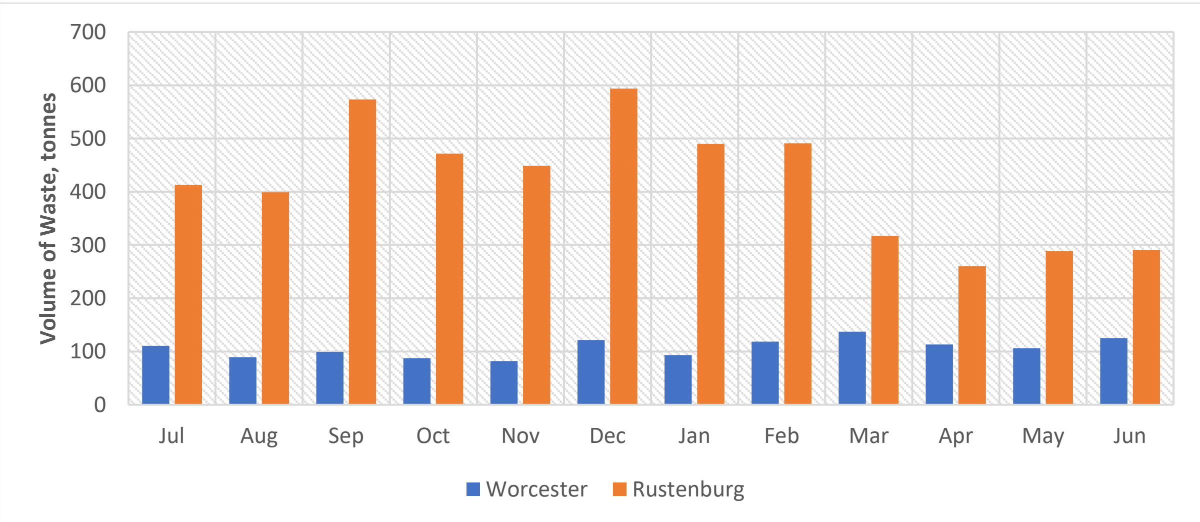

Figure 4.15: Statistics for processing wastes that are send to the rendering plants for the Worcester and Rustenburg processing plants.

For the Rustenburg plant, animal feed production takes up 67.8 % of the slaughtering wastes compared to 36 % for the Worcester plant. As was highlighted earlier in Table 4.4, this waste consists mainly of the solid waste from the slaughtering houses. While the production of animal feeds, especially chicken feeds, from slaughtering wastes is an important part of waste management processes in the company, the practice is no longer permitted in European countries because of concerns for diseases transmission, meat hygiene and ethical issues regarding cannibalism (Sari et al., 2016). The results from the interview also showed that of the wastes that went to the rendering plant, some of the by-products of the process are shipped to the landfill sites or are sent for composting. This includes excess feathers and the chicken bones and meals, averaging three tonnes and four tonnes respectively, daily (Table 4.5).

Table 4.5: Average chicken waste to Landfill (Daily Value) (Source: Interwaste)

Type of Waste	Unit of Measurement	Quantity	Waste Disposal Method
Chicken Bones and Meal	Tonnes	3	Landfilling
Emulsion Waste		73	Composting
Chicken Feathers		4	Landfilling

4.2.2.2. Composting of Processing Wastes

Composting is one of the methods that is regarded as a convenient and environmentally sound and inexpensive method that is used for the management of poultry wastes. According to Pisa and Wuta (2013) composting is a biological process that stabilises organic wastes by converting them into products that are useable as a soil conditioner and organic fertilizer. Poultry processing wastes which contain a considerable amount of excreta contain significantly high amounts of nutrients such as nitrogen, phosphorus, and other excreted substances such as hormones, antibiotics, pathogens, and heavy metals which are introduced through feed (Baba et al., 2018). Pathogens such as e-coli or salmonella may be found in the poultry wastes, and therefore make it unsuitable for direct application as a soil modifier.

Composting is performed to reduce the volume of organic waste and to eliminate pathogens. For the poultry industry, composting is a valuable waste management practice that produces organic fertilisers, a much-desired product compared to mineral fertilisers. For processing plants without the W2V plant, composting plays an important role, taking up much of the organic load of the wastewater sludge and some of the processing waste from the slaughtering houses. Figure 4.16 below shows the volumes of wastes that have been processed for composting for the Hammarsdale plant in Durban. The figure shows that increasing amounts of wastes are being sent for composting. Figure 4.16 shows the volume of wastes send for composting is negatively correlated with volumes of waste sent to the landfill site. They may highlight the positive impact composting has on the environment given the reduction in wastes deposited on the landfill sites. Figure 4.16 shows that is the increasing reuse of organic matter in the poultry processing waste to produce organic fertilisers. On average, 65.9 tonnes of the processing waste were sent to the landfill site in the 2019-2020 period compared to 52.6 tonnes 2018-2019 period for Hammarsdale processing plant (Figure 4.16).

On average about 8800 kL of wastewater was treated at the Durban facilities using the dissolved air flotation (DAF) method in the 2018-2019 period compared to about 5500 kL in the 2019-2020 period (Figure 4.16). Most of the collected organic matter from the DAF process forms the emulsion waste listed in Table 4.5 above that is sent for composting. For the Worcester processing plant, the wastes send to the composting site are comparable with the values from the Durban plant (Figure 4.17). The Worcester plant sends on average 69 tonnes of wastes monthly to the composting site, a little lower than expected when compared to the respective waste production for the two sites (Figure 4.17). The lower volumes of wastes send to the composting sites are testament of the positive impact of the W2V plants on waste disposal. The volumes of wastes that are composted at the Rustenburg plant are much higher compared to the other plants (Figure 4.17). The Rustenburg plant processes more chicken than Worcester, and also takes in production waste for production of biogas.

The amount of digestate, which form part of the waste that is composted, is therefore much larger in Rustenburg, hence the large volumes. On average, over 160 tonnes are composted at the Rustenburg processing plant (Figure 4.17). Composting takes up between 20-30 % of the processing wastes from the processing plants based on the data that was processed for this study.

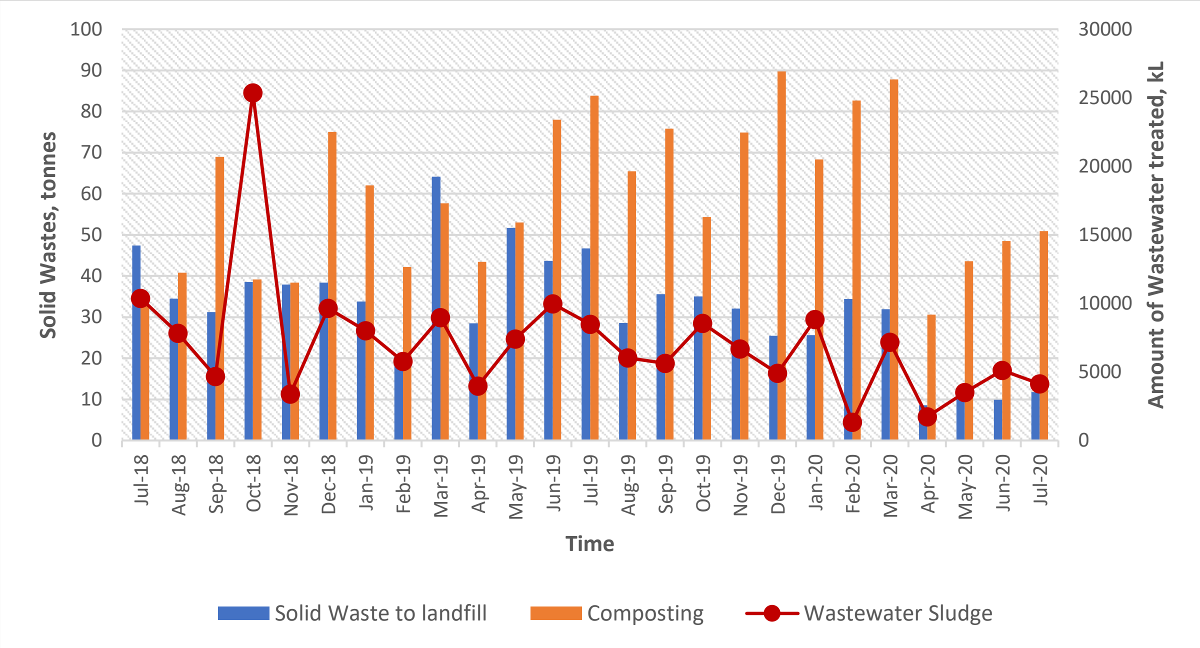

Figure 4.16: Figure showing the volumes of wastewater sludge production, processing wastes send for landfilling and composting for the Hammarsdale plant.

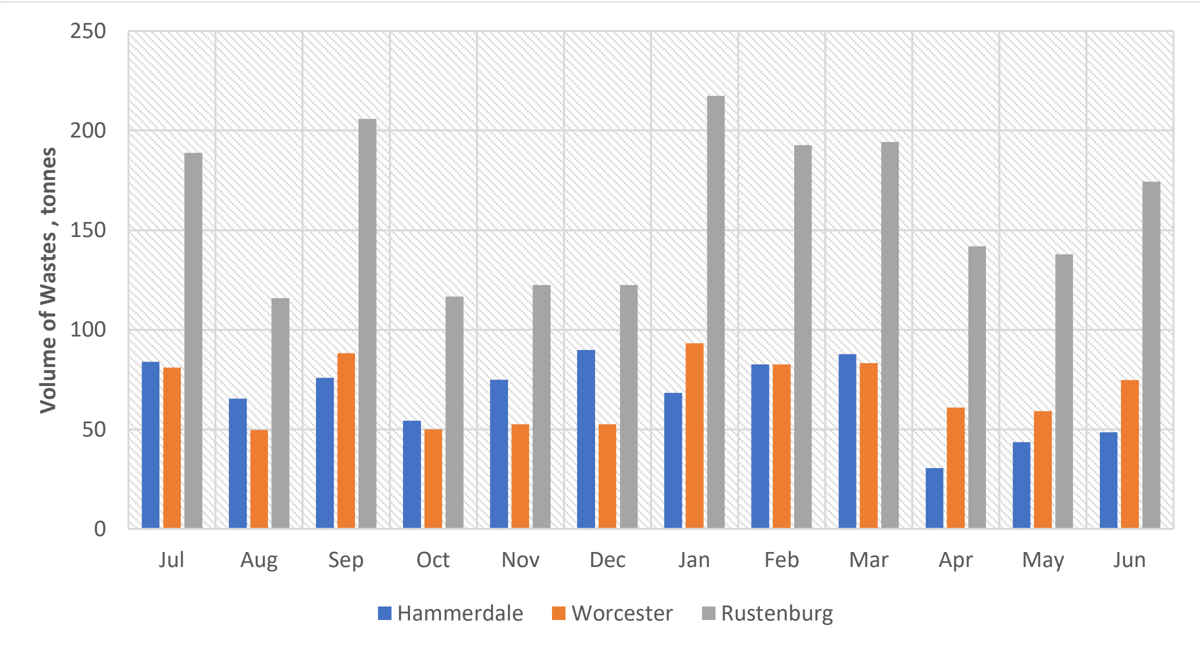

Figure 4.17: Figure showing volumes of poultry processing waste that is composted per month at the three processing sites, in Worcester and in Rustenburg

4.2.2.3. Landfilling of Processing Wastes

Landfilling remains the cheapest and the most common practice worldwide for the disposing of wastes around the world, and more especially in developing countries (Ferronato & Torretta, 2019). However, landfilling of poultry waste has a number of related negative environmental impacts such as pollution to the land, and surface and ground waters, as well as major risks to public health, and therefore not preferable for slaughtering wastes (Environment Protection Agency, 1999). As a results, handling of processing wastes is a major key performance in the company. As has been reported, poultry slaughterhouses release large amounts of waste. In this poultry enterprise, landfilling is the least preferred method as per the waste management hierarchy. The discharge of the biodegradable organic compounds from this waste into the environment has a major on the activities of aquatic life due to reduction in BOD while the high nutrient levels of the waste may cause eutrophication (Baba, et al., 2019). While correct landfilling procedures may mitigate against the risks highlighted, landfilling may also not be the solution because of the large water content of the waste, and the potential for global warming it poses through the emission of methane (Yaakob, et al., 2018). When only the environment is considered without looking at the economics, the most effective and efficient waste management processes include waste minimization measures, reuse, recycling, and energy recovery (Vavekova, 2019). These are more sustainable than traditional landfill or landfill disposal technologies.

A semi-structured interview conducted via Microsoft Teams to gather an understanding of the efficiency of the waste management processes in the company and the types of waste that generally end up at the landfill sites showed that over the years, waste going to the landfill sites has been decreasing. Within the company's activities, poultry manure and processing sludge remain the largest in terms of waste volumes. These two waste forms are used for biogas generation and manufacture of organic fertilisers. While the rendering process collects much of the solid slaughtering wastes, there is also a huge number of wastes that present a challenge in terms of disposal. The results of the interview highlighted that the feathers and the bones from the poultry processing plants as well as excess feathers and meals from the rendering plants were the major problems, in many instances ending up at the landfill sites (Table

4.5). About four tonnes of feathers, chicken bones and meal waste from animal feed production go to the landfill daily (Table 4.5). Figure 4.18 shows results from some the of the data collected from the company documents. Rustenburg, being the largest processing plant in terms of the volume of processed chicken (Figure 4.2) as well as reported total wastes reported (Figure 4.4) should have the largest amounts of wastes going to the landfill sites. However, this plant, equipped with the largest W2V plant in the company seems to be the highlight of the company, converting the largest amount its waste to animal feeds (Figure 4.15), organic fertiliser (Figure 4.17) and bioenergy. The reported results show that Rustenburg had the least amount of waste send to the landfill sites (about 6 %) according to the data acquired from the reports compared to 40 % for the Worcester processing plant (Figure 4.18). The profile for Rustenburg shows a 97 % decrease from August to November and maintains the low values for landfilling (Figure 4.18). While Worcester decreased its landfilling statistics by 21 % in the same period, its values remain, landfilling over 100 tonnes of wastes every month (Figure 4.18). The same can be concluded for Hammarsdale which has not changed much and remains stable around 40 tonnes for the quantity of wastes landfilled. At the Hammarsdale plant in Durban, 25.6 tonnes of processing waste were landfilled in the 2019-2020 period compared to 39,2 tonnes in the 2018-2019 period, a 36 % decrease.

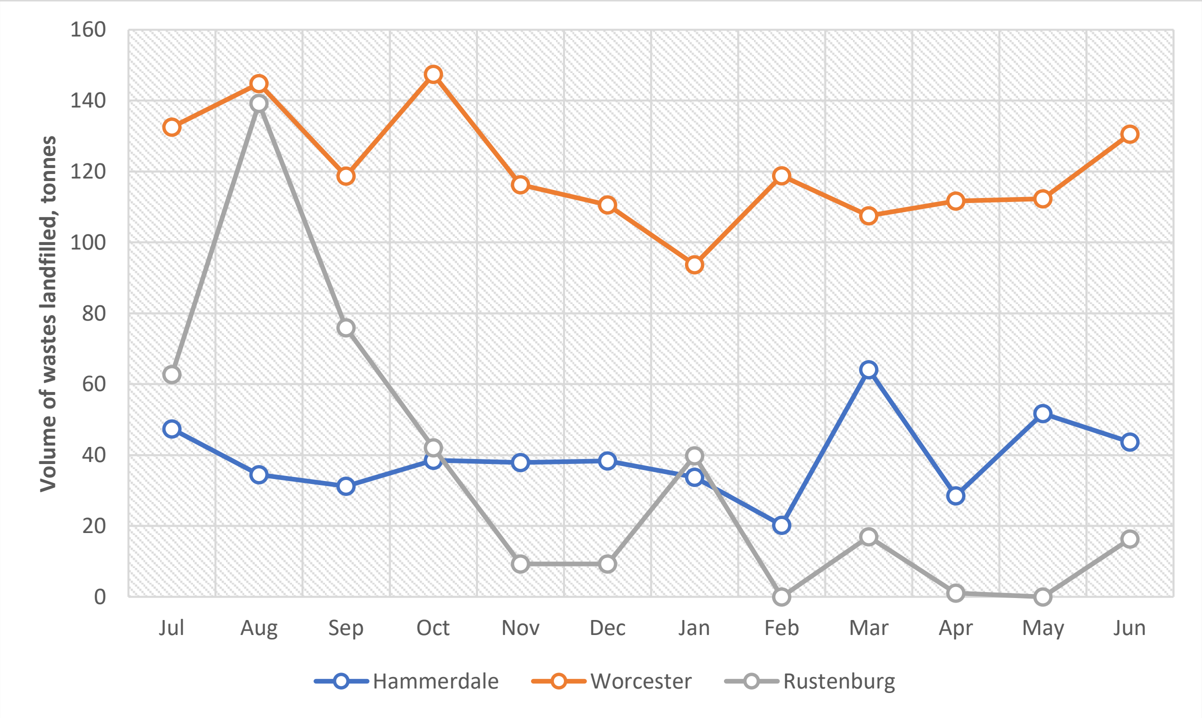

Figure 4.18: Figure showing volumes of poultry processing waste that is landfilled per month at the three processing sites, in Worcester and in Rustenburg.

The results show progress in the company in terms of its waste management preferences. The company has developed as key to its waste reduction strategy, several strategies to reduce waste going to the landfill sites around the country for all its operations. The addition of the W2V projects in Worcester and Rustenburg to the current processes of dealing with poultry processing wastes in the company was performed to minimise the need for landfilling and wastewater treatment through the municipal systems.

The building of W2V plants has been done because of the need to find the most effective and sustainable way of dealing with poultry waste and to ease pressure on the country's landfill sites which have been the main recipients of the waste from the plants. The effect of these two plants can be clearly demonstrated for the Rustenburg plant, which was commissioned in 2020, and the results showing its success in reducing landfilling (Figure 4.18). Figure 4.18 shows that much progress has been made in decreasing waste requiring landfilling while increasing wastes that is converted into useable products.

According to the company data, the building of the W2V plant in Rustenburg reduced 1000 tonnes of poultry production waste destined for landfill sites into energy production in 2020, a highlight of the results reported in Figure 4.18 above. It should also be noted that the Rustenburg plant can take a diverse of feedstock from poultry production and processing wastes, while the Worcester plant only takes the sludge. The Rustenburg plant has attempted to use feathers as feed into the W2V plant but resulted in increased incidences of plant breakdowns. The feathers and the bones are therefore not used in biogas production but are used in the rendering process to prepare animal feeds. However, excess of these wastes is shipped to landfill sites.

If the results highlighted for the Rustenburg plant are analysed, the company seems to be on track for its ambition of zero waste to landfill sites by the year 2025. However, more work will need to be done for wastes in the other processing plants for instance Worcester in this case where landfilling remains high. The company may need to increase rendering at that plant to the levels reported for Rustenburg. That should reduce pressure of solid wastes that are send to the landfill sites (Figure 4.15). Figure 4.19 below shows the statistics of the volumes of poultry wastes in the company's whole operations that have been converted to valuable products such as energy, organic fertilisers, or animal feeds. The figure shows that huge amounts of wastes that would have been destined for the landfill sites was either reused or recycled and has been improving over the years. In 2019, the company reported that only 8 % of the company's wastes were sent to the landfill site.

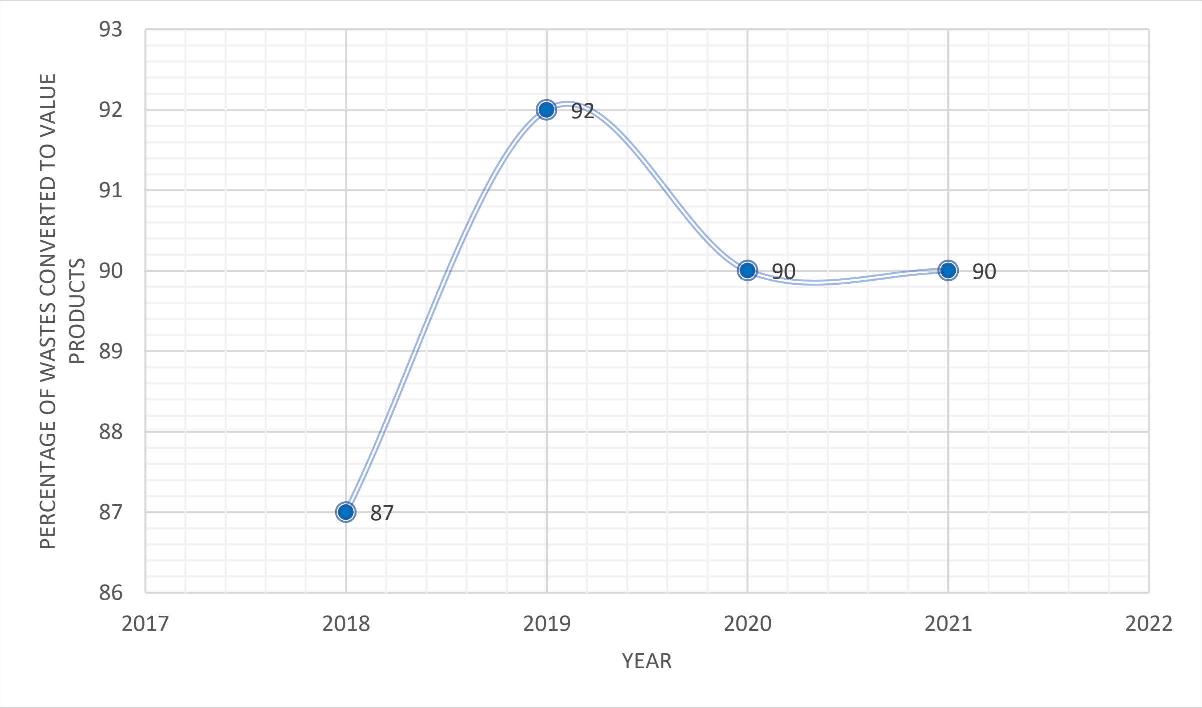

Figure 4.19: Percentage of poultry wastes converted to valuable products such as energy, organic fertilisers, or animal feeds for the whole enterprise

4.3. Bioenergy Generation and Performance of the Plants

The company is involved in two major bioenergy projects in its operations of sugar production and poultry production. Both projects involve the generation of electricity from biomass. The first one uses bagasse as biomass feed for the generation of biogas. Bagasse is one of the main by-products in the production of sugar from sugarcane. Bagasse is generally produced in large quantities in sugar production and is one of the main problematic wastes in the sugar industry. Its use in the production of electricity from the plants by the company is one indication of the efforts by the enterprise in its quest to reduce wastes destined for the landfill sites by converting them into high-value products. For this enterprise, bioenergy production from sugarcane has matured, generating upwards of 95 % of the electricity requirements for the Malalane and Komati sugar mills in Mpumalanga. The success of the biomass projects derived from bagasse has led the company to develop other W2V projects with a focus on poultry wastes. The generation of electricity from bagasse is not the focus of this project. However, it's briefly discussed because the available generation data, data on carbon footprint and related data on the performance is reported together.

At the business' Worcester and Rustenburg chicken processing facilities, the W2V plants have been constructed to produce biogas from organic waste from processing of chicken meat using the biological process of AD. An on-site anaerobic digester system is used to produce biogas from the poultry waste, which is then used for in-house electricity generation as well as the digestate which is saleable as a high-quality organic fertiliser. The process involves pumping the poultry wastes (mainly the wastewater sludge) into holding tanks and then into the continuous anaerobic digesters. The high COD wastewater sludge from the processes in the chicken processing plant is used as the primary feed in both Worcester and Rustenburg plants, while the latter also uses manure from the poultry production process as a feed as highlighted in the schematic diagram in Figure 4.1.

The plant in Worcester (Figure 4.20), a 1.5 MWh plant is expected to generate 10.5 GWh of electricity as well as 2500 MWh of thermal energy annually. The plant has been operating at between 62-65 % capacity, producing on average between 6,500 MWh to 6,800 MWh per year. In 2018, the plant produced 8,539 MWh (81.3 % of targeted capacity), converting 6407 tons of waste into energy and other valuable products. From an environmental point of view, 3,500 tons of biological waste (fat and suspended solids) no longer end up in municipal wastewater treatment systems and landfills each year. The new W2V plant in Rustenburg (Figure 4.21) is a 6 MWh plant that is already running and is expected to process both poultry production and processing wastes to generate electricity. The plant is expected to produce 34.1 GWh of renewable energy annually when functioning to full capacity, supplying 65 % of the energy needs of the Rustenburg chicken and feed processing plants, 50 % of the operations' water requirements, 100 % of the steam requirements of the animal feed mill and increase the energy self-sufficiency of the entire group by approximately 22

%. The plant is expected to process 135 tons of energy-rich wastewater sludge from the processing unit daily and an additional chicken litter from the company's farms. The Rustenburg plant was supposed to have started operations in 2019, however its

Figure 4.20: Worcester W2V Plant - Arial View (Source: RCL Foods)

Figure 4.21: Rustenburg W2V Plant - Arial View (Source: RCL Foods)

commissioning was delayed due to community engagements and later the COVID-19 pandemic delayed its commissioning. The main objective of this project was to assess the performance of the W2V plants in terms of production of bioenergy. The following key indicators were considered in the evaluation of the bioenergy plants: the generational yield biogas production versus expected from the biomass, total energy generation output in terms of heat and electricity, the environmental impacts of the W2V plants and economic impacts the W2V plants in terms of in terms of energy expert's exports, carbon credits and energy savings due to self-generation. These aspects are discussed in the sections below.

4.3.1 Production of biogas

In order to evaluate the performance of the bioenergy plants, the plant's biogas generation output was compared against its expected output from the feed based on literature. Results used for this evaluation were collected from the Rustenburg plant, recorded for a week in July 2021 because of some limitations as discussed earlier. Results from Worcester could not be obtained; however, the yield compositional data was obtained. The results were compared with real data from another plant from an independent operator at the Mariannhill Landfill site that uses general waste from the landfill to generate electricity, and also data from literature. Figure 4.22 below shows the statistics for the daily feed of poultry manure and wastewater sludge, as well as the daily volume of biogas produced using limited data for a week.

The average daily sludge feed for the plant in that week, which was around 123.7 tonnes per day, was 8.4 % off the target feed of 135 tonnes for the plant per day. An additional feed of around 76 tonnes on average, of poultry manure was also fed into the plant daily, containing an average dry matter of 61 %. The plant's daily dry manure feed was 45.4 tonnes per day, which was 82.5 % of its intended target. The daily biogas yield increased with the volumes of waste added, which would be expected given the accumulative nature of the biogas production and its production which is a slow process occurring over time (Figure 4.22). However, it is seen that Wednesday had the largest feed of sludge but resulted in less biogas production. Day 5 had the highest daily average for biogas production even though it had a much lower feed. The amount of biogas produced seemed to be not dependent on the quality of sludge COD, which was reported to be at 140000 mg/L on this day (Figure 4.22) and organic content of the manure feed which was 62.2 % on the day, the highest in the week (Figure 4.22). With a correlation of -0.32 between the biogas production and the sludge COD for this limited data, it could not conclude on whether there is significant influence on the production or not. However, it may also be concluded that biogas is a lagging indicator in terms of its response to the feed, taking up to 30 days to reach its production plateau, hence a peak is seen on Friday, even though a peak in the feed is on Wednesday. Figure 4.23 show the results of the methane content of the biogas, as well as the digestate collected daily from the digestors. The Rustenburg plant produced an average of 32.6 tonnes of digestate containing 43 % of dry matter (Figure 4.23).

The methane content of the biogas was stable at 55.3 % ranging between a minimum and maximum of 54-56 % (Figure 4.23). It should also be noted that the sludge feed for the week didn't meet the target of 160000 mg/L on any single day, which may have influenced the methane content of the biogas. The digestate formed was observed to initially increase up to a peak on Tuesday, where further increase amounts added sludge seem to produce less digestate. A decrease in the volume of feed on Wednesday seems to push production of more digestate, peaking up on a Friday, and decrease on Saturday where a very small of feed was added. The percentage of dry matter in the digestate however remained stable, around 34 % for the digestate collected throughout the week.

According to Oliveira et al. (2012), the biogas potential in the poultry litter is 0.1576 m^3/kg. According to Bijman (2014), 17 tonnes of chicken waste will produce 3400 m^3 of biogas (Bijman, 2014), while 1m^3 of methane will produce 10 kWh (Suhartini, Lestari, & Nurika, 2019). The potential for the sludge depends on the organic content. By approximating the expected total methane production using the results from Oliveira et al. (2012) and the approximation rom Bijman (2014), it was concluded that the feed was producing between 57-73 % of the total expected in a day. The results for the methane content of the biogas show that the system needs to be optimised for better production of biogas. The methane content obtained is about 14 % lower than the target of 64 % (Table 4.6).

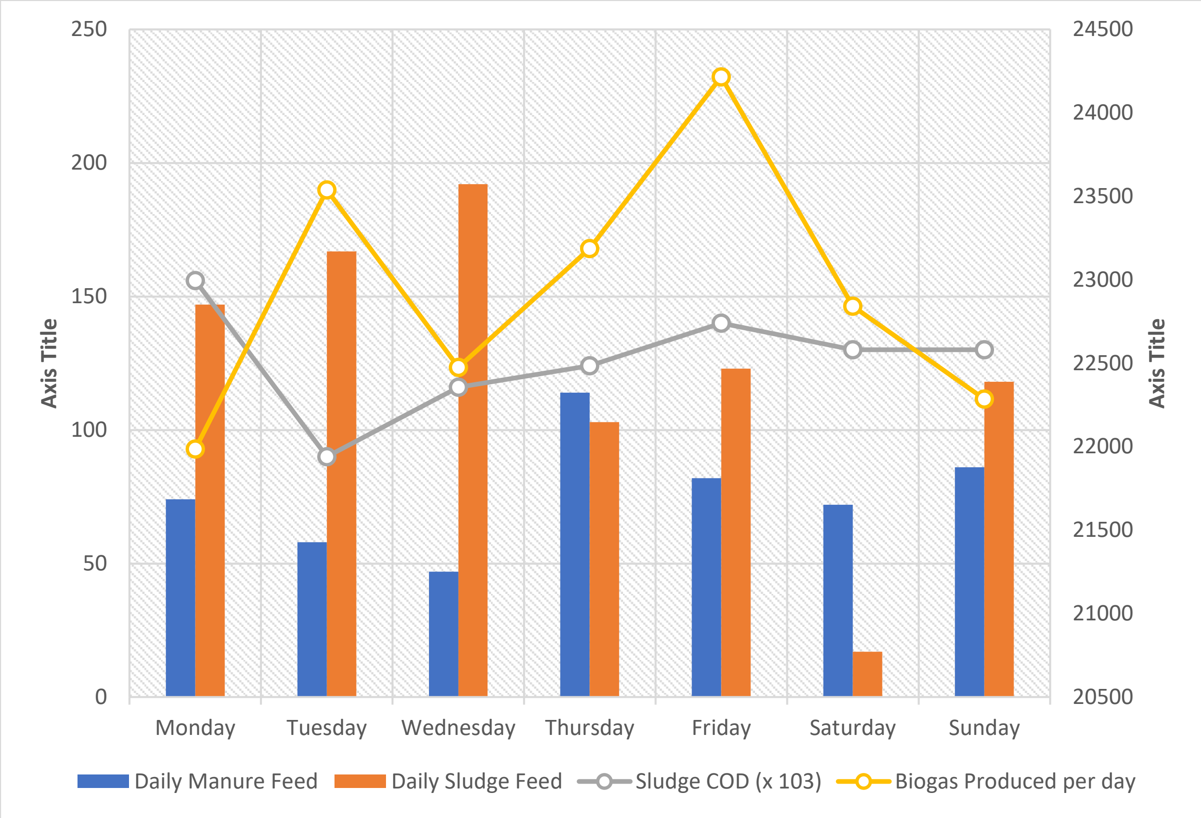

Figure 4.22: Figure showing sample results for the feed and biogas generation for the Rustenburg W2V plant

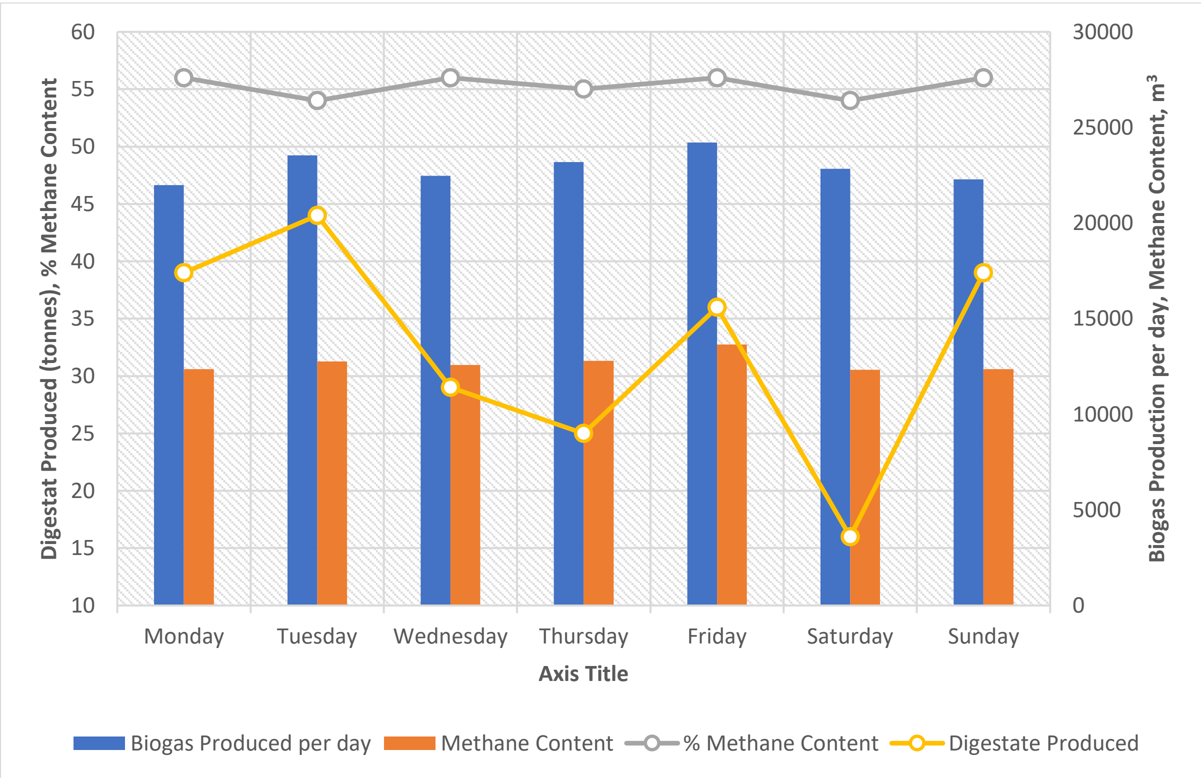

Figure 4.23: Figure showing results of biogas production, methane content of the biogas, and the digestate produced for the feed shown in Figure 4.22

The value was comparable to that of Mariannhill Landfill site which was produced from feed with about 50 % organic content, which should have lower yield compared to the feed used in the W2V plants. The methane content for the production at the Worcester plant was much higher, in the ranges excepted for poultry waste. The low methane content could have been influenced by a number of factors affecting the production of biogas from poultry waste which would need to be optimised.

Table 4.6 Biogas analysis for the W2V plants for the company compared to the Mariannhill Landfill site plant

Plant	**Type Waste**	**Energy Produced**	**Mean Daily Wastes Feed**	**CH_4 Content**	**CO_2 content**	**O_2 Content**	**Other Gases**
		kWh		**%**	**%**	**%**	%
Mariannhill Landfill Plant	General Waste (Approx. 50% Organics)	371759	~700 tons	52,0	40,5	0,8	6,6
Worcester Analysis	Sludge	222578	63.6	68,1	26,3	0,6	5
Rustenburg Analysis	Manure + Sludge	1573600	73,4 +116,9	55,3	-	-	-

The main parameters that affect the production reaction in the biogas digester include carbon to nitrogen (C/N) ratio, the temperature inside the digester, retention time, fermentation medium pH values and the presence of volatile fatty acids (VFA) (Dobre, Nicolae, & Matei, 2014). The C/N for the feed should lie in the range 15-25. High nitrogen content shows high ammonia content which is inhibitory on the effect of methanogenic bacteria. Poultry manure has a C/N ratio of 15. According to Dobre et al. (2014), the pH should be between 6.8-7.3. For the wastewater sludge used as feed for biogas generation, the COD is the main parameter that is recorded. High COD values influence lowering the pH as VFAs are formed in the process of biogas production, and therefore should be controlled (Dobre, Nicolae, & Matei, 2014). The temperature in the biogas digester is an important variable, which affects the production rate of gas (daily output) and the total amount of biogas that can be produced. The biogas producing bacteria are most effective when the mud temperature is 20-45°C. Within this range, biogas production will vary, so the scale of a biogas plant is usually optimised to ensure its maximum daily gas production.

However, due to the global pandemic, travel to the plant was limited. Observations of the plant performance were conducted through a weekly video conference. Weekly conference was set up at different times of the day to allow the researcher to identify any changes within the plant. Data available for the researcher to record and report was limited due to company protocols. Because of those challenges, not enough data could be collected to give an account of the effect of the various factors in the generation of electricity and biogas. Random on-spot observations verified some of the information obtained during interviews. Within the Worcester W2V plant, the following factors are closely monitored and affect the efficiency of the green energy production: pH, temperature, wastewater sludge into feed into the bio-digestor. The temperature of the digestor is read every hour, before and after feeding into the bio-digestor.

4.3.2. Bioenergy Generation

The results for the generation of bioenergy from the two W2V plants are presented in the Figures 4.24-4.26 below showing electricity production for the plant plotted together with the total methane content in the biogas produced. The results of electricity generation were compared with the respective capacities of each of the plants. The expected output for the Worcester plant is rated at 10.5 GWh per annum while the Rustenburg plant has an expected output of 34.1 GWh. The daily output for the Rustenburg plant for a week in July 2021 shown in Figure 4.24 shows the energy generation increasing through the week, the profile showing a week relationship with that of the biogas. Weekly generation for the Rustenburg plant reached a peak of 55515 kWh on Saturday, even though methane production had slowed down. The plant exported on average 79.6 % of their produced electricity during this week, producing on average 51733 kWh of electricity every day. The weekly target of electricity production for the Rustenburg plant was set at 480000 kWh (Table 4.7).

During this week, the plant produced 362 134 kWh, which was is 24.5 % lower than their intended target (Figure 4.24). Figure 4.25 shows additional data for average daily generation of electricity for the Rustenburg plant for a 8 weeks in in August and September 2021. On average 41812 kWh of electricity was produced daily for the eight week period, with a maximum of 50489 kWh in September (Figure 4.25). On average 79 % of the generation was exported, and the target production was off by 50%. The heat and steam production data are presented in Figure 4.21. The amounts of heat produced, and steam produced correlate with the electricity generation (Figure 4.24). The presented data are summarised for the week in Table 4.7 below show that all the targets were not achieved.

The plant produced 75.6 % of its target electricity, steam production was 62.2 % while water recovery was much lower at 44.6 % of 1500 kL per day. Thermal energy production was on average 10148 kWh per day, 30 % lower than the target for the week (Table 4.7) (Figure 4.27). The total produced for the week of 442.3 MWh is much less than the expected of 888.6 MWh approximated Suhartini et al. (2019) based on methane production. It can therefore conclude that the plant's performance is currently at about 50 %. Based on its capacity, the current generation is much lower, projected to give 18.9 GWh per annum based on the presented week's data, and which is about 55 % of its expected electricity generation output. This is expected given that the feed and biogas generation is currently not at optimum levels. As is shown in Table 4.7, the plant is not yet currently meeting its performance targets. It should be noted however that the data used in the calculation was however limited, therefore may not be representative of the operations at the plant.

The only data obtained for the Worcester showed data for the feed and the electricity production for 3 months from beginning of August 2021 until end of October. The results are presented in Figure 4.26. The Worcester plant seems to have a fixed export load, set at 83.4 % of its generation. On average, 7258,2 kWh were produced every day in the three months which were analysed, which would translate to 2.65GWh, which give 25.2 % of the intended target if the current rates of production are maintained for the year. These results seem to indicate that both plants are not running at optimum conditions and may still need more optimisation to improve efficiency. The

Rustenburg plant data were recorded during the time the plant was still in the commissioning stage. The plant in Worcester has been running since 2017 and has

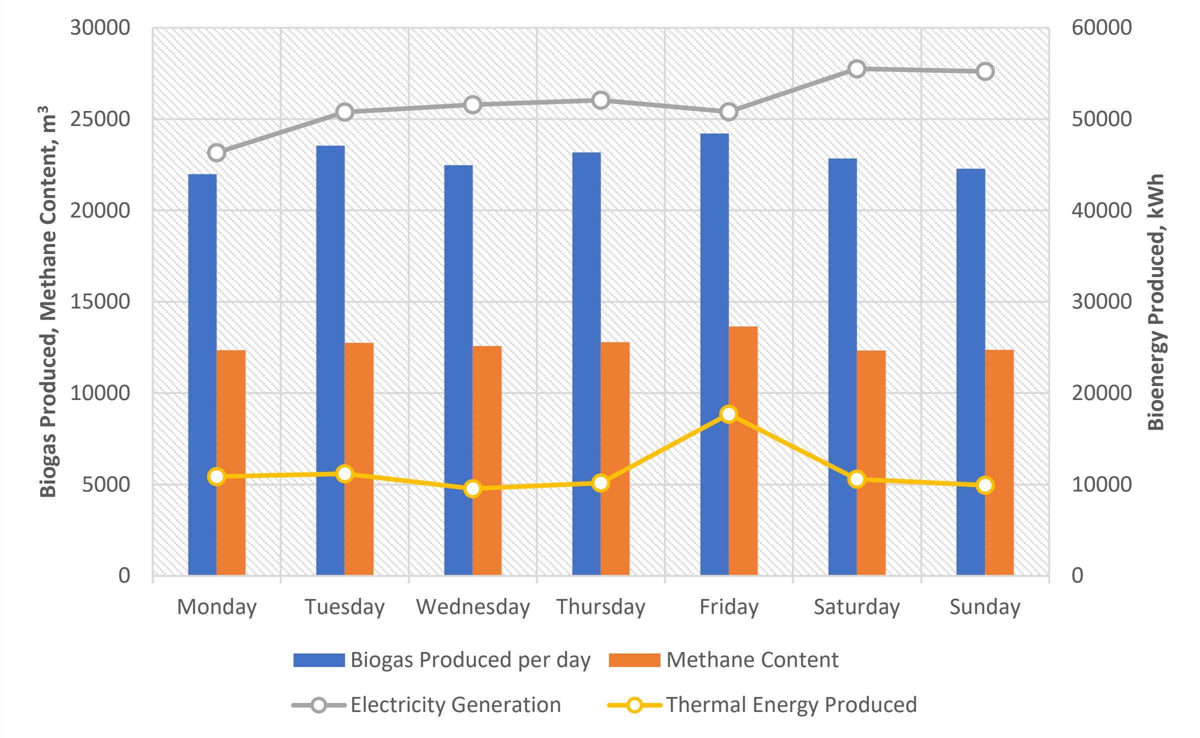

Figure 4.24: Figure showing methane production data and the corresponding electricity generation for the W2V plant in Rustenburg

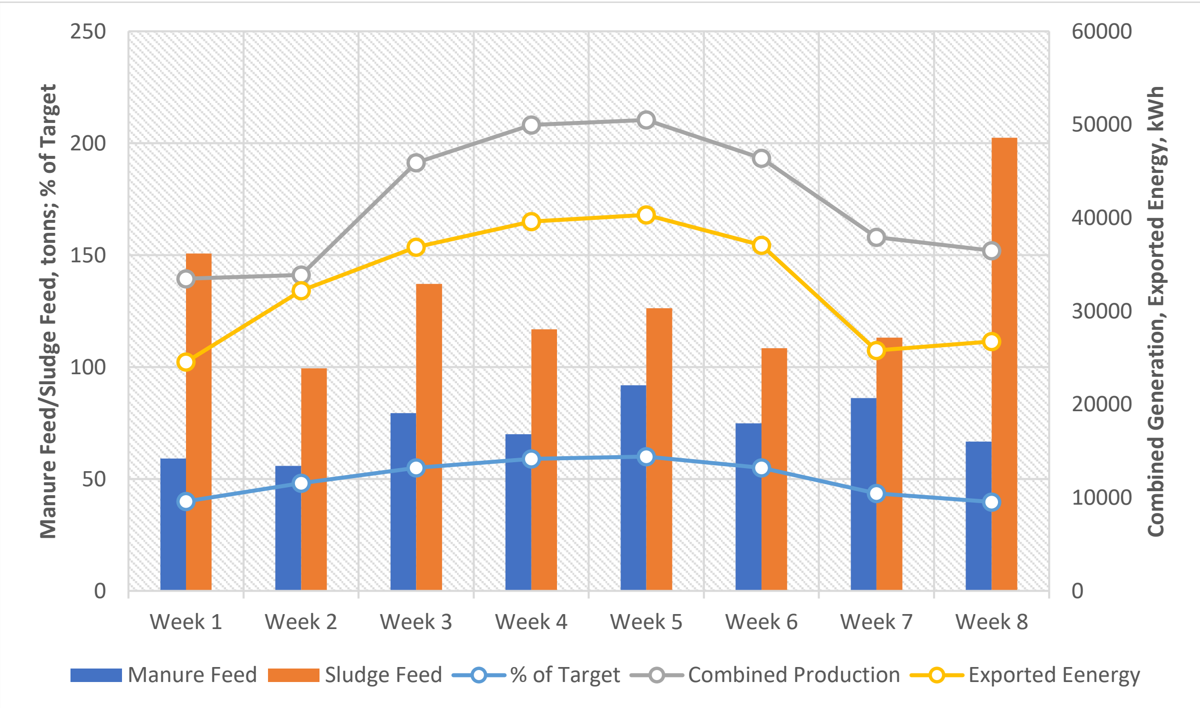

Figure 4.25: Figure showing the average daily sludge and manure feeds (in tonnes) and the corresponding daily average bioenergy production for eight weeks in August and September 2021 for the W2V plant in Rustenburg, and the corresponding percentage target production.

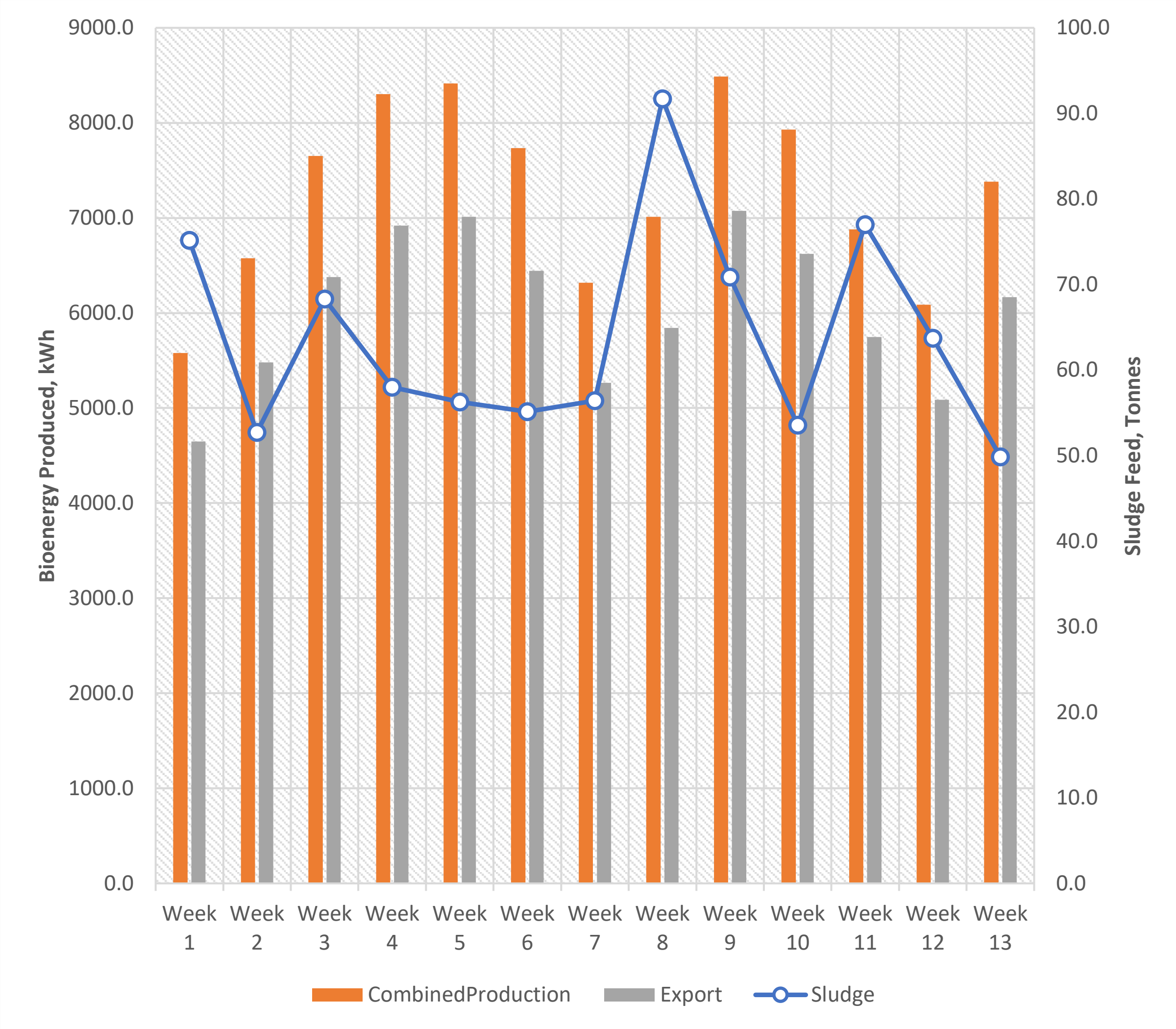

Figure 4.26: Figure showing bioenergy production data and the corresponding sludge feed for the W2V plant in Worcester.

been running at almost full capacity according to the interview data. Using data from 2018, about 712 MWh of energy was generated by the plant in Worcester, almost two times the generation from the Mariannhill plant, which is a smaller plant (1 MWh vs 1.5MWh). The Rustenburg plant, a 6 MWh electricity generator, is expected to produce around 34.1 GWh per annum when operating at full capacity. The results agree with the interview report with the SHEQ manager who indicated that the Rustenburg plant was currently performing at around 40% of its capacity, with full capacity expected within the next six to eight months. The efficiency report for this site is currently incomplete and inconsistent to conduct complete analysis to determine the factors that affect the efficiency of green energy production by the biogas plant. At this present moment, the finalisation of the W2V plant is in progress.

Table 4.7: Table showing the output of electricity generation, heat steam and permeate for the W2V in Rustenburg.

	CH_4 Production m³/ day	**CH_4 Composition in Biogas** %	**Electricity Produced** kWh	**Heat Produced** kWh	**Steam Production** tons/day	**Permeate Produced (RO Process)** kL/day
Value	12734	55.1	303481.1	80034	29.9	669.7
Target		**64%**	**480000**	**82500**	**48**	**1500**

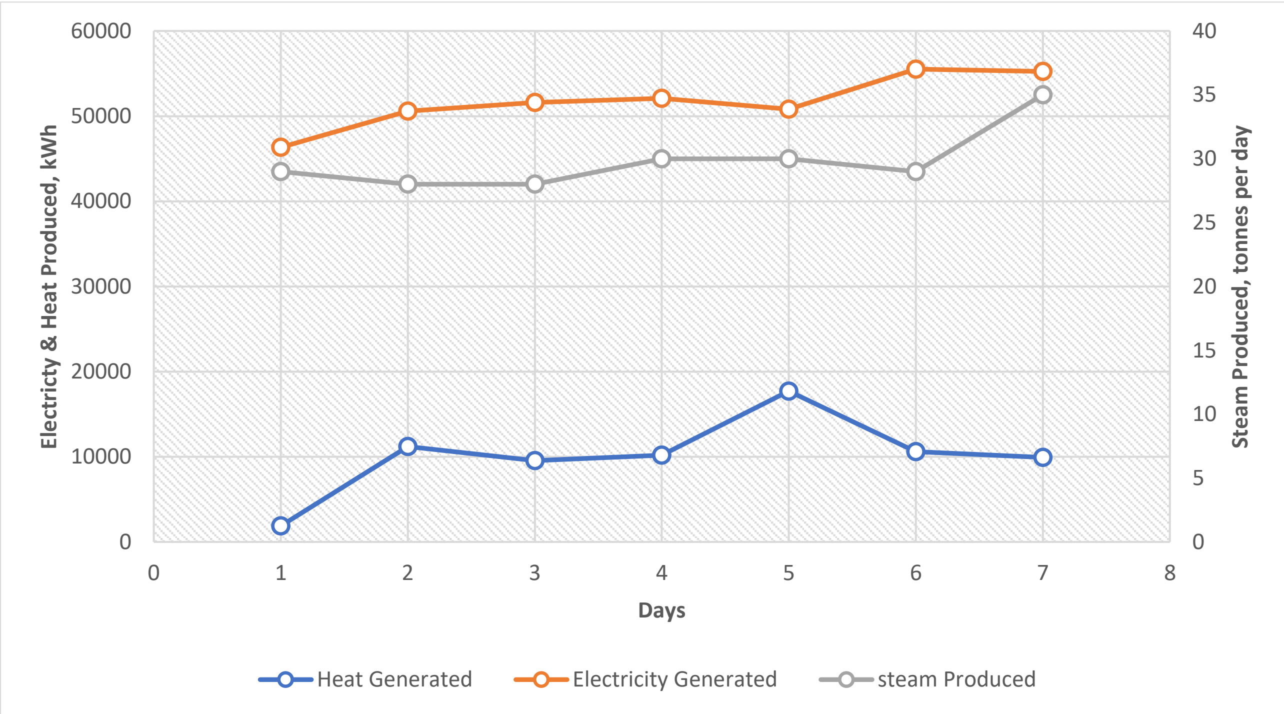

Figure 4.27: Figure showing the thermal energy, steam, and electricity output for the Rustenburg plant.

4.4. Environmental Impacts of Generating Green Energy from Chicken Waste by Selected Facilities in South Africa.

To investigate the environmental impacts related to bioenergy production by the processing plants, a semi-structured interview was conducted with the sustainability executive in conjunction with document reviews to further aid the interview process. According to the results of the interviews, the environmental impacts of the activities in the company are closely monitored and reported on timeously. The main area of concern for the poultry industry, and as has already been highlighted, is the large volumes of highly polluted wastewater sludge which is the major problem for the industry. This was one of the issues raised by the sustainability personnel as being the motivation for the development of W2V projects. Drainage water from within the plants and surface water bodies are periodically analysed.

Additional concerns involve minimising waste going to the landfill as well as the reduction in GHG emissions. Landfills are hotspots for emissions of methane, a GHG as well release of other substances harmful to both the environment, air quality and water quality. As a result, the company aims at achieving zero waste to the landfill sites by 2025, as a way of mitigating against environmental impacts of landfills. However, of the environmental impacts directly related to bioenergy production, its impacts on the water and air resources are significant. The sustainability executive laid out these issues and the various steps the company had taken to achieve its environmental goals. The issues are discussed in detail in the sections below.

4.4.1. Water usage and water quality

Slaughterhouse wastewater that is generated by the poultry processing plants is classified as high strength wastewater, containing large quantities of organic matter (nutrients, COD and BOD), minerals such as potassium, suspended solids, pathogens and fats, oil and grease (Yaakob, et al., 2018). Because its high load of BOD, COD, total suspended solids and a high level of nutrient concentration (nitrogen and phosphorus), slaughterhouse wastewater is considered highly polluted wastewater that cannot be discharged into the environment without treatment (Yaakob et al., 2018). Releasing this wastewater into the receiving water bodies without treatment can have severe environmental and public health impacts such as eutrophication and mineralisation of the water bodies (Aziz, et al., 2018). Additionally, this wastewater is a huge health risk as it may have pathogens such as e-coli or salmonella (Baba, et al., 2019). It is therefore recommended that this wastewater can only be released into the environment after proper treatment to avert possible impacts on ground and surface waters.

In general, the preliminary physical treatment process is used in on-site poultry wastewater treatment systems, involving screening to remove solid waste constituents using the DAF system (Bingo, Basitere, & Ntwampe, 2016). After removal of the organic matter, the poultry slaughterhouse wastewater is usually disposed of by discharging it into watercourses, municipal wastewater treatment works, or by scattering it on grass and croplands (Bingo, Basitere, & Ntwampe, 2016). However, given the volumes of wastewater generated in large poultry processing plants, this partially treated water is also not suitable for release into the environment because of the COD that is thousands fold above the effluent discharge guidelines. As highlighted above, chicken processing uses between 10-30 L per bird. For large poultry processing plants like the ones owned by the company, this translates to over 2500 kL of water usage every day. South Africa, being a water scarce country, this is not sustainable in the long run. Usually, the wastewater is further treated onsite in order to make is suitable for reuse, or discharge into the environment. The treatment process itself is also a very expensive exercise for the companies. The volume of the wastewater produced every day is in the range of 1500-2600 kL every day for each of the Worcester and Rustenburg processing plants (Table 4.1), while over 100 tonnes of wastewater sludge is produced daily as was highlighted in the interview results (refer to Table 4.5).

The construction of the two W2V plants has taken care of this highly polluted wastewater sludge, and therefore benefited the environment positively. The positive impact could not be investigated further without historical data on the disposal and impact of the wastewater discharge prior to construction of the W2V plants. However, it can be reported that the company has been struggling with daily production of wastewater sludge which under the current regulation, cannot to send to the landfills. And through deductive reasoning, it can be concluded that the construction of the W2V plants for generation of bioenergy has benefited the environment by converting this problematic waste into useable products. Wastewater from the two plants is further treated their wastewater using the reverse osmosis system, after the pre-treatment stage, generating clean water that is re-used in the chicken processing plant. The treatment of the wastewater, and its recycling in the slaughterhouses reduces water usage and reliance of the poultry processing plants on municipality water for chicken processing. Figure 4.28 shows data on wastewater generation for the plant in

Rustenburg, its treatment and the permeate collected after treatment. As reported earlier (Table 4.4), as much as 85 % of the COD is removed the slaughterhouse wastewater before it is transferred to the Reverse Osmosis (RO) system. Water recovery, which was calculated based on total wastewater produced vs. total permeate collected per day from the RO falls in the range between 30-60 % of the total volume of raw wastewater collected (Figure 4.28)., and between 60-75 % based on the feed into the RO system as highlighted earlier (refer to Figure 4.13). According to data from the interviews, the company has a dedicated sustainability team to drive the chicken producer sustainability agenda, focusing largely on energy and water. Their focus is the implementation of energy and water efficiency and conservation projects. As part of the projects the company is running, the W2V projects combined energy production water treatment to help clean up the wastewater. At the Rustenburg processing plant post the construction of the W2V plant, there was the implementation of numerous water recycling projects using safe, good quality water that would have been disposed of into the municipal effluent treatment works. Previously these processes used potable water. However, because of these recycling projects, these processes exclusively use recycled water resulting in a 1,5 % reduction in potable water consumption. Figure 4.29 shows the permeate produced from the treatment of wastewater sludge at the Rustenburg W2V plant, producing over 4500 kL for a week based on data collected in July 2021. Figure 4.29 also shows the production of steam, which is used in the other parts of the processing plant, and therefore improving on the plant’s energy efficiency. With the treated wastewater, the reliance

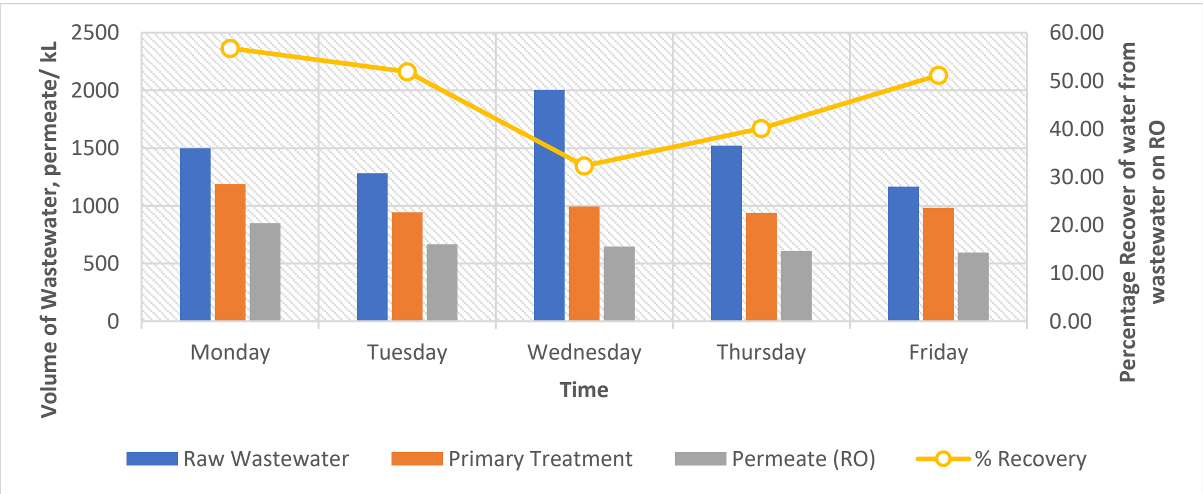

Figure 4.28: Example data for wastewater generation, volume collected after primary treatment, and the volume of permeate after reverse osmosis

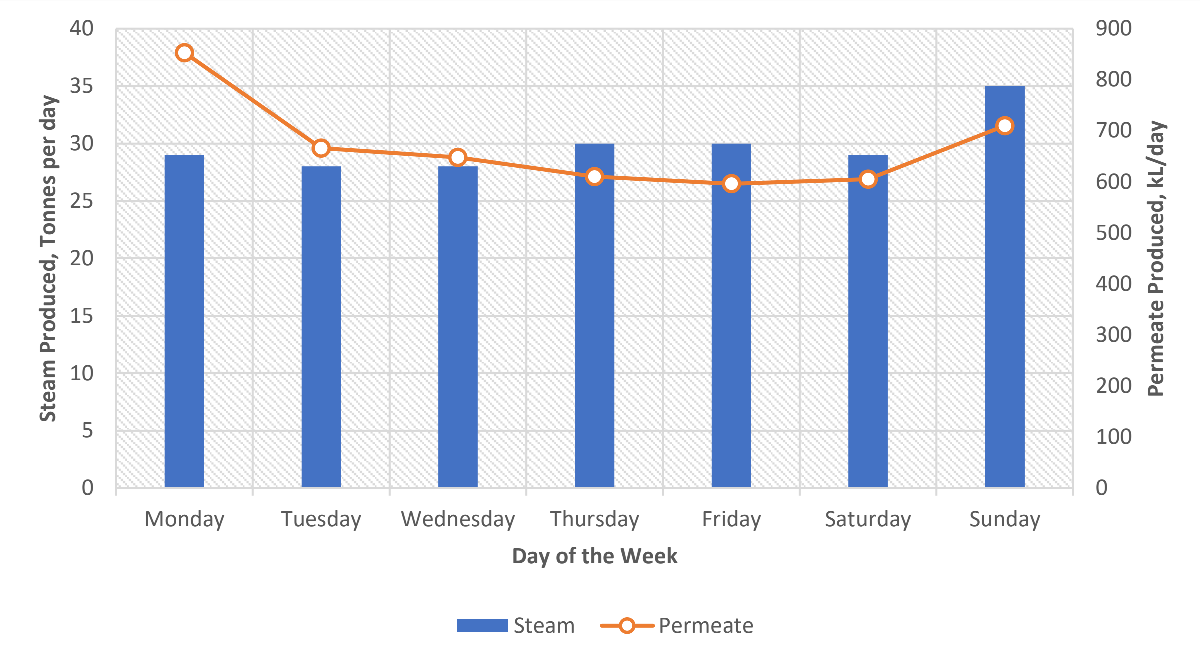

Figure 4.29: Figure showing volume of permeate collected from the water treatment of wastewater from the digestors.

on municipal water decreased by 0.9% in 2020 (RCL Foods, 2020). Therefore, their bioenergy projects have positive impacts on water usage in the company.

A case study conducted by the chicken producer in 2018 for the where water paid an important role in the preparation and processing process. An average of 4.5 million litres of water was used per month - 205 000 litres a day (RCL Foods, 2018). To achieve this, the chicken producer had set up a wastewater treatment plant and a wastewater dam to collect the treated runoff. Faced with the limitations of the treatment plant's ability to treat such a large amount of wastewater from the plant, the on-site team came up with a two-phase solution. This included the proper cleaning of the post-processed water to be reused for irrigation and possibly other uses. Whilst the remaining amount was discharged through the municipal sewer pipeline. The first part of the DAF was put into use on-site on October 31, 2017.

The DAF system removes about 81 % of organic waste from wastewater, and the quality of the water produced is four times higher than the minimum level required for irrigation quality. (RCL Foods, 2018). It was stated by the executive member that this was one of the milestones initiatives other than the W2V plant development. This did not only actively strengthen the commitment to comply with all environmental requirements, but it also reduces odours and was aligned with the chicken producer's agenda to reduce waste and greater reuse by reusing wastewater as irrigation water.

At the Rustenburg processing plant post the construction of the W2V plant, there was the implementation of numerous water recycling projects using safe, good quality water that would have been disposed of into the municipal effluent treatment works. Previously these processes used potable water, now they exclusively use recycled water resulting in a 1.5 % reduction in potable water consumption (Table 4.8). This is a total saving of 1 940kL per day, and 58 200kL per month (RCL Foods, 2018). Projects and technologies (water committees, education of team members, and quality inspections, as well as reuse systems, reservoir systems, and wastewater treatment systems) have been used to minimize the impact on scarce water resources. Levies for non-compliance regarding water discharge quality was paid by the chicken producer. This is paid yearly and documented.

Table 4.8: Total savings of portal water (Source: RCL Foods)

Water Uses	**Unit of measurement**	**Total Saved Per Day**
Live bird crate washing	kL	380
Module washing		200
Feather Washing		1360
Total Amount Saved		**1940**

While wastewater is treated and recycled, the wastewater sludge that is collected from wastewater treatment is very problematic, first because of its water content, the large volumes produced daily (over 100 tonnes daily) and excessively high COD and BOD quantities after concentration, as well as nutrients as highlighted above (refer to Figure 4.2). Discharging this waste has severe environmental and public health problems. For the Worcester and Rustenburg plants, this waste is used in the biogas generation. However, for processing plants without W2V plants, it presents a major headache given the large quantities produced daily. In a processing plant like Hammarsdale, this waste is sent for composting to produce organic fertilisers. The presence of water in the wastewater sludge presence a huge challenge however for water quality and contamination of the soil. The other problem waste is the digestate, a waste that is not directly related poultry processing, but rather from the generation of biogas. Proper management of the produced digestate is very important for the preservation of water quality. Digestate is generally containing high levels of nitrogen and phosphorus compounds which can lead to the leaching of nitrates and phosphates into water bodies (Paolini, et al., 2018). In the company, the digestate is not sold as-is from the digestors but is taken for composting for further treatment. As a result of the challenges presented by slaughterhouse wastewater and wastewater sludge, the company has a system of monitoring drain water systems, rivers and dams that are around the processing plants and those that may result in public health issues. These monitoring points are in strategic positions to trace discharge of untreated effluent into the municipal drains and into water bodies. River samples, dam samples and drain samples around the chicken processing plants and those carrying residential waste from nearby residential areas are sampled periodically throughout the year. The results presented in Table 4.9 to 4.11 are some of the results for the Worcester, Rustenburg and Hammarsdale chicken processing plants for the period between 2020 and 2021.

Table 4.9: Water quality monitoring data for the Rustenburg chicken processing plant.

Sampling Point	**N**	**pH**	**COD mg/L**	**Phosphate mg/L**	**Total Nitrogen mg/L**	**Total suspended solids**
Clear Dam	2	6.33±0.21	853±117	3.6±1.0	57.5±44.5	62.0±17.0
Mixture Dam	2	7.08±0.64	3900±1272	11,1±2.8	169.6±57.9	713.5±51.6
Municipal Drain	8	5.89±0.10	3850±2899	11.7±4.7	240.8±111.4	195.0±185.3
W2V Rainbow	19	6.38±0.54	1737±1181	6.61±5.27	140.8±132.8	196.4±242.2
Standard Values		**5.5-9.5**	**2000**	**10**	**80**	**25**

Table 4.10: Water quality monitoring data for the Worcester chicken processing plant.

Sampling Point	N	pH	COD mg/L	Phosphate mg/L	Total Nitrogen mg/L	Total suspended solids
Dirty Dam	4	6.46±0.38	1867±1708	4.62±3.29	92.4±32.2	301.8±345.3
RTB Rainbow	5	5.87±0.35	1355±905	3.92±3.09	103.3±88.6	104.3±100.8

Table 4.11: Water quality monitoring data for the Hammarsdale chicken processing plant.

Sampling Point	N	pH	COD mg/L	Phospha te mg/L	Total Nitrogen mg/L	Total suspended solids
Municipality (Morning)	36	6,72±1. 71	2006±3319	9,1±15.0	149,1±317. 4	375,3±1085. 8
RTB (#1) Night	6	6.47±1. 16	5554±5734	26.5±33. 7	544.7±741. 0	1464.2±279 2.0
RTB (#2) Night	1	7.69	4370	80.5	448.3	1688

The results of analysis for water in the dams shows evidence of discharge of pollution of the water source, most likely because of discharge wastewater effluents. The mean COD values are excessively high, even higher than ranges for domestic wastewater. According to Nozaic and Freese (2010), a typical domestic sewage or a wastewater with a high domestic component will have COD values in the ranges 500-700 mg/L. The results may indicate pollution of the surface water by the chicken processing plants. Clear dam has very high COD values, hundred-fold higher than permissible for surface water source, Mixture dam has mean COD values comparable to drain waste water, which itself is excessively high.

These results show the impacts of discharging untreated wastewater into the environment, increase its pollution levels and deteriorating its quality (Table 4.10). Even though the Clear and Dirty dams have mean values below the given standard of

2000 mg/L, their COD values are unacceptable for a surface water body. The CODs, total nitrogen, and total suspended solids have means are 10-20 times above the SANS 241:2015 limits (Table 4.9). The monitoring points located on the processing plants all show high levels of pollution to be released into the drains. While the W2V Rainbow monitoring point in Rustenburg records a mean COD that is less than the set standard, the individual readings crossed the limit five times, with a high of 5101 mg/L COD. 19,78 mg/L of phosphates and 623,10 mg/L total nitrogen content, all of them in the range 2-8 times larger than the set standards (Table 4.9).

This could be as a result periodic discharge of the highly polluted wastewater in the municipal drainage system. The same is observed for the monitoring point at the Worcester processing plant (RTB Rainbow) showing high levels of total nitrogen and total suspended solids above the standard while the other chemical parameters are generally within specifications (Table 4.10). However, the COD and the phosphate levels crossed the thresholds once out of the 5 measurements, something that could be attributed to increased efficiency in wastewater treatment due to the W2V plant. The monitoring points at the production and processing sites in Hammarsdale (Table 4.11) all show evidence of wastewater discharge. Except for one reading, all other five readings for the two sites show COD values over 3000, with a maximum reading of 15 700 mg/L. The results clearly indicate the positive of the W2V plants, showing water much worse at Hammarsdale, a processing plant without a W2V plant.

The means for all the parameters measured are above the set standards. Only one record was collected for RTB (#2) Rainbow, which shows all the parameters except the pH out specifications (Table 4.11). It can be concluded that there is evidence of wastewater intrusion into the municipal drainage system, and other sources that may be polluting the surface water sources in the surrounding areas. The reported values on the surface water sources could be related to past events, and therefore still improving as better wastewater management through recycling and bioenergy generation takes off. It should be noted that there needs to be more frequent monitoring by the company to monitor effluents from the plant and monitor possible environmental impacts.

4.4.2. Air Quality issues

Bioenergy production can impact air quality positively and negatively. Poultry wastes can be sources of odours and insects, which can be a nuisance for people living in the surrounding area and was becoming an issue with the large volumes of wastewater sludge that was piling up in Worcester and Rustenburg, presenting the plants with storage problems. The two plants produce larger volumes compared to Hammarsdale. The wastewater sludge cannot be sent to landfill sites according to the new environmental regulations in South Africa (Department of Water Affairs & Forestry, 1998). The use of poultry waste as bioenergy feed has helped the Worcester and Rustenburg plants to mitigate the problems related to improper disposal of the poultry wastes. The challenge was highlighted in Hammarsdale which still faces the same problems of high volumes of wastewater sludge, which may motivate the need for the construction of a similar plant. The use of the poultry processing waste for bioenergy production has mitigated this challenge and therefore has positively benefited air quality. Poultry processing plants use huge amounts of coal for steam production, realising huge amounts of CO_2 which is the primary pollutant responsible for global warming. The reduced emissions due to the use of fossil fuels because of the reduction in fossil fuel consumption is also another way bioenergy has impacted positively on-air quality. The results from the reports from the company show a 22.0 % decrease in the company's carbon footprint is on decrease from 1346893 CO_2eq in 2017. The period coincides with the development of the W2V plant that started operating in late 2017, proof of considerable positive environmental outcomes for the development of the W2V plant and continuous decrease (Figure 4.30). Since poultry is the fastest-growing animal protein in the world, the industry has a responsibility to balance profits with environmental and social impacts (RCL Foods, 2020). When considering potential facility upgrades or new investments, the chicken producer carries out Environmental Impact Assessments (EIAs) where required by the Department of Agriculture, Land Reform and Rural Development (DALRRD) and the Department of Environment, Forestry and Fisheries (DEFF). This enables the chicken producer to carefully consider the proposed investments' impact on the local environment by including comments and input from affected parties and other interested stakeholders.

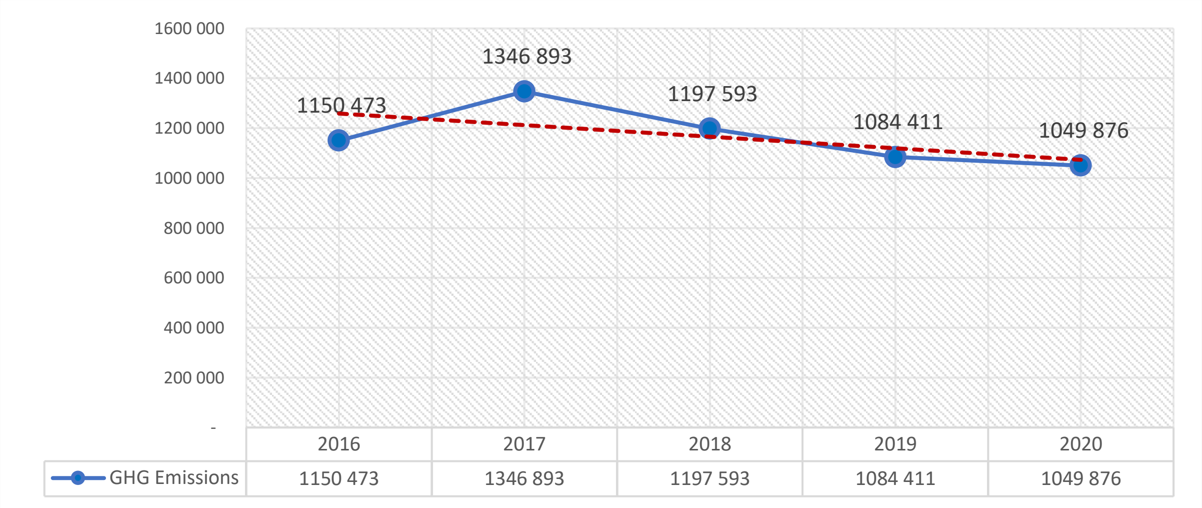

Figure 4.30: GHG Emission within the chicken producer (Source: RCL Foods)

It should be noted however that, while there is a reduction in the company's carbon footprint, there are also several issues that may impact the air quality that was noted from the interviews with the officials. Bioenergy production emits harmful compounds and air contaminants into the environment such as CO_2 from the production and combustion of biogas, CH_4 from the production of biogas, nitrous oxides including N_2O during the anaerobic digestion of poultry waste through diffusive emissions (Paolini, et al., 2018). Both CH_4 and N_2O are GHGs that are more potent than CO_2. One of the SHEQ managers indicated that the loss of biogas into the atmosphere has an impact of releasing the GHG into the atmosphere which has an impact on the air quality. Due to their high greenhouse effect potential, the emission of these two substances from biogas production processes can result in a significant contribution to the global warming budget (Paolini, et al., 2018). Biogas is also rich in volatile organic compounds (VOCs), which can also be released into the atmosphere. H_2S and SO_2 are also produced in biogas production due to the desulphurisation of organic matter. Ammonia is an additional gaseous pollutant released especially during storage of uncovered biomass. As a consequence, dedicated measures should be taken in order to reduce these emissions. As a result, the company has taken several measures to avoid direct emissions and leakages of these substances from the tanks used for biogas storage and digestors, to enhance the efficiency of combined heat and power units, to improve the electric power utilisation strategy, to exploit as much thermal energy as possible, to avoid leakages. Results of the video surveillance of the bioenergy plants showed of transportation and storage of biomass for the W2V plants in covered containers.

4.5. Carbon Credits and Cost Savings Due to Green Energy Generation Projects

The economic assessment of the W2V plants only focused on the cost savings through the selling of energy (capital cost, operation cost, and transportation cost), and profit (selling of energy, carbon credit through carbon avoids - acne, and additional profit from selling the by-products) Informal discussion with key informants was conducted to validate the findings in the document reviews. The chicken producer has a carbon disclosure project, which has a team dedicated to ensuring the minimisation of the producer's carbon footprint. Documents relating to the carbon disclosure project and sustainability report for five years were reviewed.

The ongoing power interruptions and the recent introduction of the carbon tax made the chicken producer decide that the key focus in the environmental sustainability space would be to develop an energy self-sufficient plan and eliminate coal usage within operations. With coal being a major contributor to the producer's carbon footprint, the chicken producer has been investigating biomass as an alternative heating fuel to heat chicken houses, as part of our Zero Coal ambition. The chicken producer has other projects which anticipate significant energy savings as a result of newly approved solar and LED lighting projects. The chicken producer is working with Eskom's demand-side planning team to reduce our power demand where possible during extreme pressure periods in the system.

The results are presented in Figures 4.31 - 4.33. Coal is used in the company's operations for generating steam at the poultry farms and processing plants, and sugar mills. The development of the W2V plant which started operating in 2017, which produces steam and thermal energy as by-products can be pointed out as the reason for the 17 % decrease in coal usage in 2018 from the highest value in 2016. Electricity usage however doesn't show much since the inception of the W2V plant in Worcester.

The amount of electricity from self-generation projects using poultry wastes are much more than 10 times smaller than that produced from bagasse (13.5 vs 145.0 GWh for generation for sugarcane waste for 2021). This could mean that while the W2V plants are adding to the energy generation, its impact is reduced by the expansion of the enterprise-wide activities, hence an increase in the need for Eskom power. Diesel usage also showed a 16 % decrease in 2018, and slowly went up again most likely driven by the business expansion. Reduction in reliance on coal is much more remarkable and is expected to further decrease as the Rustenburg plant increase its output, thus making the current operations more efficient, competitive, and internationally aligned.

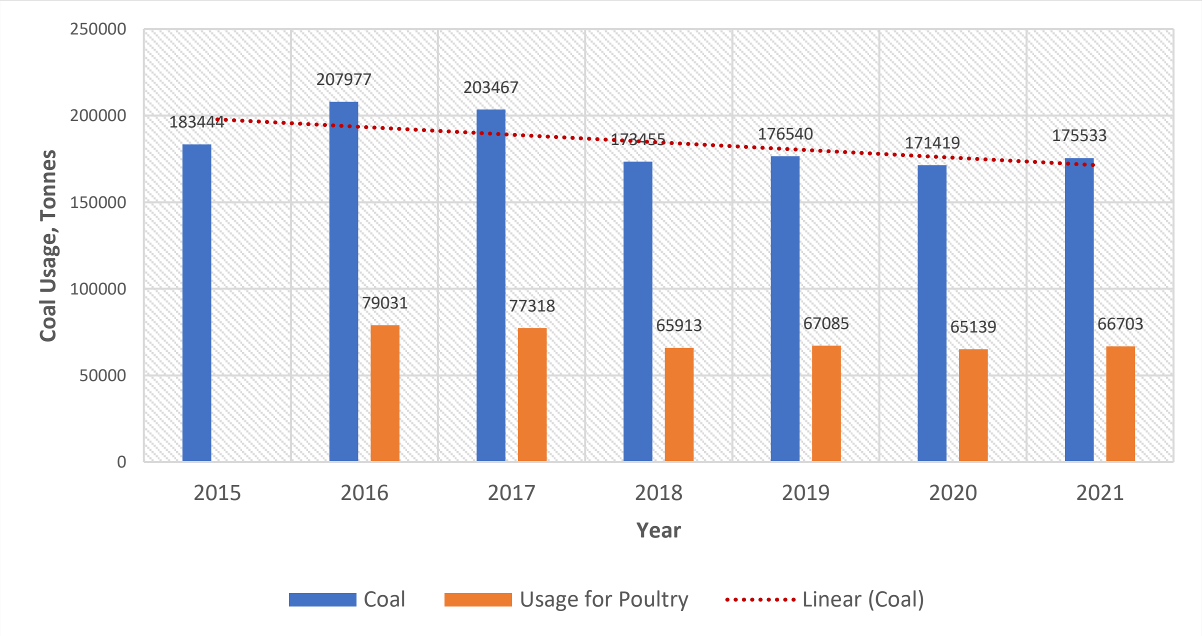

Figure 4.31: Variation in the amounts of coal used each year for the whole enterprise

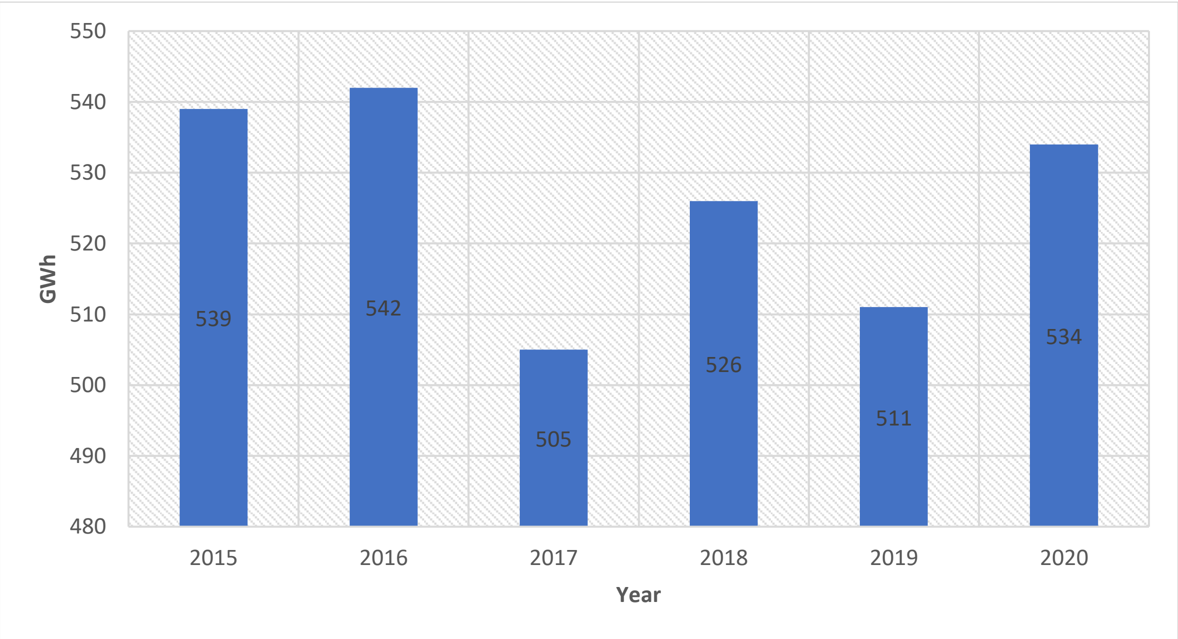

Figure 4.32: Variation in the electricity usage from Eskom for each year for the whole enterprise

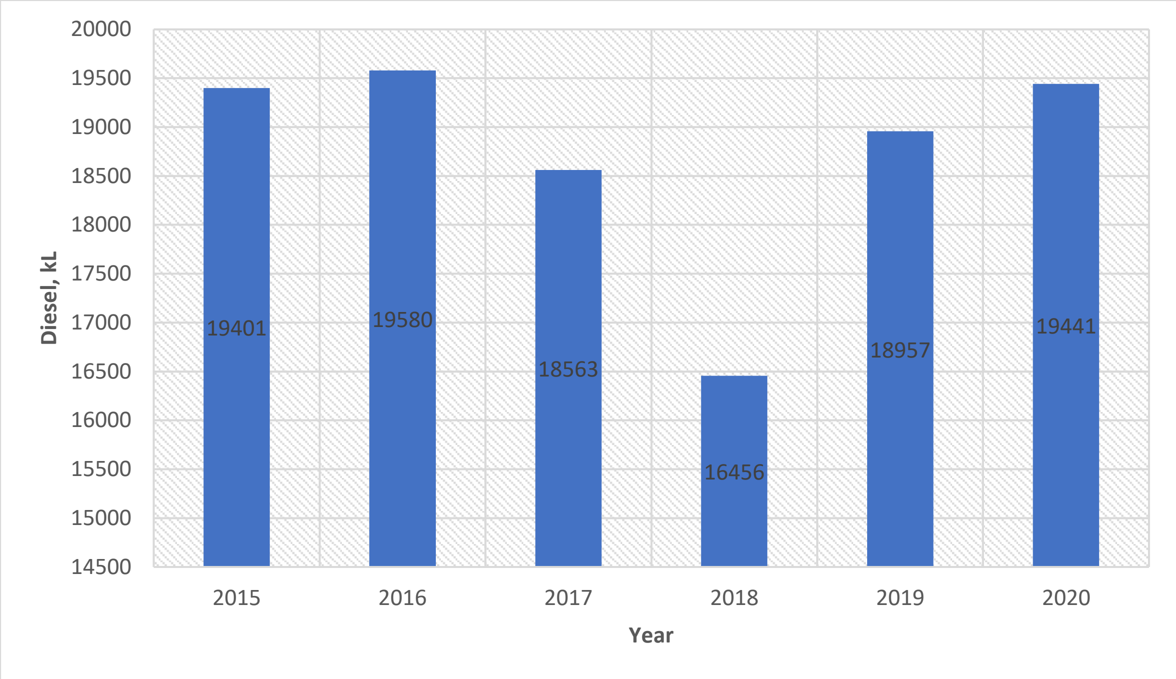

Figure 4.33: Variation in the amounts of diesel usage each year for the whole enterprise

The company conducts a carbon footprint review since 2015, which marks it as the baseline assessment. This was also the first time all divisions of the company including the chicken producer. The findings report was reviewed using the standard international methodology for Greenhouse Gas (GHG) corporate accounting and reporting, namely the World Business Council for Sustainable Development/World Resources Institute GHG Protocol for Corporate Accounting Standards. This review assisted the chicken producer and the other divisions to assess the alignment of the procedures and methodologies to the above protocol, as well as the technical correctness of the quantification procedures/methodologies of our GHG Inventory. Figure 4.34 below shows the carbon footprint of the company. The figure shows three scopes of carbon footprint recorded as direct emissions from the company's (scope 1), indirect emissions from the use of purchased electricity (scope 2), and other emissions from up and downstream in the value chain. The company has gradually been decreasing its carbon footprint, with a remarkable 15 % decrease observed in 2018, in line with earlier observations on coal and diesel usage. In 2020 CO_2e (carbon dioxide equivalent) for scope 1, 2 and 3 emissions were 1 049 877 tons. This is a 3% decrease mainly due to lower coal usage. The Carbon Efficiency (tCO_2e/PHW) noted for the chicken producer was 0.025 for 2021 (RCL Foods, 2021).

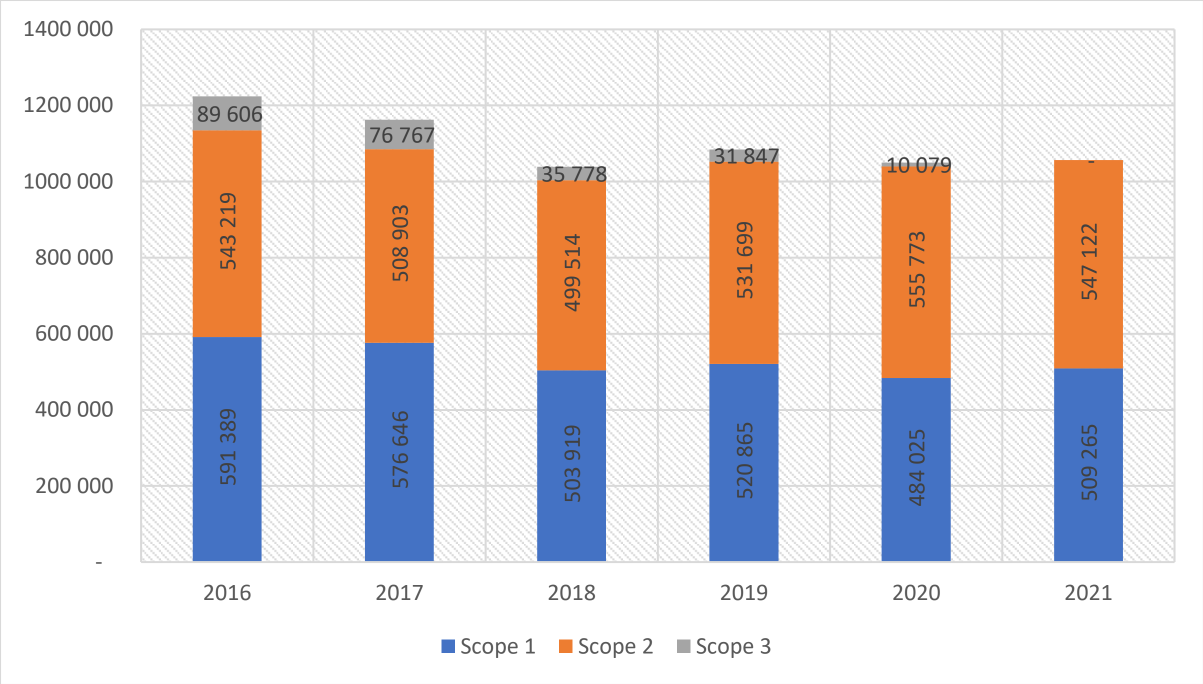

Figure 4.34: Carbon Footprint by Scope for Chicken Producer (Source: RCL Foods, 2020)

Carbon Disclosure Project (CDP) Climate Change survey takes place annually. The South African CDP surveys the top 100 JSE-listed companies. The Chicken Producer achieved a B rating in 2020. This was the highest score in the South African Food & Beverage sector (RCL Foods, 2020). Climate change has the potential to fundamentally disrupt the food production industry across the globe and specifically within Africa. The chicken producer aims to position themselves well against future environmental threats in the long term. The chicken producer has adopted a three-phase "Energy Roadmap" that focuses on energy self-sufficiency in its individual business units including the chicken producer. Finally, exporting excess energy through appropriate trading platforms is seen in Figure 4.35. To date, the company is generating 35% of its total energy usage, with a target of increasing this energy self-sufficiency to 50% by 2025 (Remgro Group, 2019).

Critical issues for the chicken producer, at the group level, included the availability of potable water. Despite the fact that the national drought was broken in South Africa, local infrastructure issues continue to be an operational challenge in many areas. The implications of a carbon tax in South Africa, which was introduced in June 2019, is also being closely monitored. This followed the requirement to submit greenhouse gas emissions in accordance with the National Atmospheric Emission. Inventory System (NAEIS) was introduced into South Africa in 2018.

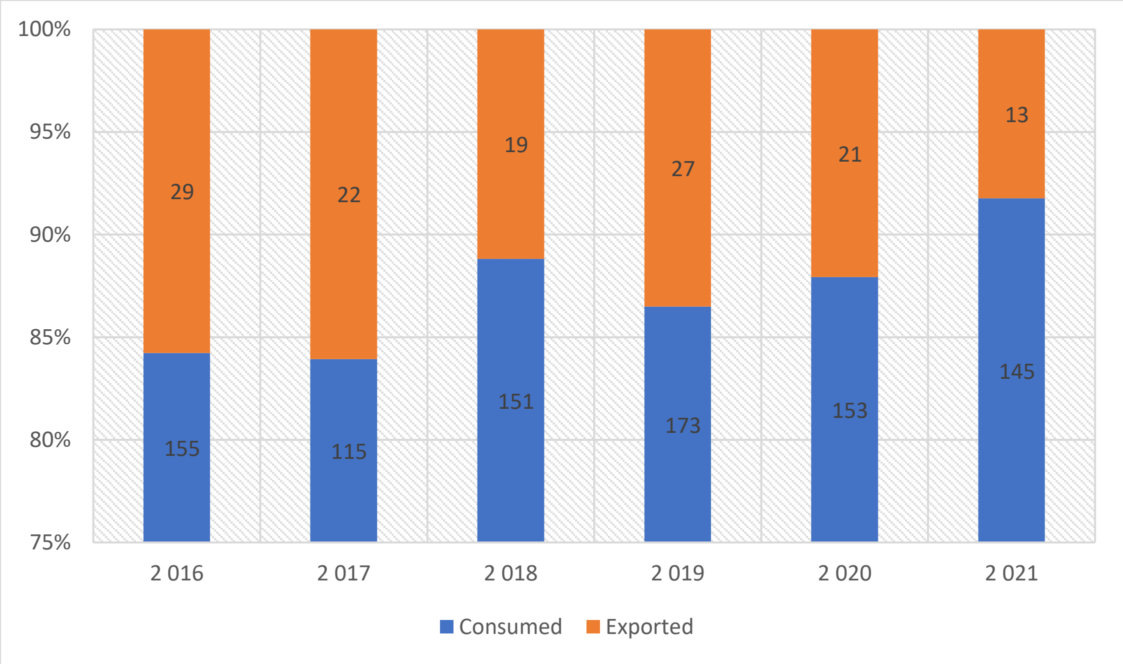

Figure 4.35: Co-Generated Electricity Consumed and Exported (Gwh) (Source: RCL Foods, 2021)

Carbon offsets are carbon credits, generated in South Africa, that can be sold to carbon taxpayers to reduce their carbon tax liability. The carbon credits achieved by the chicken producer for the past 4 years is an average of 8199.3 carbon credits for Worcester W2V Plant whilst Rustenburg W2V plant achieved 18900 carbon credits for 2021 (Figure: 4.37). The Department of Energy has developed the administration system for these offsets. Clean Development Mechanism (CDM) offset standard is used by the chicken producer. The researcher also reviewed the explanatory memorandum on the carbon tax bill, 2018 to verify the current carbon disclosure documents provided by the chicken producer. For emissions above the tax exemption threshold, the proposed blanket carbon tax is R 134 per tonne of carbon dioxide equivalent.

Based on Scope 1, 2 and 3 of CO2e emissions, the carbon tax calculated shows a decrease in 2018 when the Worcester W2V was commissioned. Although the W2V plant is currently not operating at its optimum, the company is still seeing a saving year on year. The results seen are in line with the interview, whereby the sustainability manager confirmed the carbon taxes paid yearly have decreased ~15% since 2016 after the commissioning of the W2V plants.

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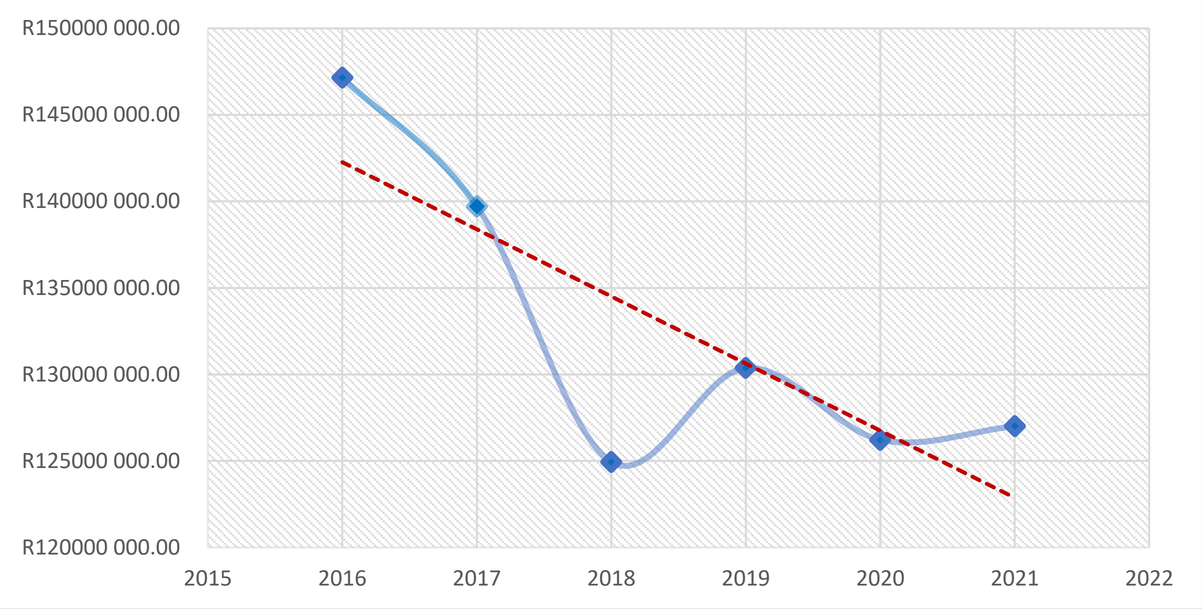

Figure 4.36: Carbon Tax Calculation based on CO2e emissions (Values in R'000)

Given the above tax exemption, this means that the initial effective carbon tax rate ranges from R6 to R48 per tonne of carbon dioxide equivalent. Section 5 of the bill stipulates that as of December 31, 2022, the nominal rate of the carbon tax will be increased annually at the rate of consumer price inflation plus 2% and will be adjusted for inflation as of then (National Treasury, 2018). A GWP is a relative measure of how much heat a GHG traps in the atmosphere (a measure of how much a GHG contributes to global warming) relative to CO_2. Currently, on all the sustainability reports CO_2 is reported on. There are no reports on Methane (CH_4). Nitrous Oxide (N_2O), Sulphur hexafluoride (SF_6), Hexafluoroethane (C_2F_6) and Carbon tetrafluoride (CF_4). The carbon tax bill has this as gas liable for a carbon tax. Methane (CH_4) is the second most important greenhouse gas (GHG) after carbon dioxide (CO_2) and is confirmed to have a global warming potential of 21~25 times that of CO_2 (Moodley, 2014). The carbon tax paid was not disclosed by the chicken producer. In 2021 was the fifth carbon footprint review since the chicken producers baseline assessment in 2015, which was the first full year in which data was available for all divisions as a single company. During the interview, it was disclosed that the chicken producer received a rebate of R155 780 (in R'000) against government tax to the value of R338 824 (in R'000), due to the carbon credits earned in 2021 (RCL Foods, 2021). There is an average saving of 35% - 45% of government payable tax saved by the producer yearly due to carbon credits.

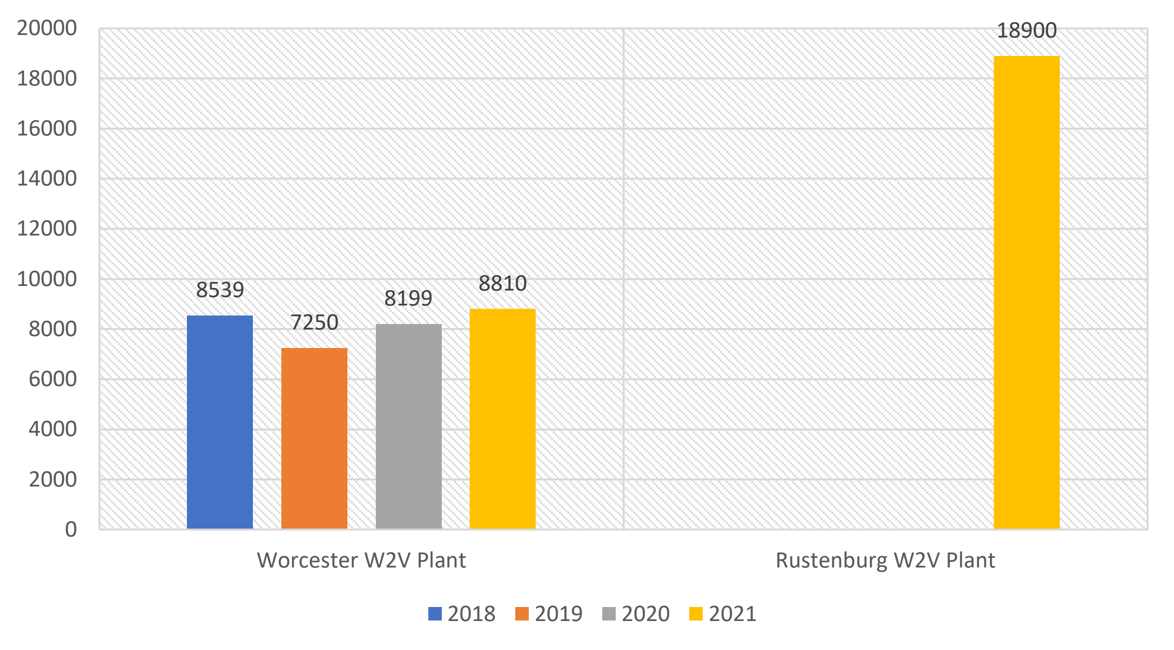

Figure 4.37: Carbon Credits Generation at Worcester and Rustenburg W2V plants

In addition to the rebates on the carbon tax, the chicken producer also has seen a decrease in the cost of the electricity purchased (Table 4.12). In 2019, the Worcester W2V was fully functional and provided self-generated electricity which saved the chicken producer 26% from the estimated consumed electricity. With the current increase in electricity costs to 2.17 for households and 1.051 for businesses in South Africa, the below table takes this into account upon calculations. On average the chicken producer is 25% yearly on their electricity bill.

Table 4.12: 4-year electricity produced and purchased comparison

Year	Total Consumed (Produced and Purchased)	Estimated Cost of Electricity - Rate 1.051 (Produced and Purchased)	Savings from own electricity (Self-Generated Consumed)	Percentage Saving
	kWh	R	R	%
2021	686000000	R 720 986 000.00	R 168 160 000.00	23%
2020	695000000	R 730 445 000.00	R 167 109 000.00	23%
2019	686000000	R 720 986 000.00	R 183 925 000.00	26%
2018	683000000	R 717 833 000.00	R 166 058 000.00	23%

The CDP runs an annual survey of the world's leading businesses in terms of their management of climate change impacts, water security and forests. The South African CDP surveys the top 100 JSE-listed companies. The chicken producer maintained its B rating for Climate Change in 2020 and scored a B- for Water Security. And scored a C for the Forests survey, participating in this section for the first time (RCL Foods, 2021).In addition to the above cost saving, 83% of electricity that is produced at the chicken producer is exported to Eskom Grid at a value of 73 cents (Daniel, 2021), resulting is an overall average profit of 4.9 million rands per annum (Figure 4.38).

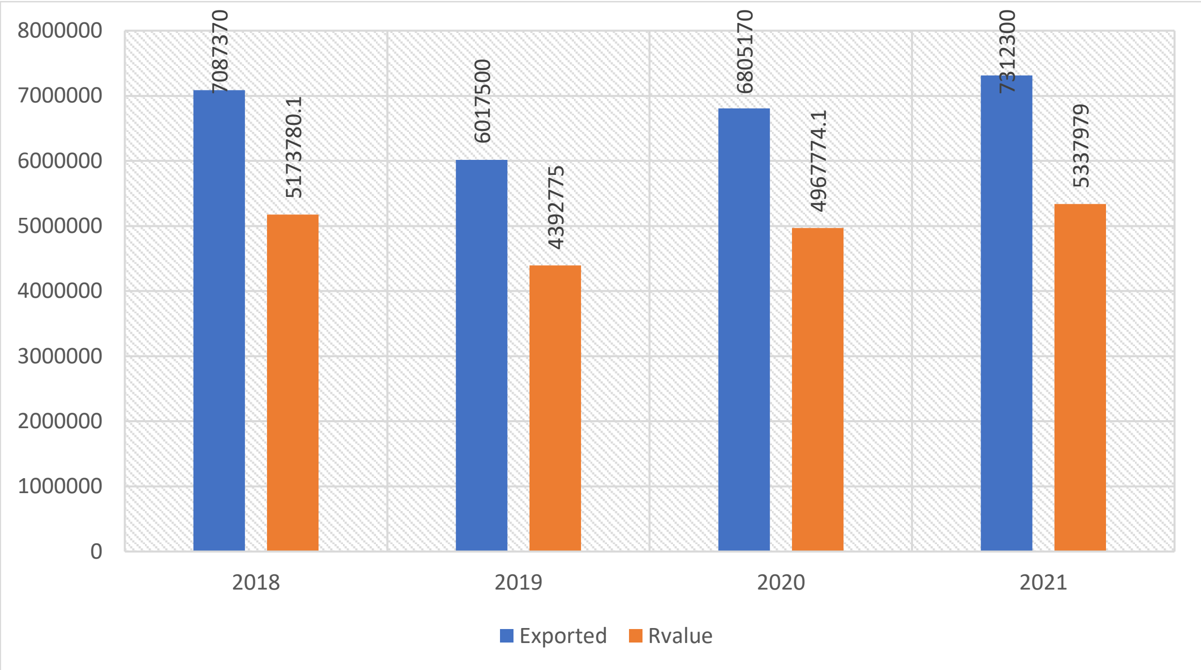

Figure 4.38: Profits of Exported Electricity at Worcester (R-Value)

4.6. Conclusion

In this chapter, the research findings in terms of results, interpretation and discussion were outlined. The analysis was completed and explained using frequencies, percentages, column-charts, pie-charts, means, t tests, correlations from audited secondary data.

CHAPTER 5: RECOMMENDATIONS AND CONCLUSION

5.1. Introduction

The chicken industry is a very important sub-sector in the South African agriculture sector, providing the most affordable source of animal protein and is the largest contributor to total gross agricultural production. However, this study has demonstrated that this expanding industry maybe developing into a major environmental and public health risk because of the associated waste management challenges related to poultry slaughtering wastes. From these results, it was shown that poultry processing produces excessively large volumes of wastes, and that some of these heavily polluted wastes the processing plants maybe going through the municipal drains from time to time (Pedroza, et al., 2021). Of the various waste types produced in the poultry processing industry, wastewater and the feathers were observed to be the most problematic that may threaten the environmental sustainability of this industry. Following are some of the key findings:

5.2. Summary of Key Findings

Wastewater from the slaughterhouses was observed to be highly polluted, carrying large quantities of COD with an average concentration of about 15000 mg/L and electrical conductivities of around 250 mS/m. The study found out that the two processing plants were producing between 1500-2500 kL of this highly polluted wastewater every day. Looking at a much bigger picture, according to the Global Agriculture Information Network report of 2020 (GAIN, 2020), RCL Foods and Astral Foods, the two largest poultry companies in the continent slaughtered 260 million and 228.3 million broilers respectively in 2017 alone. By using the approximations from Chavez et al. (2005), the daily wastewater generation from the two companies' various facilities translates to 7120 kL and 6254 kL. For processing plants without W2V plants, this translates to wastewater that is generated every day, and released into the environment with minimal treatment. Therefore, this industry poses risks to the environment and public health because of the high organic pollution load of the wastewater. This wastewater cannot be discharged or disposed of into the environment without treatment. For plants without W2V plants, these statistics are problematic because the water that is released into the municipal system after the DAF process still showed considerably large amount of pollutants, with COD values around 2000 mg/L and electrical conductivity of over 300 mS/m. Results of analysis of the municipal drains from the processing plants showing heavy pollution, with COD values ranging from 900-15000 mg/L is evidence of the risk that this industry has on freshwater sources and costs related to water remediation.

While attempts have been made to treat the wastewater before discharging into the municipal drains, the wastewater sludge collected from the DAF treatment process results in large volumes wastewater sludge (100-120 tonnes daily). This waste was reported to present additional challenges for storage and disposal. Because of its large water content which is over 70 %, this waste can't be composted or landfilled. This waste may be the most complicated for the poultry industry, with COD values reported around 90-160000 mg/L. This study observed that the development of the W2V plants was driven by the need to deal with this waste. There may be need for further investigation to check how this pollutant is currently being handled by the various processing plants around the country.

The study observed that while feathers were used in the rendering process, the volumes produced were higher, resulting in the need for landfilling. The two processing plants were projected to produce between 10-15000 tonnes feathers each annually. By using the approach by Ashard et al. (2018) and data for the total birds slaughtered by RCL Foods and Astra Foods in 2017 (GAIN, 2020), between 35-44 mega tonnes of feathers were produced from the companies' poultry processing facilities in that year. Much of this waste currently ends up on the landfills, which is potentially problematic because landfilling is not environmentally sustainable. The results therefore show that in an effort to achieve zero waste to the landfills, and improving the environmental sustainability of the industry, feathers maybe become a problematic waste that the poultry industry will need to develop efficient solutions for reuse or disposal.

Landfilling of biomass is particularly problematic because of the possible emissions of methane from the degradation of the biomass, and production of ammonia and water which may end up seeping into and polluting the groundwater because of the state of the landfills in the country (Bruggers J., 2021) (Lu, et al., 2021). Methane gas is a GHG that is more potent than CO_2 and therefore is an important gas that may have a real impact in managing global warming (Lu, et al., 2021). Landfilling is especially worrisome in the South given the state of landfill sites around the country. A report from the Department of Environmental Affairs (Creamer Media Reporter, 2018) show that more than 50 % of the landfill sites are not licensed, and even a larger percentage of the landfills in the country do not have systems to harvest the produced methane. Converting poultry waste into energy provides a realistic solution to the waste management challenges in the poultry industry. The construction of the W2V plants has had some distinct benefits for the poultry processing plants. First of all, the system has allowed the plants to recycle their water, and therefore reduce reliance on municipality water, therefore saving the company money, and also saving water, a benefit to the environment. Currently, the plants are recycling between 500-1000 kL of water every day, with targets of recycling up to 1500 kL daily. From the volumes of wastewater produced and treated, the recovery of permeate was observed to be around 30-60 %. Additionally, the poultry processing industry uses coal for heating purposes. The W2V produces steam, and thermal energy, both of which are a benefit to the company and the environment through reduced use of coal and exporting of the thermal energy for other company processes. The results from the Rustenburg showed heat generation of about 10000 kWh per day, which is equivalent to burning 4500 kg of coal. It therefore means that the W2V plant reduces the reliance on coal usage for heating, a positive for the environment.

The data for waste management from the investigated sites showed an 84 % decline in landfilling for the Rustenburg plant from values in August 2020 to the values in June 2020. This period coincides with the period when the plant was commissioned and started working. The trend could be attributed to the construction of the W2V plants which now takes all the wastewater sludge produced by the plant as well as manure. Together with reduction in water usage and coal usage discussed earlier, these issues show that bioenergy from poultry can have several related positive impacts on water and energy use, and the environment. It can therefore be concluded that bioenergy production from poultry will significantly reduce wastes going to the landfills, therefore mitigating the related environmental impacts due to improper disposal.

The development of W2V plants decreased the company’s carbon footprint by 22 % in 2021 from the values reported in 2017. The Worcester plant went online in 2018, starting to be fully operational in 2019. This reported decrease was also reflected in the decreased reliance on coal of about 17 % in 2018, as discussed earlier. The investment into bioenergy generation by the company has benefited the company millions of rands as a result of rebates on carbon tax which are set in the Carbon Tax Act of 2019 at 5-10 %, and between 23-26 % percent in savings on energy use because of self-generation of electricity which is used within the company. Therefore, on the economic side, the bioenergy has also saved the company millions in water savings, energy savings, and savings on carbon tax liability due to bioenergy generation. Considering the factors at play in this discussion, it can be concluded that bioenergy generation in the poultry industry is very beneficial to the environment and therefore recommended for other production and processing sites.

5.2. Conclusion

On the key objective of the study related to the performance of bioenergy in terms of electricity generation, the research observed that both plants were not operating to their optimum conditions with the plants preforming at about 30-50 % of their technical capacities for the two plants. This conclusion is supported by biogas generation which was at 55.3 % for the Rustenburg plant, much less than the target of 64 %, as well as electricity production from both plants which missed daily generational targets by 50-70 % for the two plants. The possible reason for less than optimum production of methane at the Rustenburg plant could be biogas leakage from the digestors, which is a possibility since it was still a new plant. That would be worrying given that it would release methane, a potent GHG in the atmosphere. These results for bioenergy production showed that more work needed to be performed to determine the best conditions for biogas and bioenergy generation in order to reap the full benefits of the plants.

5.3. Recommendations

This study faced many challenges related to access and availability of information need to complete the study. The study showed some challenges that may need to be addressed in the future to help related studies as there seems to be huge gaps in some of the data. In order to address this challenge, a robust information system maybe needed for capturing data from all the centres so that its easily available and can help advice decision making in the company. It is important to understand the dynamics of waste generation and handling. Information obtained within the food manufacturing company can be shared with municipalities to assist with the improvements to the integrated waste management plan which is a requirement of the National Environmental Management Waste Act (No. 58 of 2008).

In conjunction, improving planning tools or even creating new tools that will allow the enforcement of waste management by-laws where breaches occur. Working with the municipalities and engaging with front line individuals for waste management within the chicken producer is vital for success in maintaining an updated information system. Currently, information is available, but the staff is unaware of this. A central platform with searchable information will assist in driving good practices and enforcing changes within the legislation.

5.4. Future Research

While conducting this research it was found that there are many opportunities for further research on various aspects within the poultry industry in South Africa such as the waste management in the poultry production, detailed impacts of slaughterhouse waste on the water resources and the situation of this highly polluted wastewater sludge for other players in this industry with the country. The following are proposed topics that may be conducted for further research that will lead to the improvement of waste management within the chicken producer

I. Investigate the environmental footprint of food waste in the South Coast area in KwaZulu Natal
II. Investigating opportunities for the recycling of bones, feathers, and blood from chicken waste

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