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Systematic Eco-efficiency Assessment of Pork Meat Production through Life Cycle Assessment and Product System Value

A dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Engineering

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March 2021

DECLARATION

I, **Chule Qalase**, Student Number: **0302491G**, a student registered for the ERA00 MSc Engineering course in the year 2020, hereby declare the following:

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ABSTRACT

Pork consumption has increased as a source of animal protein worldwide – in the first world and developing countries such as South Africa. The expanding interest in pig products increases the pressure on natural resources as water and land are needed to produce pork. This study's main goal was to evaluate the pork product system's sustainability through an eco-efficiency assessment based on pork's growing demand.

Two sustainability tools, namely life cycle assessment and environmental life cycle costing, were used to determine pork production subsystems' economic and environmental performances and thus the product system's eco-efficiency. The ratio of three environmental damages – human health, ecosystem quality, and resource availability against the value-added as an economic performance indicator – was used to calculate this study's eco-efficiency. This study specifically used a functional unit of 1 kg of pork carcass from the cradle to the farm gate. These results were determined using the ReCiPe 2016 and Impact 2002 methods through SimaPro 9.0 version with the ecoinvent 3.5 database.

The pork production showed significant environmental impacts: non-renewable energy use was 36.46 MJ, global warming potential was 4.03 kg CO_2-eq, and terrestrial ecotoxicity was 2.85 kg 1,4-DCB. Pork production contributed to freshwater and terrestrial eutrophication of 0.86 g P-eq, fossil resource scarcity of 0.75 kg oil-eq, and terrestrial acidification of 0.16 g SO_2-eq. Other impact categories were land use of 5.8 m^2a crop-eq, marine eutrophication of 4.55 g N-eq, and water consumption of 1.98 m^3. The results revealed that the most significant environmental impacts are from feed production, manure management and, lastly, from the equipment's electric energy at the farm abattoir.

The cost of producing 1 kg of pork from the farm gate was ZAR22.04. The total cost of producing 1 kg of pork from the farm to the abattoir gate was ZAR35.70. The value add of pork was calculated to be ZAR17.17/kg for the entire pork meat production system.

The economic hotspots for the entire pork product system costs were attributed to animal feed production at the farm subsystem. The feed costs contributed more than 75% of the total costs at the farm. The other costs were attributed to energy, water, and veterinary costs. At the abattoir subsystem, live pigs were the highest cost, followed by utilities such as energy (electricity, coal, and gas) and water, and then labour and cleaning chemicals.

The study results showed that the pork meat production system's eco-efficiency result for the human health environmental impact indicator was 5.61×10^{-07} DALY/ZAR/units. The result for the ecosystem quality impact indicator was 2.84×10^{-09} species. yr/ZAR units. The result for resource availability was 1.05×10^{-02} USD2013/ZAR. The findings indicated that the pig farm and abattoir were processes where eco-efficient strategic improvements could be made. Mitigation strategies should be developed to concentrate on animal feed production and use renewable energy sources at the abattoir. The use of water could be improved by automating the abattoir processes.

Therefore, this study achieved its goal as it identified economic and environmental areas of interest in this specific case study for South Africa. This framework could be extended to study the eco-efficiency of other meat production chains as well as other sectors.

Keywords: Life Cycle Assessment; Pork Production; Sustainability; Natural Resources; Eco-efficiency, Life Cycle Costing.

LIST OF PUBLICATIONS

This thesis culminated in the publication of a paper and an abstract that are both under review.

(i) Chule Qalase, Kevin Harding, 2021. Environmental Impact of pork production in a South African Facility. Submitted to the *Journal of Environmental Management*

(ii) Chule Qalase, Kevin Harding 2021: Abstract Title: Eco-efficiency Assessment of Pork production through Life Cycle Assessment and Product System Value in South Africa. Submitted to the LCM2021 Conference to be hosted in Germany in September 2021.

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LIST OF ABBREVIATIONS

3D	Three-dimensional
CFC	Chlorofluorocarbon
eLCC	Environmental Life Cycle Costing
FAO	Food and Agriculture Organization of the United Nations
GWP	Global Warming Potential
ISO	International Organization for Standardization
IWRM	Integrated Water Resource Management
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelised Cost of Electricity
LPG	Liquefied Petroleum Gas
Naphtha SR	Naphtha Steam Reforming
NG VR	Natural Gas Vapour Reforming
NWA	National Water Act (Act 36 of 1998)
PAW	Pig Abattoir Waste
SDG	Sustainable Development Goal
SETAC	Society of Environmental Toxicology and Chemistry
SPC	Sustainable Production and Consumption
UCG	Underground Coal Gasification
UV	Ultraviolet
UNEP	United Nations Environment Programme
USA	United States of America
WBCSD	World Business Council for Sustainable Development
WWTP	Wastewater Treatment Plant

NOMENCLATURE

1,4-DCB	1,4-Dichlorobenzene
CFC-11-eq	Trichlorofluoromethane Equivalent
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
DALY	Disability Adjusted Life Years
H_2	Hydrogen Gas
H_2SO_4	Sulphuric Acid
HCL	Hydrogen Chloride
HNO_3	Nitric Acid
kBq	Kilobecquerel
kg/FU	Kilogram per Functional Unit
$LCC_{cradle\text{-}gate}$	Total Life Cycle Costs of a Product from Cradle to Gate
m^2a	Cubic Metre per Year
m^3	Cubic Metre
MJ	Megajoule
mPt	Millipoints
N-eq	Nitrogen Equivalent
N_2O	Nitrous Oxide
NH_3	Ammonia
NO_3	Nitrate
NO_x	Nitrogen Oxide
P-eq	Phosphorous Equivalent
$PM_{2.5}$	Particulate Matter with Diameter <2.5 μm
SO_2	Sulphur Dioxide
SO_2-eq	Sulphur Dioxide Equivalent
Species. yr	Species Disappearing in One Year
USD2013	US Dollars (Reference Year 2013)
UV/H_2O_2	Ultraviolet Hydrogen Peroxide
UV/O_3	Ultraviolet Ozone
ZAR	South African Rand
ZAR/FU	South African Rand per Functional Unit

CHAPTER 1 INTRODUCTION

1.1 Background

This chapter introduces the study, states the aims and objectives of the research, and gives an overview of the rest of the thesis.

Animal food is an essential source of proteins, together with the minerals, vitamins, and amino acids that are used to sustain human health (De Smet & Vossen, 2016). Along with many other factors, increases in salaries and the global urban population have changed the way consumers eat, thereby creating a market for animal-based proteins in recent years. In 2013, pork's worldwide production amounted to 113 million tons, with China and the United States of America (USA) contributing roughly 48% and 10%, respectively (FAO, 2016). However, pork accounted for less than 7% of South Africa's meat consumption in the same year (Müller, 2015).

The pork industry worldwide has significant challenges, firstly, the growing demand for pork and the requirements that must subsequently evolve to more complex environmental regulations. Significant concerns have been raised about the possible implications of growth in the pork sector; more specifically – it will increase the use and the degradation of natural resources, contribute to climate change, exhaust water supplies, affect biological diversity, and trigger ecosystem changes. The second concern is economic challenges such as the cost of production, purchase of animal feed, labour, and utilities. Furthermore, stringent controls are required through veterinary services to prevent an outbreak of diseases. Such issues have led to an increased interest in evaluating pig production systems' sustainability through eco-efficiency, determining their environmental and economic performances, and improving how the industry will meet the projected demand.

Eco-efficiency, proposed by the World Business Council for Sustainable Development (WBCSD) in 1991, is achieved by delivering competitively priced goods and services that satisfy human needs while reducing ecological impacts and resource intensity (DeSimone & Popoff, 2000). Eco-efficiency is a relative measure that addresses the relationship between environmental performance and the value of a product system (SANS 2014). Ideally, increased eco-efficiency is achieved by reducing a product system's environmental impacts while maintaining or increasing the value produced (Mickwitz *et al.*, 2006).

Eco-efficiency is used as a support system to maximise the overall system by considering both the economic and environmental aspects. Eco-efficiency brings many advantages to the practical application of producing goods, which can be measured from the macro-economic, meso-economic, and micro-economic stages (Permpool, Mahmood & Ghani, 2021; Saling *et al.*, 2002). Eco-efficiency is among the principles of industrial ecology intended to encourage sustainable development. Private businesses have embraced eco-efficiency as the latest business proposition (Permpool *et al.*, 2021; Secchi *et al.*, 2019). The concept consolidates the environmental and economic pillars of sustainable development, reduces the consumption of resources, and improves nature while maintaining or enhancing the manufactured product's value (Caiado *et al.*, 2017; Permpool *et al.*, 2021). The framework has already been implemented for various products and services to demonstrate how to enhance the sustainability of companies and products, such as:

- Water (Stanchev & Ribarova, 2016).
- Wastewater (Lorenzo-Toja *et al*., 2016).
- Sewers (Petit-Boix *et al.*, 2018).
- Agriculture (Todorovic, Mehmeti & Scardigno, 2016).
- Food (Laso *et al.*, 2018).

- Automotive (Levidow *et al.*, 2016).
- Energy (Burchart-Korol *et al.*, 2016).

An eco-efficiency assessment is a comprehensive and science-based approach that comprises environmental impact data and cost data to calculate a product's sustainability (Woon & Lo, 2016). The concept can help focus the attention and efforts on improving resource use, optimising processes, and reducing or preventing waste generation (Maktabifard, 2018). As per Gémar *et al.* (2018), product systems' performance can be determined by quantifying their eco-efficiencies by defining improvements, monitoring trend, and prioritising actively.

Another critical objective of eco-efficiency is governing environmental sustainability, which operates at varying tiers of the organisational framework and is implemented differently. The implementation (i) optimises the effects of the economic resource; (ii) increases the environmental efficiency perceived from a purely environmental perspective; and (iii) overlaps primary elements that can be perceived as economic-environmental efficiency that stems from the calculation of the added ecological Impact induced by the created monetary unit.

Therefore, an eco-efficiency assessment can help pork meat production systems since it is a tool that decision-makers can use to measure and achieve sustainability. This concept is proposed by Permpool *et al.* (2021) and Secchi *et al.* (2019) as a way in which businesses can contribute to sustainable development. Eco-efficiency encourages companies to become more competitive while being more environmentally responsible at the same time.

Eco-efficiency evaluations can help accelerate the provision of products and services to reduce the burden on the environment. Furthermore, it raises awareness among industries regarding the economic and environmental benefits of establishing a circular economy and

implementing eco-friendly designs and resource-efficient production. The eco-efficiency evaluation results can be used to highlight strategies and policies for enhancing the sustainability of pork production from the farm to the abattoir gate.

Thus, this research facilitated the integration of environmental life cycle costing (eLCC) and life cycle assessment (LCA), thereby providing an instrument with both environmental and economic performance indicators. In this context, this study looked to the concept of eco-efficiency as an indicator for measuring the environmental aspects of products and services to minimise environmental impacts and create greater values. The results of an eco-efficiency assessment can enable decision-makers to, for example:

- Determine where economic and environmental hotspots are in pork production.
- Determine whether it is necessary to improve the technologies used by the pork meat production processes.
- Decide on recommended appropriate strategies to address pork meat production's environmental and economic costs.
- Use these results for strategic decision-making processes to attain sustainable development goals for pork meat production systems.

1.2 The rationale of the study

Large quantities of natural resources, such as water and land, are required for animal production, requiring about 35% of total cropland and 20% green water for feed production (FAO, 2016). Non-renewable fossil fuel energy resources such as coal and liquid fuels (diesel, petrol, and gas) are used to produce pork. Coal is the main energy resource used for generating electricity in South Africa.

Waste flows such as slurry, wastewater is produced at pig farms, and abattoirs produce effluents loaded with plenty of organic matter from blood, fat, and offal. Few studies are provided in literature that have calculated pork production systems' environmental performance's current and future challenges. These published LCA studies are country-specific, namely:

- Denmark (Dalgaard, Halberg & Hermansen, 2007; Nguyen, Hermansen & Mogensen, 2011).
- Germany (De Vries & De Boer, 2009, Reckmann, Traulsen & Krieter, 2012; Reckmann, Traulsen & Krieter, 2013; Weidema *et al.*, 2008).
- Portugal (González-García *et al.*, 2015).
- Austria (Winkler *et al.*, 2016).
- Spain (Noya, Aldea *et al*., 2017).
- France (Basset-Mens & Van der Werf, 2005; Basset-Mens *et al.*, 2007).
- Ireland (McAuliffe, Chapman & Sage, 2016; McAuliffe, Takashi & Lee, 2018).
- USA (Pelletier *et al*., 2010; Thoma *et al*., 2015).
- Serbia (Lukić *et al.*, 2015).
- Italy (Pirlo *et al.*, 2016).

Lastly, only two studies have been conducted in South Africa (Devers, Kleynhans & Mathijs, 2012; Müller, 2015).

It is worth noting that all the studies only evaluated the environmental consequences of pork production processes and negated their economic forecast, thereby making it challenging to determine pork production systems' eco-efficiency. According to the author's knowledge, no studies in the literature reviewed pork's economic performance using eLCC of the entire pork value chain.

Thus, this study sought to fill the literature gap and, therefore, the eco-efficiency of pork production processes had to be measured. Hence, this is the first published work for an industrial facility of a pork production system in South Africa. It was, therefore, imperative that this study be carried out in a South African context.

Several studies have combined LCA and functional value (eLCC) in various sectors such as confectionery and frozen desserts, wastewater treatment, and sewers (Konstantas, Stamford & Azapagic, 2020; Lorenzo-Toja *et al*., 2016; Petit-Boix *et al*., 2018).

The eco-efficiency perspective includes implementing environmental and economic decision-making instruments such as LCA and product system value through eLCC (in this study) to measure eco-efficiency (Stanchev & Ribarova, 2016). In addition to the eLCC, value add was also considered in this work. Value add is characterised as revenue minus the cost of acquired products and services to express the increase in net income due to the manufacturing of final products. As per Konstantas *et al.* (2020), eco-efficiency follows the International Organization for Standardization's (ISO) frameworks for LCA (ISO 14040 2006) and ISO 14044 (2006), and the product system value adopted by the Society of Environmental Toxicology and Chemistry (SETAC) for the life cycle costing (LCC) method (Hunkeler, Lichtenvort & Rebitzer, 2008; Swarr *et al.*, 2011). These are the most effective methods because of their systematic approach and appreciation of products and services' entire life cycle.

Sustainable production of pork requires economically viable, ecologically sound, and socially acceptable farms – both now and in the future. Sustainability approaches can be used to determine how economically, and environmentally sustainable pork meat production subsystems are. Thus, a pork production system's eco-efficiency evaluation performance was undertaken to assess pork production processes' baseline sustainability

and help the pork sector move towards achieving its sustainable development goals. The following study questions were formulated to achieve the result:

- What is the environmental and economic baseline of a typical South African pork meat production system from the farm-to-abattoir gate?
- Where are the environmental and economic hotspots?
- How does environmental performance compare with pork production literature studies from others?
- What recommendations can be drawn from this study in terms of economic and environmental costs and benefits?

1.3 Aim and objectives.

The study aimed to provide a holistic decision-making framework for various public and private stakeholders interested in pork meat production to measure and improve the sector's sustainability performance. This study determined the baseline eco-efficiency of a South African pork production system through a life cycle approach. Based on the ISO 14045: 2012 guidelines, this research's objective was to evaluate pork production's eco-efficiency using the product system value (eLCC) and LCA as tools to evaluate economic and environmental performance. This was done by identifying and quantifying the materials and resources used and the waste generated. The above study questions were addressed using the following specific objectives of this study:

- To determine the pork meat production system's eco-efficiency based in South Africa through environmental and economic performances.
- To use LCC and LCA to identify the hotspots throughout the entire pork process stages.

- To recommend possible strategies for improving the sustainability of pork production and waste handling to drive towards a circular economy perspective.

1.4 Structure and presentation of the thesis

The structure of the thesis is described below.

Chapter 1 was the introductory chapter and set the scene for the research project.

Following this, **Chapter 2** provides an in-depth literature review of the eco-efficiency concept and its link to sustainability. This chapter connects eco-efficiency to other sustainability tools such as cleaner production. It highlights previous research that used the eco-efficiency concept. The chapter details steps that must be followed to conduct an eco-efficiency assessment. LCA and eLCC are discussed in detail, and the chapter introduces value add as a tool used for calculating the economic and environmental ratio to determine the system's eco-efficiency.

Chapter 3 features the various stages pursued of this research and the strategies associated with each stage.

Chapter 4 presents the research results and examines the results of the methodology research.

Chapter 5 interprets and discusses the results obtained. It condenses this research's discoveries and endeavours to give proposals to improve the pork production system's eco-efficiency.

Chapter 6 presents the concluding chapter and the recommendations for possible research areas of this study.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter provides a background on South African pork processing and the stages of rearing pigs at farms up to the level at which they are ready to be taken to an abattoir. A high-level literature review on pork production was undertaken to establish the theoretical framework and the paradigm in which the concept and the methodologies of eco-efficiency were developed. Different readings about sustainability and sustainable development in this chapter provide the background to eco-efficiency and the need for developing tools such as LCAs and eLCCs.

In trying to relate these broad concepts to industry functioning, the literature search was widened, and a body of literature pertaining to industry responses to environmental problems was accessed. An even more extensive literature review was undertaken to collect information about LCAs in the pork industry and their methodologies. Since this is a relatively new field to South Africa, there was not much information available locally on eco-efficiency.

This chapter gives a high-level pork production account: from the pig farming stage to the abattoir pig slaughtering stage. It highlights the typical economic and environmental challenges associated with this sector. Selected literature on the LCA studies on pork production is discussed. The chapter further describes local legislation related to environmental and meat safety in South Africa. The chapter gives a brief background on sustainability and its links to the eco-efficiency concept. It presents eco-efficiency as a management tool with its definitions, history, methodological framework, applications, and limitations. A brief discussion on LCA and eLCC as tools for conducting eco-efficiency

follows. The chapter ends by showcasing studies on eco-efficiency in different industries and adding to the body of knowledge and its relevance in the South African context.

2.2 Background to pork production in South Africa

The South African Pork Association identifies the pork meat industry in South Africa as small, varied, excellently well organised, and matching the rest of the world's processing outputs (Devers *et al.*, 2012). The increase in income earned by ever more urbanised consumers have led to money being spent on pork due to increasing pork consumption (BFAP, 2013). Overall consumption of pork meat has increased by 53% in the agricultural sector (Müller, 2015).

The Department of Agriculture, Forestry, and Fisheries (BFAP, 2013) reported that livestock output contributes approximately 50% to the gross value of agricultural production in the country, whereas the pork industry adds just 4.4% to overall livestock production. From a worldwide perspective, the South African pork industry is an insignificant player in global markets with only a 0.18% contribution to total pork produced worldwide, which, at the same time, makes it sensitive to changes in the world pork markets (BFAP, 2013).

South Africa's primary pork producers have taken several actions to lower production costs, such as blending their feed. However, numerous other factors outside the control of the primary producers affect production costs significantly. The essential cost for primary producers is animal feed at approximately 70% of the farm's production cost due to the problematic nature and the resulting large quantities of feed consumed per pig.

The pork value chain in South Africa is complex. Various vertical integration levels make it extremely hard to identify a specific supply chain that spans the entire industry at various

supply chain stages. However, in many circumstances, a single organisation operates in more than one phase, which essentially reduces the cost of manufacturing the finished product by introducing vertically integrated systems. An example of such an integrated vertical organisation in South Africa is the Eskort Group that controls the overall pork value chain (from farm to pork products).

Pork is mainly sold in South Africa via two separate chains: fresh pork or processed pork products. Various pork carcasses are used in various markets, with smaller and skinnier pork carcasses favoured throughout the fresh meat market, whereas larger baconers are produced for processing. Lighter pigs are classed as porkers (50–65 kg), whereas heavier pigs (66–83 kg) are categorised as baconers. About 70% of pork baconers in South Africa are marketed mainly for the processing market (although a few light baconers are sold on the fresh meat market), and 30% are only sold to the fresh meat market. The average slaughter mass in South Africa is 78 kg, which is wholly dependent on what the pigs eat (BFAP, 2013).

2.2.1 The pork production cycle

According to Roelofse (2013), pork production relates to different physiological stages throughout the life cycle of pigs. Each phase has various stages relating to the growth of pigs; all these stages require different resources, and the environmental impacts of pigs differ in every phase. Figure 2.1 shows a description of each phase of a pig's life. This a simplified process diagram of the pork production process at the farm subsystem.

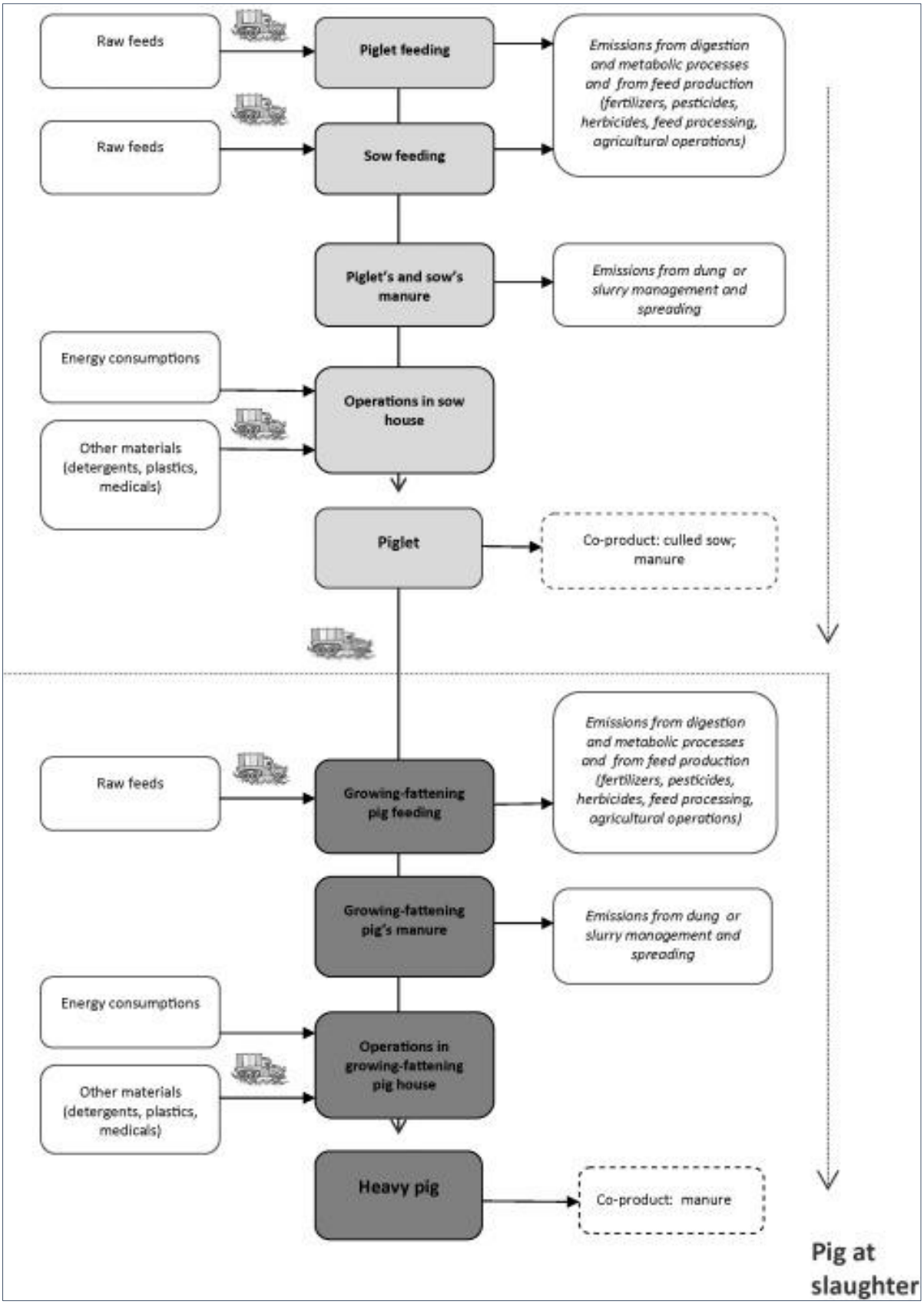


Figure 2.1: Typical process flow of pork production at the farm gate [Source: Pirlo et al. (2016)]

Breeding

Breeding is done using artificial insemination or normal mating (Kyriazakis & Whittemore, 2006; Pluske, Le Dividich & Verstegen, 2003; Roelofse, 2013). A boar-to-seed ratio of 1:15 is common practice for pig farms that use normal mating (Kyriazakis & Whittemore, 2006; Roelofse, 2013). Artificial insemination enables a producer to restrict males' ratio to females on the piggery to just 1:50 because sperm is collected from an off-farm breeding operation. Artificial insemination gives farmers access to quality genetic lines worldwide and allows the best possible production results (Roelofse, 2013).

After ablactation, the female pig is put in a pen next to the males' pen. The males' appearance and scent in the neighbouring pens cause the female pig to go into heat. The process normally happens around 5–7 days following ablactation. If the female pig is in constant heat, it is inseminated artificially or placed into the same pen as the male to enable natural mating (Kyriazakis & Whittemore, 2006; Roelofse, 2013). Male pigs are kept separately to prevent violence (Kyriazakis & Whittemore, 2006).

Gestation

The average gestation period (pregnancy) lasts 115 days, which depends heavily on temperature, breed, and litter size (Roelofse, 2013). The expectant female pigs are housed in groups or individually (Kyriazakis & Whittemore, 2006; Roelofse, 2013).

Farrowing

The female pig is transferred to a gestation crate a week prior to parturition to make adaptation easier. Diligent observation is essential to ensure the piglets' complete survival for at least the first week after farrowing. The gestation crate helps prevent piglets from

being crushed to death by their mother. About a week after birth, the piglets are vaccinated, and iron injections administered (Kyriazakis & Whittemore, 2006; Roelofse, 2013).

A crawl zone encourages the piglets to warm up (heat, bedding, and heating). In general, heating and floor heating lamps control the temperature of the creeping and weaning zone (Kyriazakis & Whittemore, 2006; Roelofse, 2013). The heat allows piglets to use their energy to develop rather than warming their bodies. The piglets stop attempting to warm themselves by laying down in the seeds and thus risk accidentally getting killed by their mother. During the first 45 days, the piglets are placed in an environment heated according to ambient conditions (Kyriazakis & Whittemore, 2006). The area for feeding piglets is closed to the mother to avoid piglets being killed by exposure to the farrowing pen (Kyriazakis & Whittemore, 2006).

Weaning

When piglets are between the ages of 21 and 28 days and have an average live weight of 7.5 kg to 9 kg, they are separated from the sows (Roelofse, 2013). The weaning age can, however, be lowered to 19 days. The decreased ablactation age from 28 days to 21 days enables the female to give birth to more piglets in a year and decreases opportunities for transferring sicknesses/diseases to its young. This decreased weaning period demands more nutritious food, housing monitoring, and expertise (Pluske *et al.*, 2003). An ablactation age of less than 28 days is not recommended for small-scale farmers due to the increased maintenance and shelter considerations. The female pigs are relocated to a reproduction area, and the ablactation pigs are moved to weaner quarters or kept in the nursery. The weaners are equipped with heating (Roelofse, 2013).

Growing and finishing

The weaned pigs are moved to a place where they will grow for 58 days. By then, their live weight is about 20 kg. Alternatively, they are allowed to grow for 70 days, at which point they will have a live weight of about 25 kg. The activity is done to increase feeding and room allocation demands and lower ambient temperature needs. The growers are moved to the finisher housing at 118 days (live weight 58 kg) (Kyriazakis & Whittemore, 2006; Roelofse, 2013).

Slaughtering

The slaughtering step entails putting pigs on trucks, transporting the pigs and subsequently delivering the pigs for slaughter. These pigs are marketed at the abattoir from 118 days of age (58 kg live weight) to 168 days of age (or when their live weight is 100 kg). These culled breeding stocks are marketed as porcine for sausage (Roelofse, 2013).

According to BFAP (2013), South Africa's abattoirs have different business models. On the one hand, abattoirs simply offer a slaughter facility for pig producers or contractors who pay the abattoir. On the other hand, abattoirs acquire the producers' pigs until they execute the specific slaughtering and process them before distributing them directly to distributors or consumers. The abovementioned is the business model used at the abattoir in this study.

Some abattoirs sell entire carcasses at a retail level, conducting the slaughtering step, whereas others trim the carcass into prime parts, selling individual prime cuts at the retail level. However, irrespective of the business model selected, the abattoir's crucial factor is ensuring throughput. Other supporting activities such as steam production (in boilers) and ice and cold air production (ice plant and refrigeration) are needed. Additional important areas or sub-areas are waste and wastewater discharge.

The processing of all animals follows chronological process steps, which are explained in the following paragraphs. Figure 2.2 shows the high-level process flow of pork meat processing at the abattoir. Various waste streams are generated in these processes and, depending on the economic value, include slurry/manure flushed through the sewerage system.

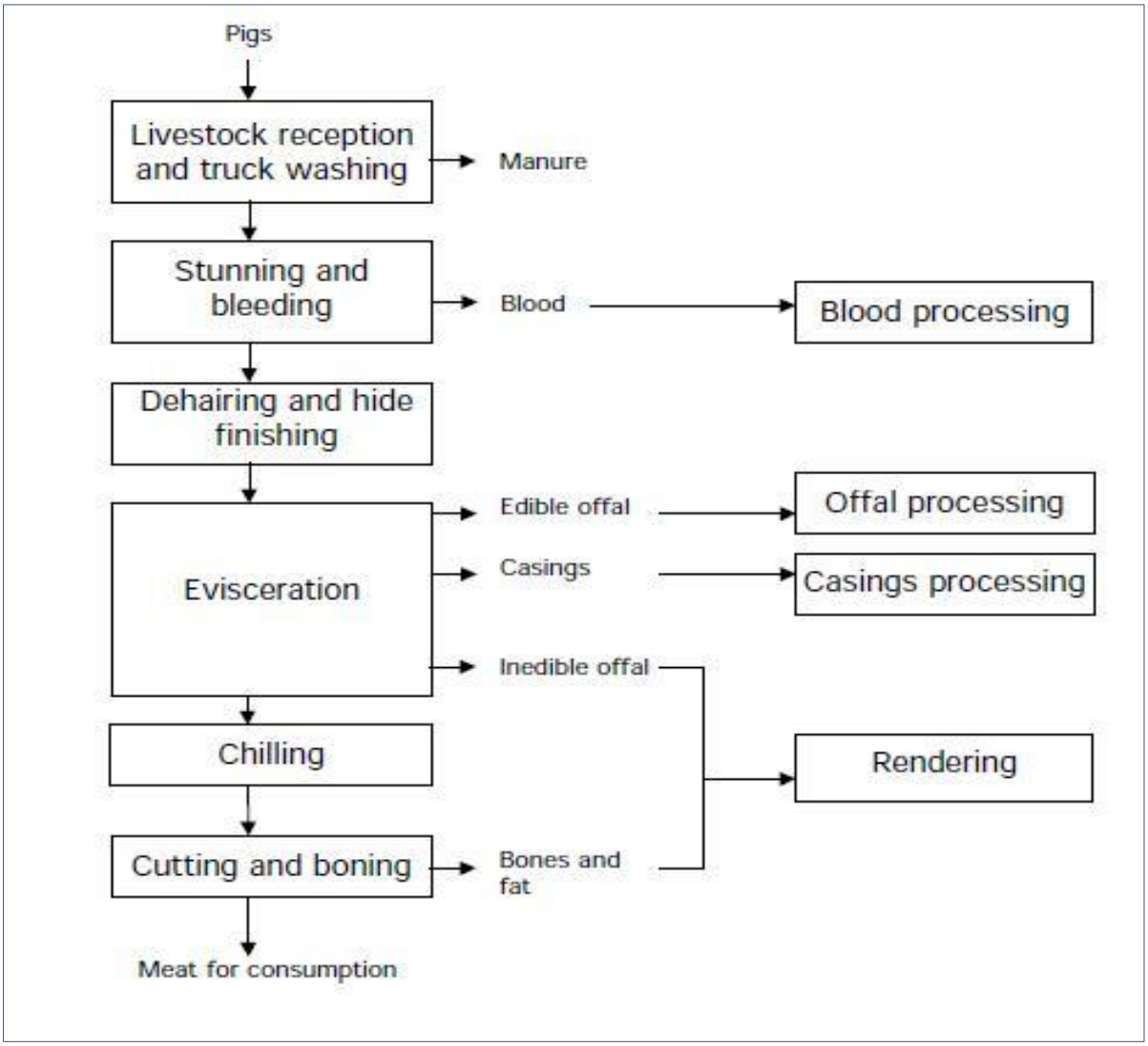


Figure 2.2: A typical pig slaughter product system

Lairage

Animals are sent in trucks to the abattoir, where they are loaded into holding pens. They rest for a day or two in preparation for slaughter. Animals classified as dirty are washed

with municipal clean water, while the lairages are cleaned at least once a day. The pigs are clamped at their hind legs and hung on an overhead rail or dressing trolley.

Stunning

The pigs are taken through a bolt pistol or electric shock to the slaughter area, where they are stunned.

Sticking/bleeding

The animal goes through sticking, whereafter it bleeds. Its blood is gathered for further processing or in a trough for disposal.

Scalding/dehairing

Steam is blended with cold running water to create hot water at about 82°C to disinfect hardware and knives. After that, the carcass reaches a dehairing machine in which spinning rubber strips or 'fingers' flake most of the hairs off. The final hair removal mechanism is performed by manual scrubbing and finally singing (burning using an open flame). During the entire process shift, water from the scalding tank is disposed of continuously at the end of each slaughter period.

Evisceration

After the scalding, the carcasses are delivered to the evisceration area, where dressing and evisceration occur. This first phase involves either hanging the carcasses from an overhead rail or unshackling the animal and placing it in a cradle. The head is detached and washed with water, and the tongue and brain are retained. The carcasses are opened to remove the viscera. The handling of by-products involves removing condemned meat, blood, and offal

and taking it to a safe disposal site. The carcass is split, washed, and transferred to quick chilling at a cold storage area within the abattoir gates to prepare for further processing.

Quality checking

In this stage, the carcasses and viscera are inspected for any defects in the meat or diseases to determine whether they are suitable for human use. Every carcass and its components are marked and retained intact, whenever possible, until complete inspection. Inedible by-products (bone, fat, heads, hair, and condemned offal) are produced at different stages of the process and dispatched for safe disposal at the landfill.

Transportation of pork for further processing into various products, consumption, and waste transportation to its final disposal fell outside this study's scope.

Chilling

Cold storage needs to be available at an abattoir. The carcasses must be contained at temperatures between 0°C and 5°C. Maintaining appropriate cold room temperatures requires large refrigeration systems. It must be noted that refrigeration is one of the abattoir's most electricity-intensive operations because it is necessary to maintain cold temperatures via an ammonia cooling system. The above system is responsible for using 60–70% of all the facility's electrical energy. Water is used to cool the air, and there is water loss by evaporation. The handling of by-products involves removing condemned meat, blood and cut carcasses to a safe disposal site.

Deboning and cutting

After the carcasses have been chilled, they are deboned and cut to specific products according to customer requirements. Some value-adding is done on-site based on customer

requirements. The abattoir does provide its own added value and continues to supply meat as required by customers.

2.2.2 Pork production and its associated environmental issues

It is estimated that the higher demand for pork will lead to an increased demand for natural resources. The farming of animals significantly affects the natural environment (De Vries & De Boer, 2009). Animal farming has a significant impact on air, water, and soil (De Vries & De Boer, 2009; Gutierrez *et al.*, 2016). Large quantities of natural resources, including water and land, are required for livestock breeding, with about 35% of the total agricultural land and 20% of rainwater needed for animal feed (FAO, 2016). Increasing land demand will change ecosystems, decrease natural habitats, and threaten biodiversity (FAO, 2016).

It is calculated that emissions from the global pig farming industry (farm and abattoir) constitute 700 million tons of CO_2-eq per year, or roughly 9% of the total livestock industry (MacLeod *et al.*, 2013). Methane (CH_4) and nitrous oxide (N_2O) are the greenhouse gases most emitted by agriculture and contribute 21 and 310 times as much global warming potential (GWP) as carbon dioxide (CO_2), respectively (MacLeod *et al.*, 2013).

Governments actively advocate for the decreased use of scarce resources and more efficient use of the resources to mitigate and adapt to climate change. For these global efforts, the effect of livestock supply chains on climate change has now been calculated. As a result, the pig farming industry is looking to improve its environmental performance (Djekic *et al.*, 2014).

2.2.3 Case studies on pork production

As shown in summary in Table 2.1, several studies have been carried out recently in the scientific community by calculating pork production systems' environmental performance

(farm and abattoirs). The consulted literature studies on the pork sector focus on producing pig animal farms – from pig farms, abattoirs, meat-processing plant, retailers to households.

The local pork meat production industry faces various kinds of challenges from consumers, the market, and the authorities. These challenges include operational and production costs, which are due to increasing electricity costs and labour. Furthermore, there are challenges of unpredictable access to clean water (drought), cost of feed, diseases, and preventing the breakout of diseases.

For abattoir operations, acquiring live pigs to be slaughtered is among the most significant costs incurred. There are necessary additional costs for the further conversion of fresh pork meat into processed products. According to BFAP (2013), maintenance and operating costs contribute up to 48% of overall slaughter costs, followed by energy costs and fixed overheads. Farms and abattoirs must be kept free of pathogens and other diseases. Therefore, the pig industry needs to find production alternatives that mitigate the environmental impacts resulting from their industrial operations, particularly in the stages that significantly affect the environment and pork processing's economic performance.

As stated in Chapter 1, environmental and economic pressures are associated with the specific procedures used to raise pigs and produce pork meat in the farms and at abattoirs, following legal food safety standards. As a result, these challenges need to be given a holistic perspective and define places where further change is necessary.

Table 2.1: Reviewed LCA studies on pork production

Reference	Functional unit	Main boundaries	Geographical areas	Time boundaries	LCIA methods	Impact categories
(Dalgaard *et al.*, 2007)	1 kg pork	Cradle-to-abattoir gate	Denmark	1995–2015	EDIP method, SimaPro+, IPCC 2006	GWP, EU, AP,
(Nguyen *et al.*, 2011)	1 kg pork delivered from the abattoir	Cradle-to-abattoir gate	Denmark	2010	SimaPro, Impact 200+	GWP, EU, AP, NRE, LU
(Reckmann *et al*., 2013)	1 kg of pork slaughter weight	Cradle-to-slaughter gate	Germany	2010–2011	SimaPro, CML 2 Baseline	GWP, EU, AP
(Winkler *et al.*, 2016)	1 kg fresh Austrian pork (carcass weight)	Cradle-to-grave	Austria	2007–2010	SALCA	GWP, EU, AP
(Noya, Villanueva-Rey *et al.*, 2017)	100 kg live weight	Cradle-to-farm gate	Spain	2016	SimaPro ReCiPe Midpoint H	CC, TA, FD, ALO, ME
(Noya, Aldea *et al.*, 2017)	1 kg of cut pork	Cradle-to-slaughter gate	Spain	2016	SimaPro, ReCiPe, H, Midpoint	CC, TA, FD, ALO, ME
(González-García *et al.*, 2015)	1 kg of meat (carcass weight)	Cradle-to-abattoir gate	Portugal	2014	Gabi Software, ReCiPe Midpoint H	CC, TA, FD, ME, HT, FE, OD, POF, WD
(Lukić *et al.*, 2015)	1 kg of pork	Cradle-to abattoir gate	Serbia	2013	CCaLC, with ecoinvent database	GWP, AP, EP, ODP, PS, HT
(Devers *et al.*, 2012)	1 kg of carcass weight	Cradle-to-abattoir gate	South Africa	2010–2011	GaBi CML method	GWP, EP, AP, energy use
(Müller, 2015)	1 kg of pork meat	Cradle-to-farm gate	South Africa	2013	GaBi, CML 2001	GWP, EP, AP, and EU
(Thoma *et al.*, 2015)	4 oz boneless meat	Cradle-to-final consumption, including waste disposal	USA	2008–09	SimaPro, ReCiPe	GWP, CC, FD, WD, ALU
(Pelletier *et al.*, 2010)	1 kg of live weight	Cradle-to-farm gate	USA	2009	SimaPro, CML 2001	EU, EF, AP, and EP
(Stone *et al.*, 2012)	1 head of pig produced from gestation (29 kg) to market weight	Cradle-to-farm gate	USA	2011	SimaPro, ReCiPe, midpoint	CC, TA, TE, ME, FE,

Reference	Functional unit	Main boundaries	Geographical areas	Time boundaries	LCIA methods	Impact categories
(Basset-Mens *et al.*, 2007)	1 kg of live weight	Cradle-to-farm gate	France	2006	SimaPro 1.1 method	EU, CC, AP, TA, LU, Pesticides use
(Basset-Mens & Van der Werf, 2005)	1 kg live weight pork	Cradle-to-farm gate	France	1996–2001	SimaPro 1.1 method	EU, CC, AP, TA, LU, Pesticides use
(McAuliffe *et al.*, 2017)	1 kg of live weight	Cradle-to-abattoir gate	Ireland	2016	SimaPro CML (2013)	GWP, EP, AP
(Pirlo *et al.*, 2016)	1 kg of body weight	Cradle-to-farm gate	Italy	2016	SimaPro ecoinvent database (v 2.0, ILCD)	PO, AD, AC, EP, GWP

Legend

AC: *Acidification*
AD: *Abiotic Depletion*
ALO: *Agricultural Land Occupation*
AP: *Acidification Potential*
CC: *Climate Change*
EDIP: *Explain, Demonstrate, Imitate, Practice*
EF: *Emission Factor*
EP: *Eutrophication Potential*
EU: *Eutrophication*
FD: *Fossil Depletion*
FE: *Freshwater Aquatic Ecotoxicity*
GWP: *Global Warming Potential*
HT: *Human Toxicity*
ILCD: *International Reference Life Cycle Data System*
LU: *Land Use*
ME: *Marine Eutrophication*
NRE: *Non-renewable Energy Use*
ODP: *Ozone Depletion*
PO: *Photochemical Oxidation*
POF: *Photochemical Oxidants Formation*
PS: *Photochemical Smog*
SALCA: *Swiss Agricultural Life Cycle Assessment*
TA: *Terrestrial Acidification*
TE: *Terrestrial Ecotoxicity*
USA: *United States of America*
WD: *Water Depletion*

Water and energy resources are essential for pork meat production processes. Water is a non-renewable natural resource that plays an essential role for both humans and ecosystems. Water is further one of the resources that are becoming increasingly scarce due to increasing demand from different human and economic activities, which are caused in part by the effects of climate change (Lemos *et al.*, 2013). According to Buckley, Friedrich and Von Blottnitz (2011), this is especially important for developing nations like South Africa, where access to freshwater is one of the most substantial assets recognised inherently with the nation's financial and social improvement goals.

Pork production systems, such as farms and abattoirs, create vast amounts of waste slurry and wastewater with a high organic waste content due to diluted blood and suspended solids. Waste recovery can contribute to a circular economy in biogas production and a compost source for farming to replace synthetic fertilisers and reuse supplements. This waste can further be used as a source of protein for other essential synthetic compounds. Nevertheless, if not treated adequately, pig waste and wastewater can result in significant health risks, air and environmental contamination/pollution, and visual problems.

In the process of slaughtering a pig, a large volume of organic, general, and sludge wastes are generated as by-products, which is an effect that cannot be avoided. As a result, waste and sludge management is crucial to prevent detrimental environmental impacts. Buonocore *et al.* (2018) state that the proper handling of this by-product is necessary. Proper waste handling is among the most significant waste management issues, especially in emerging economies such as South Africa. Developing countries lack clear regulatory frameworks and proper strategies and methodologies for choosing alternative sludge management systems that will not require high investment costs and operational complexity.

Because of the undeniably strict policies, strategies, laws, guidelines, expanding treatment costs, rapidly approaching water shortages, and environmentally aware consumers, the management or treatment of slurry and wastewater has become a significant concern in the meat-processing industry and, specifically, in the pork sector (Basitere *et al.*, 2017). There are opportunities for pork meat production systems to use specific sustainability approaches for their plants by implementing circular economy strategies by optimising the recovery of valuable organic materials and generating biogas from the emissions generated in the process (Buonocore *et al.*, 2018; Huijuan *et al.*, 2016). Consequently, those in authority must use appropriate sustainability tools that can help towards sustainable development. Achieving sustainability requires a realisation of solutions that can strengthen and push approaches to a circular economy (Spinosa *et al.*, 2011).

Although the international demand for meat, especially pork, must be addressed, consumers, researchers, and producers have become increasingly aware of meat production's environmental effects. Additional impacts entail odours, water pollution, habitat degradation, global climate change, and visual pollution (Müller, 2015). Since the advent of sustainable development in the 1980s, environmental protection and the fight against climate change have become the world's top concerns. The willingness to act has contributed to the development of several concepts to reduce environmental impacts Benoit (2018). Eco-efficiency is one of these concepts, according to Benoit (2018).

The reviewed studies shared some critical information on using LCA as a valuable tool for modelling these production systems' complexes. A recent scientific review of LCAs by McAuliffe *et al.* (2016) provides a chronological review of the state-of-the-art pork production LCAs under three themes: feed production, entire-system livestock rearing, and waste management. The study considered how LCA applications have addressed

technological improvements in animal husbandry and highlighted methodological limitations, particularly cross-study comparisons. Some important considerations can be seen in that different studies use different functional units, system boundaries, life cycle impact assessment (LCIA) methods, and impact categories.

The reviewed literature (see Table 2.1) shows the different types of functional units that are used in the LCAs of pork production systems:

- 1 kg live weight at the abattoir.
- 1 kg of pork carcass weight at the slaughter gate.
- 1 kg of bone and fat-free meat.
- 1 kg of edible protein.
- Typical average daily intake of pork meat.

In terms of system boundaries, the studies had differing systems boundaries, as shown in Table 2.1. It is worth noting that no studies were found in the literature that addressed the eLCC to determine the product system value by following the SETAC perspective (Hunkeler *et al.*, 2008; Swarr *et al.*, 2011). Therefore, none of the pig studies addressed the pork production process's eco-efficiency in the pork meat production system.

The critical environmental concerns relating to the rearing of pigs include water and air pollution. The environmental policy measures influencing the pig sector aim to reduce its adverse effects on pork industry ecosystems. One of the causes of the primary pollution of water is the improper handling of pig manure. Although pollution of water is more local or regional, cross-border pollution may occur. The primary pollutants from agriculture into surface water, groundwater, and marine water are mainly manure nutrients, nitrogen, and phosphorus, which damage habitats by eutrophication and degrade their recreational use.

The main goals of such policy measures are to minimise overall pollution and odour. Some countries have put measures in place in recent years to address specific issues, especially ammonia pollution. Most policy initiatives were inspired and sometimes developed and implemented at a certain level through regional levels.

Lopez-Ridaura *et al.* (2009) conducted a study using the LCA technique to evaluate different slurry management strategies' environmental performance. Some of the analysed slurry management systems appeared identical to the slurry management methodology used in the case studies featured in this case (Müller, 2015).

In most countries, policy initiatives continue to be an essential part of overall environmental strategies. Pig farmers must adhere to a range of regulations that affect their thresholds and methods of production. Initially, laws were implemented to restrict pollution from point sources, including preventing or restricting pig manure's direct disposal in water bodies. Regulations are enforced increasingly to limit non-point source emissions by restricting the amount of manure generated, the amount that can be spread, and how it can be distributed. Also, there has been a clear trend towards increasing the number of regulations and enforcing pig farmers' stricter requirements.

Alternate uses for pig manure, including using it as an energy source, have been promoted in both on-farm and off-farm activities. Countries like the Netherlands and Denmark have recently implemented incentives to boost the farmer's exit from the sector to reduce pork production's environmental pressures more rapidly. European countries apply more initiatives, which are generally more stringent as well. There is no question that perhaps the different policy interventions introduced since the mid-1980s for environmental concerns have minimised the support policies' environment. One pertinent question is: How far do

agricultural-environmental policies solve issues generated through agricultural support policies, among other factors?

However, particular attention is given to coal and oil and water scarcity to identify the water and energy needs across the whole life cycle (González-García *et al.*, 2015; Reckmann *et al.*, 2012).

2.2.4 Legislation governing meat sector, environment, water, and wastewater.

The Constitution and Bill of Rights (Act 108 of 1996) highlight sustainable development in the Republic of South Africa. The legislation relates to constitutional rights about the environment, water, access to information, and administrative justice. Such rights and other obligations became enshrined in law through the National Water Act (NWA; Act 36 of 1998) and the Water Services Act (Act 108 of 1997).

The most significant environmental policies for the pig industry are the National Environmental Management Act (Act 107 of 1998) and the National Environmental Management Act (Act 59 of 2008), or the Waste Act and the National Environmental Management Act (Act 39 of 2004) or Air Quality Act. In general terms, these laws identify the conditions for on-site storage and disposal of waste, licensing requirements, establishment of waste management systems, setting off air emissions limits, and enforcement of criminal penalties. The Laws highlight a requirement to introduce sustainable production and sustainable technologies to mitigate source emission generation. The National Waste Management Strategy (NWMS, 2011) is a statutory provision of the Waste Act to help achieve its targets.

The Waste Act's goal is based on waste management system measures, guiding South African waste management. The waste management hierarchical structure comprises

alternative options for waste management arranged in the discerning priority order at a certain level throughout the life cycle of waste: waste avoidance and reduction, reuse and recycling, recovery and treatment, and disposal as the ultimate resort.

The NWA is the crucial legislation that provides the legal basis for water management in South Africa. It must maintain ecological integrity, economic development, and social equity when managing and using water. The NWA introduced the concept of Integrated Water Resource Management (IWRM), which includes all water resource elements, such as water quality, water quantity, and aquatic ecosystem quality.

The IWRM strategy demonstrates both targeted resources and intended mechanisms for the supply. The NWA provides the legislative framework for just positive and sustainable water resource management within South Africa. The Act's goals are to preserve, use, create, maintain, control and manage water resources supporting the IWRM with all stakeholders interested in participation. The Act stipulates the requirements to create a national water resource strategy, among others.

In South Africa, the laws most pertinent to meat abattoirs are the Meat Safety Act 2000, Act 40 of 2000: Abattoir Regulation, and Abattoir Operations. This Act is responsible for laying down legislation to ensure the safety of meat and dairy products; to lay down and preserve essential requirements for abattoirs; to monitor and control the import and export of meat, and to lay down strategies for the safety of meat or provide for matters concerning meat products. This Act's provisions are governed by the National Director of the Department of Agriculture, Forestry and Fisheries.

This strategy culminated in the oversight of food safety programmes for private operators to introduce and maintain. Section 11(1)(e) of the Meat Safety Act (Act 40 of 2000) decided

for the control of the Hygiene Management System and Hygiene Assessment System and is one of 11 essential government standards for abattoirs.

Below are the acts that are used in South Africa to regulate meat and food safety:

- The Animal Diseases Act (Act 35 of 1984) of the Department of Agriculture, Forestry and Fisheries.
- Animal Protection Act (Act 71 of 1962). Treating animals sent for slaughter.
- Meat Safety Act (Act 40 of 2000). Its objective of enhancing safe meat production and preserving abattoirs' cleanliness is to provide for the required standards following the provisions laid down in the Meat Safety Act (Act 40 of 2000). International developments in food safety strategies began to shift towards co-regulation during the 1990s.
- Red Meat Regulation Act (Act 1072 of 2004). Under the Red Meat Regulations, guidelines for red meat abattoirs have been developed for hygiene management systems, adapting similar techniques used in the United Kingdom and improving the Hygiene Assessment System's examination procedure. Those same concepts are essential for implementing and representing meat safety at abattoirs in South Africa during handling and processing.

The biggest problem in developing economies such as South Africa is untreated wastewater runoff from meat-processing firms. Laws and regulations are vital components and tools for helping meat-processing companies cope with environmental and economic effects. Waste produced and wastewater from the meat-processing industry must meet legal requirements concerning its efficiency in removing the waste produced and treating wastewater that conforms to discharge regulations. Therefore, abattoir managers must set aside money for capital, operational and maintenance costs, which negatively affect these production

systems. Nonetheless, regulatory compliance with environmental laws could provide an incentive and an alternative source of revenue to abattoirs, including resource recovery from treatment processes, like anaerobic treatment biogas production. Worldwide, the requirements and laws governing the meat-processing industry vary considerably.

In most cases, the Water Services Act deals with water services or accessible (drinkable) water and sanitation services provided to households and other municipal water users by municipalities. The NWA provides norms and standards for wastewater purification before discharging in the receiving water bodies, including general and special requirements that set limits for factors including pH, temperature, chemical oxygen demand, suspended solids, and metals.

Specifically, the NWA lists the analysis methods for assessing these factors. Any manufacturing, municipal or private wastewater plant that discharges to a river or the sea should meet specific requirements. By-laws are established in municipal areas under the Water Services Act, which provides rules and regulations for the water supply and discharge of effluents for that area. As a South African standard, all municipally based abattoirs must discharge their effluent to municipal wastewater treatment plants (WWTPs) rather than discharging directly to receiving water bodies. These effluents must furthermore meet the municipal by-laws and national limits regarding effluent discharge. The typical values for the wastewater quality of red meat wastewater are:

- pH: 5.7– 8.4.
- Chemical oxygen demand: 730–8 900 mg/ℓ.
- Suspended solids: 1 700–3 048 mg/ℓ.
- Total dissolved solids: 595–2805 mg/ℓ.
- Total nitrogen: 1.0–24.0 mg/ℓ.

Abattoirs discharging untreated or poorly treated wastewater have been known to cause pollution, which degrades and surface water bodies. Untreated wastewater at the abattoir causes eutrophication, temperature variation limits, oxygen transfer in the water mass, water pollution, and freshwater depletion for portable use (Bustillo-Lecompte & Mehrvar, 2017), particularly in developing economies such as South Africa.

One other issue with abattoirs is that they generally use a vast amount of water. Abattoirs are estimated to account for 24% of all water used in the food and beverage sectors and 90% of wastewater (Bustillo-Lecompte, Mehrvar & Quiñones-Bolaños, 2016 & Naderi *et al.*, 2017). Water is consumed throughout processes such as slaughter, processing, packing, and cleaning abattoir plants. It should also be noted that the abattoir industry, like all food manufacturing industries, follows the ISO 22000 International Standard on Food Safety and others follow other regulatory standards like the ISO 14000 series of standards, which promote effective environmental management systems in organisations.

2.2.5 Characteristics of pig abattoir waste

The abattoir generates much waste, including organic waste in the form of blood, bones, fat, hair, non-edible offal, and meat offcuts; meat that does not meet the quality specifications (condemned meat); and animals that die on arrival. The inorganic waste emanates from packaging (including cardboard, plastics, and wood). Metal waste in the form of scrap is also found in the abattoir. Wastes such as coal ash, oils/greases, or wastewater are further possible wastes.

Pig abattoir waste (PAW) contains large quantities of fats, protein, suspended solids, biodegradable organic residue, and other nutrients that define abattoir waste and wastewater (Basitere *et al.*, 2016; Cammarota & Freire, 2006). PAW is identified as high-strength wastewater due to several components of carcass debris, protein, fat, oil, and grease and the

high levels of biological and chemical oxygen demand. The quality of wastewater depends entirely on an abattoir's processes, the number of animals slaughtered, and the chemicals used in the plant to clean the facilities (De Nardi, Fuzi & Del Nery, 2008; Jayathilakan *et al.*, 2012).

Heavy metals and pharmaceuticals, including antibiotics, may be prominent in veterinary drug PAW (Bustillo-Lecompte & Mehrvar, 2017). Furthermore, PAW may contain non-pathogenic and pathogenic microorganisms that might not be deactivated through abattoir cleaning or sanitation processes. Moreover, in contrast to domestic wastewater treatment, PAW is categorised by elevated levels of the following among other significant pollutants: chemical oxygen demand, biological oxygen demand, total organic carbon, total nitrogen, total suspended solids, and total phosphorus (Bustillo-Lecompte & Mehrvar, 2017).

Subject to the variance in the quality of wastewater produced, the quality parameters of pig wastewater should be analysed and monitored since they are dependent on the processes used in abattoirs. These analyses could include measuring the above parameters (Bustillo-Lecompte & Mehrvar, 2017).

2.2.6 Pig abattoir waste treatment

Animal carcasses and meat by-products may be disposed of in several ways, including anaerobic digestion, composting, and rendering. Biosecurity, current environmental laws, greenhouse gas emissions, and successful resource recovery have been studied for each of these approaches for dealing with large quantities of waste products. Biosecurity assurance is complex in co-composting animal carcasses and meat by-products with manure and other materials. However, published research suggests substantial amounts of methane and nitrous oxide are released during composting. Through anaerobic digestion, biosecurity can be

achieved more effectively, and greenhouse gas emissions are minimal if digestate storage tanks are closed.

Nevertheless, there is limited experience in digesting meat by-products and no complete health and environmental regulations. The rendering of meat is an established and highly regulated industry that involves cooking meat to remove moisture and destroy pathogens. This ensures that fats and proteins are recovered entirely from raw material. Energy consumption and other plant processing operations release approximately 25% as much carbon emissions as meat by-products.

Although equal quantities of meat by-products are processed by rendering, composting, and anaerobic digestion, differences suggest that rendering is the most sustainable method for managing large amounts of produced carcasses and meat by-products. Because of the many environmental impacts and the degradation capability related to abattoir wastewater, direct dumping of the untreated pork wastewater into the environment is impractical; therefore, wastewater must be managed and treated appropriately.

PAW treatment methods are similar to existing municipal wastewater technologies and consist of preliminary, primary, secondary, and sometimes tertiary treatment. PAW management strategies following preliminary treatment are diverse, but they can be grouped into five main subgroups: physicochemical treatment, biological treatment, advanced oxidation processes, mixed techniques, and land use (Valta *et al.*, 2015). The benefits and drawbacks of each programme are described below.

Physicochemical treatment involves separating the PAW into several elements. Usually, any solids are separated from liquids by sedimentation or coagulation/flocculation, and pollutants are removed by electrocoagulation and membrane technology (Almandoz *et al.*, 2015; Bull, 1982; Eryuruk, Tezcanun & Bakir Ogutveren, 2014; Johns, 1995; Mittal, 2006).

Bustillo-Lecompte and Mehrvar (2017) classify biological treatment systems into anaerobic, aerobic, and constructed wetlands. Aerobic processes are more prevalent as they often operate at a greater rate than anaerobic systems. Anaerobic processes demand much less sophisticated infrastructure because no aeration system is required. Anaerobic and aerobic processes can further be broken down into various processes with their benefits and negative aspects (Bugallo *et al.*, 2014; Bull, 1982; Bustillo-Lecompte & Mehrvar, 2015; Bustillo-Lecompte & Mehrvar, 2017; Johns, 1995; Mittal, 2006; Tritt & Schuchardt, 1992).

Advanced oxidation processes are versatile and include ultraviolet (UV)/H_2O_2 and UV/O_3 to oxidise and degrade the organic and inorganic materials present in PAW by hydroxyl radical reactions (·OH) (Barrera *et al.*, 2012; Bustillo-Lecompte *et al.*, 2014; Bustillo-Lecompte & Mehrvar, 2015; Cao & Mehrvar, 2011; Luiz *et al.*, 2009; 2011; Melo *et al.*, 2008; Mittal, 2006).

Eventually, paired systems are cost-effective with increased removal efficiency, which can lead to lower operational and management costs than individual processes (Bustillo-Lecompte *et al*., 2014; Bustillo-Lecompte & Mehrvar, 2017 Cao & Mehrvar, 2011; Chan *et al.*, 2009; Luiz *et al.*, 2011; Tritt & Schuchardt, 1992).

A land application typically includes direct irrigation of the PAW onto agricultural land (Bull, 1982; Mittal, 2006).

2.3 Sustainable development

The idea of sustainable development was established concerning a growing awareness of an evolving environmental crisis. This seems to have been one of the world's critical impulses around the end of the 20th century (Du Pisani, 2006). According to Huppes and Ishikawa (2005), the word 'sustainability (also referred to as sustainable development) refers to a way

of organising society to exist in the long term. Kloepffer (2003) states that the term sustainability became renowned for its use in the report 'Our Common Future by the World Commission on Environment and Development, better known as 'The Brundtland Report' in the global arena. According to Kloepffer (2003), this report links environmental protection with global development and emphasises humankind's responsibility for future generations. This can be recognised in the famous definition (Kloepffer, 2003): "Sustainable development is a development that meets the needs of the present without compromising future generations' ability to meet their own needs".

In the past, economic growth has been associated with increased resource consumption and, therefore, potential damage to the environment (Benoit, 2018). At that stage, working on process upgrades was popular to industrialists without understanding the potentially relevant environmental impacts of these so-called improvements. There was some feeling that it could be acceptable to pollute economic growth if a balance were found between economic growth and environmental protection (Du Pisani, 2006). There is currently a drive to move from this form of production towards a circular approach to overcome the conventional production and consumption pattern that focuses on continuous growth and increasing resource performance (Noya, Aldea *et al.*, 2017).

Sustainability issues have been discussed in recent literature by Caiado *et al*. (2017), Leal Filho, Manolas and Pace (2015) and Park, Egilmez and Kucukvar (2015) report that the United Nations (UN) has increased awareness about sustainability. The UN has determined the 2030 Agenda with 17 sustainable development goals (SDGs) to identify critical interlinked concerns and activities in the current economic, environmental, and social setting to tackle the international aspect of sustainability (Valente *et al.*, 2019). Countries and the

business sector hope to achieve their SDG sustainable development by investing in innovative and greener concepts (Caiado *et al.*, 2017; Rashidi & Farzipoor Saen, 2015).



Figure 2.3: United Nations sustainable development goals (United Nations)

On their website, the WBCSD (2017) states that:

> *The SDGs provide the private sector with a lens to translate global needs and ambitions into business solutions across the value chain. These solutions will enable companies to manage their risks better, anticipate consumer demand, build positions in growth markets, secure access to needed resources, and strengthen their supply chains while moving the world towards delivering the SDGs.*
>
> *Leading businesses have long been engaged in integrating sustainability at the core of corporate strategy, decision-making, and governance* (WBSCD, 2017).

Michelsen (2006) points out that businesses' role in the struggle to reach sustainability has been debated. There are numerous examples of companies placing environmental issues on the agenda, and according to Michelsen (2010), there are at least four reasons why environmental issues need to be addressed by companies, namely: consumer pressure, potential cost savings, legislation, and ethics.

The principle of eco-efficiency is one of the essential tools that can be used for assessing the achievement of SDGs. Eco-efficiency is a tool used for estimating sustainable development (ecological impacts with some economic performance legitimately) (Caiado *et al.*, 2017) as it measures environmental and economic aspects, which are two of the pillars of sustainable development (Phatarachaisakul & Prasertpong, 2014).

2.4 Introduction to the eco-efficiency concept

2.4.1 Background of the eco-efficiency concept

The idea of sustainable development traditionally originated in the 1987 UN's World Commission on Environment and Development Report called 'Our Common Future' (WBCSD & UNEP, 1998). This report requires "production that meets the present generation's needs without undermining future generations' capacity to meet their own needs". The eco-efficiency concept was first introduced in the 1990s as an instrument for sustainability analysis (Zhang *et al.*, 2008), thereby linking environmental impacts directly with some economic performance (Caiado *et al.*, 2017; Müller *et al.*, 2014), working as a valuable tool towards sustainable development (Phatarachaisakul & Prasertpong 2014).

Georgopoulou, Arampatzis and Assimacopoulos (2014) stated that the framework of eco-efficiency is a tool for aiding environmental decision-making – both as an objective strategy and as a step forward in the direction of sustainability. It has close ties to eco-innovation as it consolidates economic performance innovations and connects them to the environmental performance of goods or production processes throughout their life cycle.

The WBCSD defined Eco-efficiency in 1992 as:

> *The delivery of competitively priced goods and services that satisfy human needs and bring the quality of life while progressively reducing ecological impacts and*

resource intensity throughout the life cycle to a level at least in line with the Earth's estimated carrying capacity.

The Organization for Economic Co-operation and Development describes eco-efficiency as "the efficiency with which ecological resources are used to meet human needs". They define it as a ratio of the value of products and services produced by a firm, sector, or economy to the sum of the firm's environmental impact, the sector, or the economy. ISO 14045 (2012) states that "eco-efficiency is a quantitative management tool that enables the consideration of life cycle environmental impacts of a product system alongside its product system value".

According to the WBCSD (1998), eco-efficiency includes resource efficiency and waste reduction to achieve economic progress for business (Van Berkel, 2007b; Verfaillie & Bidwell, 2000). Likewise, the eco-efficiency concept draws on and supports the UN's productive resource efficiency and cleaner production programmes. This is done to pursue the Sustainable Production and Consumption (SPC) framework of the UNEP and the WBCSD. Both UNEP and WBCSD developed and promoted common concepts, namely eco-efficiency and cleaner production. Both organisations were heavily interested in the shared acceptance of these concepts and decided to work with each other to promote these concepts. UNEP first defined the cleaner production concept in 1994 as the "continuous application of an integrated preventative environmental strategy to processes, products, and services to increase efficiency and reduce risks to humans and the environment" (Van Berkel & Narayanaswamy, n.d.; Szilagyi & Mocan, 2018). The new initiative brings public sector priorities and WBCSD that complement one another together.

The SPC's mission extends to the whole business sector network and its linkages and functions as an essential element. SPC was established at a Ministerial Roundtable in Oslo in February 1995. The Ministerial Roundtable defines SPC as:

> *... the production and use of products and services that respond to basic human needs to provide a higher quality of life while minimizing the use of natural resources, toxic materials, and waste and pollution emissions across the whole product life cycle, so as not to jeopardize future generation's needs.*

Specifically, SPC was described as a crucial part of the more comprehensive Sustainable Development Agenda by the WBCSD to focus on sustainable development and resource and service services (for example, patterns of utilisation) supply-demand adaptation.

According to Luís and Eliseu (2015), eco-efficiency should have the following characteristics: improve the organisation's performance decision-making; consider market diversity inherent in it; promote standardisation and tracking over time; be transparent, observable, open, and verifiable; and be comprehensible and essential in identifying and improving the climate, human health, and quality of life. In a nutshell, eco-efficiency is a strategic tool supporting companies' decision-making to develop and implement improvement policies. This will help companies to set their environmental and economic performance priorities and goals.

Put simply, eco-efficiency aims to 'deliver more from less. Minimising pollution and emissions by using less energy and much less raw material is eco-friendly. Moreover, it is ideal for manufacturing since it decreases the cost of doing business and then eliminates future pollution exposures. It is further a requirement for the sustainability of businesses.

Manufacturing companies and other industries have started seeing the environment as the management problem causally linked to their competitiveness and efficiency. Leading organisations go further than traditional compliance practices to incorporate environmental performance in their core business practices. The procurement and use of goods and resources in product development, procurement, technology evaluation, vendor selections, marketing, and sales are gradually incorporated into decision-making processes. Eco-

efficiency is a concept that arose to embody the notion that economic and environmental efficiencies can be accomplished simultaneously. Indeed, several recent studies and reports suggest that pursuing eco-efficiency enhances environmental performance and can bring economic benefits such as:

- Reduced operating costs.
- Improved production processes.
- Reduced liability and risk.
- Enhanced brand image.
- Increased employee morale.
- Increased opportunities for innovation.
- Increased opportunity for revenue generation, including new market openings and price premiums.
- Better supplier management.
- Better relationships with customers.

2.4.2 The link between sustainability tools and eco-efficiency

Eco-efficiency bears similar characteristics to other environmental management methods, including environmental impact assessment or environmental design, cleaner production, eco-effectiveness, and circular economy. The technical alternatives for minimising resource consumption in manufacturing and promoting reuse through recycling and remanufacturing are achieved. Eco-effectiveness points to a standpoint of the LCA that follows products from the cradle to the grave. Eco-effectiveness is an emerging phenomenon that allows businesses to respond to changing marketplace dynamics. Industries such as pork manufacturers experience increasing demands from more stakeholders to be sustainable. The producers who adopt eco-efficient methodologies are proactive in reacting to competitive demands and

fulfilling consumer requirements while safeguarding the environment and people's safety and health.

Like the cleaner production concept, eco-efficiency integrates company success and environmental sustainability objectives by building a connection through which corporate behaviour can sustain sustainable development, thereby balancing economic growth and environmental change. Like its twin concept of cleaner production, eco-efficiency is essentially about the intelligent use of materials, energy, water, and other natural resources simultaneously as undertaking business. The intention is to improve the environmental performance of processes, products, and services while minimising the associated environmental costs and improving economic performance. The framework of resource efficiency and cleaner production is about waste and pollution reduction, including inefficient use of materials, energy, and water instead of treating them after being produced.

In contrast with the cleaner concept of production, the eco-efficiency concept is defined in Van Berkel (2007a; 2007b) as:

> *The provision of eco-efficient goods and services that fulfill human desires and produce a good life while gradually decreasing ecological impacts and resource intensity over their life cycle to a degree consistent with Earth's expected carrying capacity.*

The definition of eco-efficiency goes beyond using scarce resources and reducing pollution by emphasising value creation to commercial enterprises and society and accounting for competitive needs. Instead of reducing waste or emissions, companies can increase productive resource efficiency by adding value to the goods and services they produce, obtaining bottom-line profits, and rewarding shareholders. The sustainability approach has been implemented in manufacturing, paramedics, control, logistics, supply chain management, and others (Govindan *et al.*, 2014)

Yeo *et al.* (2016) state that eco-efficiency facilitates overall environmental performance and the commodity system's profitability as a management tool. Eco-efficiency supports sustainable development principles, including using raw materials efficiently, avoiding pollution, reducing emissions, minimising waste, recycling, reusing materials within the production processes, or sharing resources with external production processes. Compared with former end-of-pipe approaches, it embodies pollution reduction through process change, which links the eco-efficiency concept with circular economy principles.

A circular economy contrasts with a conventional unsustainable (linear) economy focused on excessive consumption of resources and waste disposal. Like eco-efficiency, a circular economy encourages implementing a closed-loop production model to maximise production efficiency and minimise pollution (Noya, Aldea *et al.*, 2017). Therefore, the circular economy is best described by the low consumption of raw materials throughout the production system and a minimal release to the environment, allowing the full use of resources to increase global efficiency Noya, Aldea *et al.*, 2017. Thus, the circular economy accomplishes a more robust equilibrium and cohesiveness between the economy, the environment, and society.

An eco-efficient organisation understands and seeks to minimise the environmental impact of its products throughout its life cycle. Such businesses will provide benefit from their activities by monitoring and assessing their impact at every stage. Assessing environmental impacts for cleaner products can help companies in their quest for continuous improvement by identifying ways of maximising profits by reducing waste and liabilities, raising productivity, and demonstrating its sense of responsibility towards its customers and the environment.

Companies are beginning to use environmental assessment systematically to delineate objectives, obtain data, recognise impacts, handle negative consequences successfully and, ultimately, communicate with interested parties. Furthermore, many organisations have included impact on their production environment as part of product and process development, with measures to mitigate results whenever possible. Today, most companies are pursuing sustainable development in terms of green principles. One of the most important criteria for measuring overall performance is eco-efficiency, which is in line with studies by Caiado *et al*. (2017) and Rashidi and Farzipoor Saen (2015).

Mickwitz *et al.* (2006) suggest eco-efficiency to promote a transition from unsustainable to sustainable development. Eco-efficiency has received significant attention in sustainable development literature (Brady, Henson & Fava, 1999; Choucri, 1995; Zhang *et al.*, 2008).

2.4.3 The standardisation of eco-efficiency (ISO 14045)

Eco-efficiency evaluations were not standardised until recently, resulting in people either performing eco-efficiency according to the WBCSD methodology or adopting other non-standardised methodologies (Charmondusit, 2010; Charmondusit & Keartpakpraek, 2011; Charmondusit, Phatarachaisakul & Prasertpong, 2014; Kharel & Charmondusit, 2008).

In 2012, ISO 14045 (2012) defined eco-efficiency assessment as a quantitative management tool that allows for a product system's environmental impacts to be analysed together to benefit a stakeholder from a life cycle perspective (Zhang *et al.*, 2019). As per the eco-efficiency framework (ISO 14045 standard), eco-efficiency is a sustainability tool that relates a product system’s environmental performance to its value. In such a specific instance, such as in ISO 14045, a product or service value’s environmental impact and ecological performance are measurable outcomes concerning environmental issues. The

standard defines the product system's value as a value or desirability assigned to a product system.

Eco-efficiency assessment covers principles such as the perspective of the life cycle, comprehensiveness, functional unit approach, iterative character, transparency, and scientific approach priority (Burchart-Korol, 2013). This ensures that the eco-efficiency evaluation considers the entire product and services life cycle from the cradle to the grave.

Oliveira, Camanho and Zanella (2017) report that the ISO 14045 standard states that there are two criteria for conducting an eco-efficiency assessment. The first is an environmental criterion that focuses on reducing emissions and controlling waste. The second is the value of the product system, which includes customer support and user-friendly functions.

Eco-efficiency is measured as the ratio of economic and environmental performance, or the ratio between environmental and economic performance (Huppes & Ishikawa, 2005). Four types of eco-efficiencies are summarized in Table 2.2 depending upon which variable is the numerator and which is the denominator. With the first pair, as environmental productivity and its inverse, the environmental intensity of production refers to the realm of production. The second pair, environmental improvement cost and its inverse, environmental cost-effectiveness, are defined from an environmental improvement measures point of view.

If the focus is on improving environmental performance, then eco-efficiency will consider the cost of improving the environment. When exchanging the numerator and denominator and focusing on economic value, eco-efficiency will become environmental intensity, thus concentrating on environmental improvements, thereby leading to the environment's cost-effectiveness (Huppes & Ishikawa, 2005; Konstantas *et al.*, 2020).

Table 2.2: Four types of eco-efficiency [Source: Huppes and Ishikawa (2005)]

Performance ratio	Focus on the economic value	Focus on environmental improvements
$\frac{economy}{environment}$	Environmental productivity	Cost of environmental improvement
$\frac{environment}{economy}$	Environmental intensity	Environmental cost-effectiveness

The most used mathematical expression of eco-efficiency is shown in Equation 1:

$$Eco\text{-}efficiency = \frac{product\ or\ system\ value}{environmental\ performance} \qquad (Equation\ 1)$$

According to Equation 1, eco-efficiency is improved by increasing environmental performance while maintaining or increasing the output value. Depending on the study's goal, most studies use an inverse of Equation 1 to determine eco-efficiency, which is economic performance divided by environmental performance (Konstantas *et al.*, 2020; Petit-Boix *et al.*, 2018).

The eco-efficiency assessment, therefore, can be used to help decision-making based on the sustainability of various alternative evaluations and screening in the following circumstances:

- Identification of best operating and process control strategies and strategic planning for budgeting and investment analysis.
- Selection of technologies/processes for eco-efficient waste and wastewater treatment and further effluent reuse and reclamation.
- Identification of the best practice environmental option for sludge management, including sludge-to-energy projects.

- Identification and implementation of cost-effective but environmentally friendly maintenance plans.
- Expansion, decommissioning, and regionalisation options.
- Sludge beneficiation projects.
- Industrial effluent modelling.
- Improvement of process or product development.
- Public policymaking.
- Sustainability assessment.

Concerning the possible use of the eco-efficiency concept, it is worth noting that the result of the eco-efficiency assessment relates to the product system, not the product per se. Therefore, a product cannot be eco-efficient; its product system includes production, use, and disposal. Eco-efficiency is a relative concept, and a product system is only more or less eco-efficient with another product system.

In most industries, infrastructure planning and development and operational and management of the manufacturing processes involve several decisions from many situations. Industrial plants, therefore, need tools to assist in making decisions based on the sustainability of different alternatives in various circumstances; eco-efficiency is one of the tools to be used for this process.

Stakeholders are increasingly sensitive about manufacturing companies' environmental performance, and the pork meat sector, as reported, contributes immensely to the use of natural resources and generates waste. According to scientific studies, companies should use this trend to gain a competitive advantage. Although many companies are willing to exploit this potential, they face a significant challenge in evaluating their specific possible benefits. To reduce the prevailing uncertainty of manufacturing companies in the integrated

assessment of environmental and economic performance (eco-efficiency), a performance measurement system is needed to support decision-makers in selecting and interpreting appropriate indicators on a sound data basis.

2.4.4 A general framework of the ISO 14045 standard

The ISO 14045 framework states that an eco-efficiency assessment has five different stages, as shown in Figure 2.4, which include: (i) goal and scope definition; (ii) environmental assessment; (iii) product system value assessment; (iv) quantification of eco-efficiency; and (v) interpretation. Stanchev and Ribarova (2016) state that the improvement of the eco-efficiency evaluation standard (ISO 14045, 2012) had improved the concept.

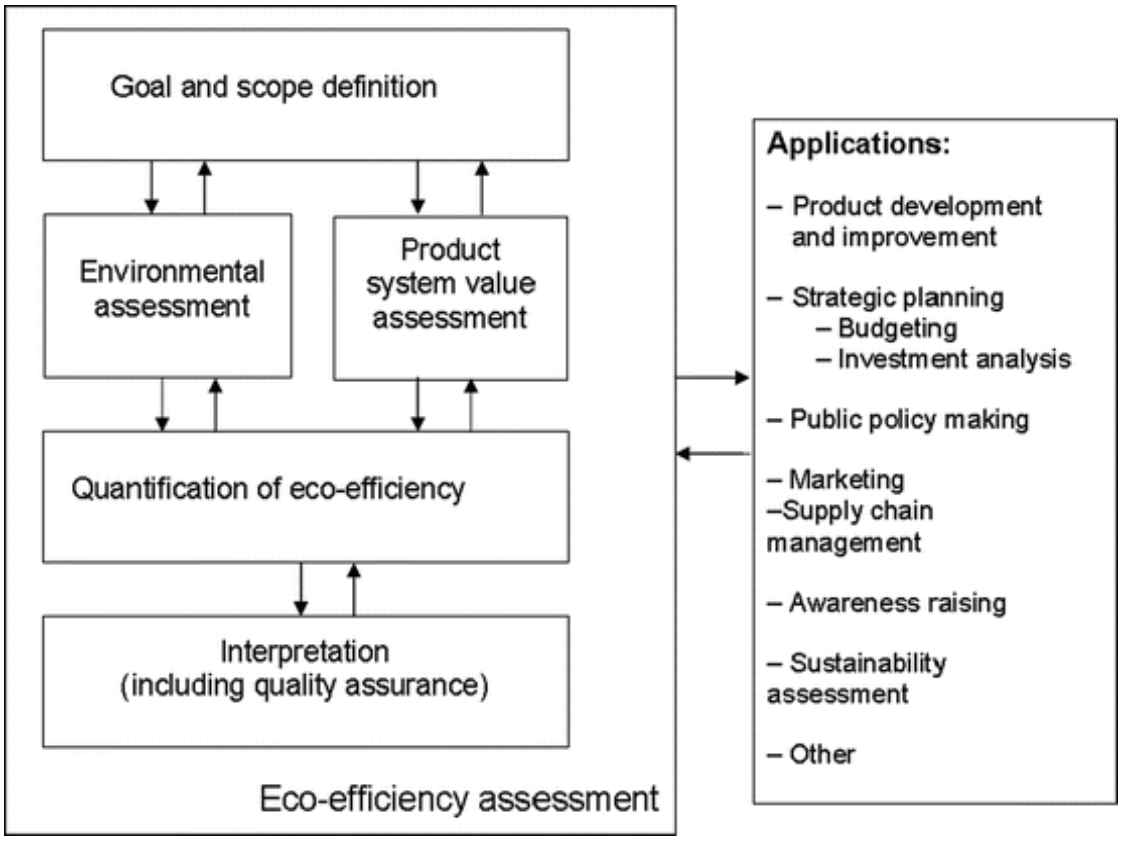


Figure 2.4: General framework of the ISO 14045 eco-efficiency 2012 standard [Source: ISO (2012)]

Goal and scope definition

In conducting the eco-efficiency assessment, the ISO 14045 (2012) requires that eco-efficiency results be determined by relating the environmental assessment results to the product system value assessment results according to the assessment's goal and scope definition. The standard definition of the goal describes the purpose of the assessments, the assessment's intended audience, and the results' intended use. The scope of the assessments gives insight as to the actual description of the production system to be assessed; the function and functional unit; the system boundary of the product system; the quantity and nature of the products to be produced in the production systems; the location of the study; the boundary; the allocations to external systems; the environmental assessment method and types of impacts; the value assessment method and type of product system value; the choice of eco-efficiency indicator(s); the interpretation to be used; the limitations; the reporting; and lastly the disclosure of results.

Stakeholders who have an interest or influence on the product system will also be recognised. The research scope should be defined adequately to ensure that the study's width, depth, and detail are consistent and necessary to meet the stated objective (ISO 14040/4, 2006). Problems to be addressed when determining the scope of the research include the method under research (including its functions and boundaries), the functional unit; the allocation of environmental impacts for products and by-products stemming from the very same process; the data specifications; assumptions; constraints; type of critical review (if any); and the type and structure of the research study.

The eLCC and LCA tools require that a system boundary be set for the studied system. Cut-off criteria are used to establish boundaries (cradle to grave, gate to grave, cradle to gate, or gate to gate). System boundaries evaluate which sections of the production systems

concerned are included or excluded from the LCA and LCC assessment (Kleynhans *et al.*, 2012; Müller, 2015).

The environmental performance throughout the product's production from one stage of production to the next is assessed by a gate-to-gate strategy (Kleynhans *et al.*, 2012; Müller, 2015). The cradle-to-gate method comprises production processes from the cradle (extraction of raw materials) up to the factory gate's production stage (Figure 2.5). The gate-to-grave method includes processes from the factory gate where products are distributed, used/consumed, to their end or disposal. Once the product's manufacturing phase and its end-use are completed, the gate-to-grave approach determines its environmental impact.

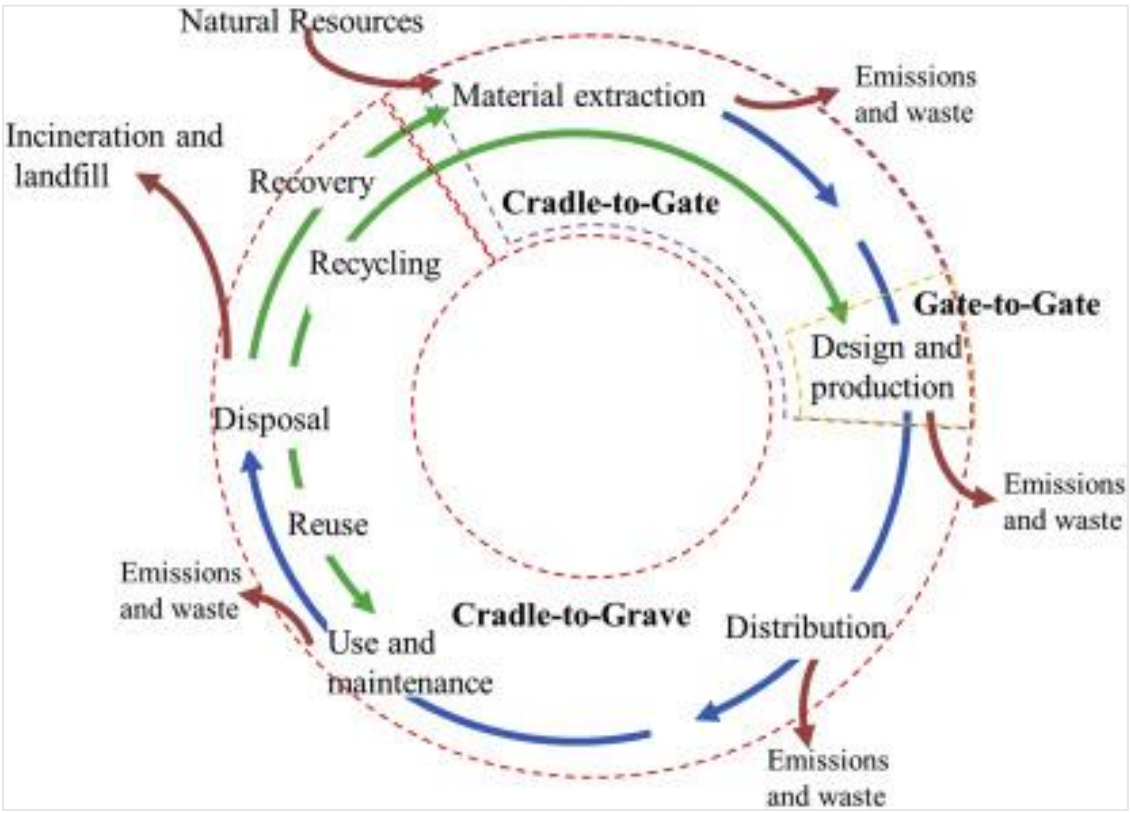


Figure 2.5: Representation of product life cycle

Environmental assessment method – life cycle assessment

The eco-efficiency standard framework requires that the environmental assessment be based on the ISO 14040 and ISO 14044 LCA methods. The standard states that it should be determined which elementary flows, cut-off criteria, allocation rules, impact categories, category indicators, characterisation models, and weighting methods will represent the eco-efficiency assessment's environmental aspects. The selection of the criteria, as mentioned earlier, should be consistent with the study's goal. Exclusions made for the eco-efficiency assessment should be described and justified.

Hauschild, Rosenbaum and Olsen (2018) state that environmental pollution and resource scarcity (energy and materials) issues have motivated that an LCA-oriented approach to be created to profile the product accordingly. The strategy originated as a framework for addressing energy efficiency issues, raw materials, and waste disposal (Müller, 2015). The interest in recognising and quantifying products and services' environmental impact dates back to the 1960s and 1970s. Müller (2015) notes that the oil crisis of the 1970s, waste management, packaging, and energy debate were the critical drivers of LCA development.

Over the past two decades, the LCA tool has demonstrated its actual worth in assessing water systems' environmental sustainability with outstanding improvements for modelling levels in the inventory and impact assessment (Sala, Farioli & Zamagni, 2013).

The LCA is a tool used to quantify products/processes and the environmental performance of services by contemplating all their stages from the cradle to the grave and recycling if required (Finnveden *et al.*, 2009; Guinée *et al.*, 2011). LCA applications include:

- Improvement of products performances and their development.
- Strategic planning and decision-making.

- Product and process development or processes improvement.
- Marketing for internal or external communication.
- Identification of key performance indicators.
- Selection of suppliers or subcontractors.

The LCA standards from ISO 14040:2006 to ISO 14044:2006 define LCA as a compilation and evaluation of the inputs, outputs, and the capability environmental effects of a product system throughout its lifestyles cycle. Through LCA, environmental aspects and capacity influences during a product's life cycle – from raw cloth acquisition through production, use, and disposal (for example, cradle to grave) – are assessed. LCA evaluation, consequently, is used to quantify the ecological aspect of sustainability. The LCA methodology is distinct in four distinct stages: goal and scope definition; life cycle inventory (LCI); LCIA; and interpretation, as shown in Figure 2.6.

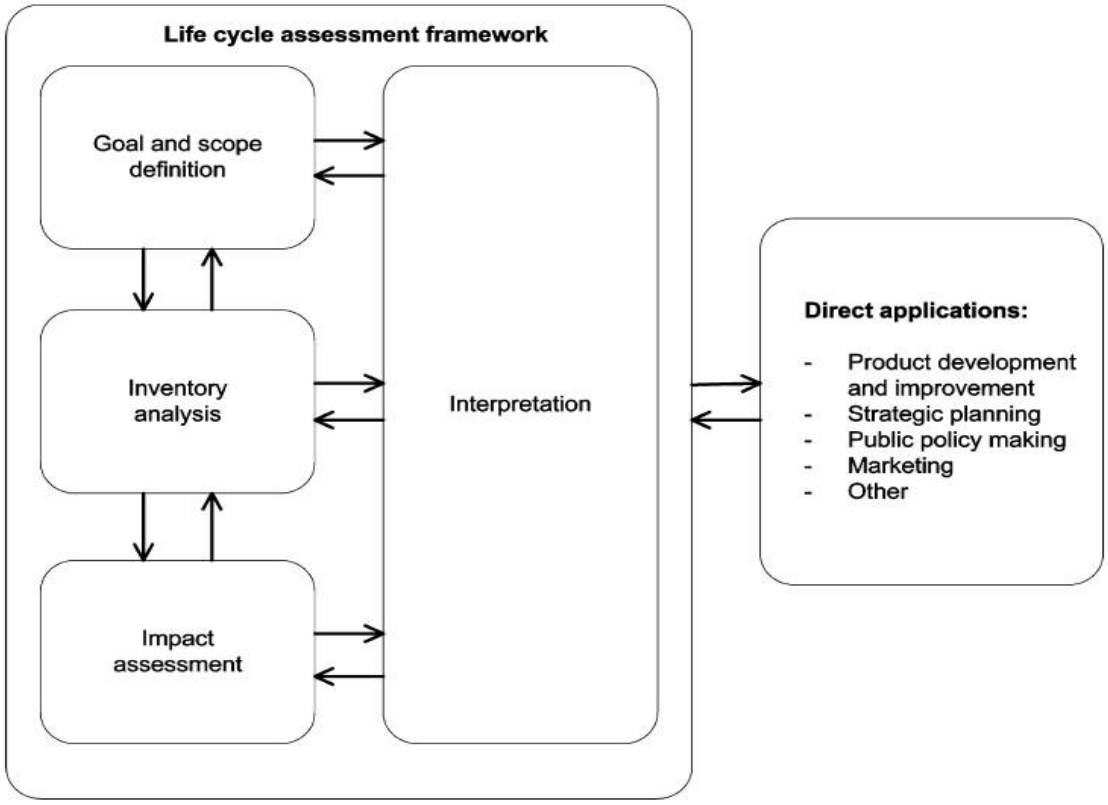


Figure 2.6: Stages of LCA (adapted from ISO 14040/4)

LCA is an iterative approach as follows:

LCA Stage 1: Goal and scope definition

The first step within the eco-efficiency, LCA, and eLCC concepts is characterised by defining the assessment's purpose and scope. The function of the studied system is described, and the functional unit that characterises the features of the system under study is chosen by relying upon the study's objectives. The system boundary is outlined using the objectives of the study.

LCA Stage 2: LCI

LCI is a methodology for estimating the consumption of resources and the quantities of waste flows and emissions caused by or otherwise attributable to a product's life cycle. In this second step, data collection leads to an inventory of material flows (inputs and outputs), resulting from the system's energy and mass balances under study. In case of missing data, assumptions are made throughout this step. The LCI is often the longest step within the LCA and eLCC because it is affected by data availability and is time-consuming. In a regular eco-efficiency assessment, the standard permits collecting data within the LCI step for assessment. According to Rebitzer *et al.* (2004), LCI can be best described as a model of one or more product systems. Each product system fulfils a function that is quantified in functional units.

Three types of LCI models are reported in the literature (Frischknecht & Stucki, 2010), namely the attributional, consequential, and decisional models. The different focuses of the model LCAs are reflected in the LCA's methodological choices (Frischknecht & Stucki 2010; Reckmann *et al.*, 2012).

The first type of LCI is the attributional LCI. This type of LCI aims to quantify the total potential environmental impacts of a given product using average data. Allocation is assigned for processes with multi-objectives, which means that impacts are shared between processes. The attributional LCA aims to explain the ecologically appropriate physical flow to and from the life cycle as well as its subsystems (Curran *et al.*, 2005) in a status quo situation (De Vries & De Boer, 2009; Reckmann *et al.*, 2012) about the functional unit (Nguyen *et al.*, 2011). The activities included within an attributional LCI can substantially contribute to the product being evaluated and its function. The material and energy flows are routinely pursued upstream from the process and aligned with the reference flow through natural resource production and downstream of the product's final disposal (Rebitzer *et al.*, 2004).

The second type of LCI is the consequential LCI, which is a better approach for decision support as it looks at how a given system is affected by a change, such as installing a new technology (Lévová & Hauschild, 2011). Consequential LCIs typically only include processes that are affected by a change in demand in the system. These processes are also called marginal processes or technologies. Marginal data typically describes the change in demand. Consequential LCA applies system expansion or substitution for multi-objective processes issues (Lévová & Hauschild, 2011).

Consequential LCA is structured to measure environmental impacts (De Vries & De Boer, 2009; Reckmann *et al.*, 2012) of a change in the functional unit level generated to display future progress (Dalgaard *et al.*, 2007; Rebitzer *et al.*, 2004). In the consequential LCA, the processes included are expected to be affected in the short and long term by the decisions to be supported by the study (Rebitzer *et al.*, 2004). Lundie, Peters and Beavis (2004) mention that in most cases, consequential LCA is suitable for decision-making by catching the

environmental consequences of decisions (Nguyen *et al.*, 2011). An increasing number of studies have used consequential LCA (Dalgaard *et al.*, 2007). In comparison (Lundie *et al.*, 2004), it is argued that LCI attribution is more commonly used as it is best adapted to finding environmental areas throughout the value chain (Nguyen *et al.*, 2011).

The third type of LCI is decisional LCI. Compared with explaining a consequential process outlined above, decisional LCI uses actual or perceived financial and contractual connections, and economic actors (business-to-business relations) are the core reason for data. Decisional LCI encourages the efficient utilisation of limited natural resources (like the price system that helps allocate traditional economic resources such as labour, land, and capital).

LCA Stage 3: LCIA

LCIA is the third step of LCA. Three steps outline the LCIA section, namely: characterisation, normalisation, and weighting. Characterisation allows the quantification of inventory flows into impact indicators quantified by each flow's contribution to the environmental damage. The normalisation step allows the impact of every studied system to be split by the corresponding reference impact calculated over a region or a country and the relative importance concerning this abstraction reference. Lastly, weights are selected for decision-making, which needs to represent the stakeholders' environmental priorities.

Environmental impacts were categorised with inputs and outputs and classified into several midpoints and endpoint impact indicators. These differ between single environmental impacts for midpoints and indicators such as temperature change to higher aggregation environmental levels such as the impact on human health.

LCA Stage 4: Interpretation

Interpretation is the last step of LCA/eco-efficiency. Results from LCIA for generic LCA studies and LCI for generic eco-efficiency assessments are given and discussed. During this stage, sensitivity analysis ought to be conducted to assist decision-makers. Generally, sensitivity analysis is done to validate results and ensure consistency.

Product system value assessment

The most crucial aspect of the eco-efficiency assessment focuses on defining the product value expressed as a functional, productive, or economic factor (monitory value). Annexure B from ISO 14045 provides various examples of how to apply the eco-efficiency assessment methodology. Otherwise, all the necessary examples have different product system values, and the results obtained are not equivalent. ISO 14045 defines three ways to present a value system: functional value, monetary value, and other values (aesthetic, brand, cultural and historical). However, the standard does not specify the economic value assessment tool as it does with the environmental assessment. The product system's value can be measured in many ways since it can cover different value aspects, including functional monetary and aesthetic aspects.

The profits generated by businesses are equivalent to gain in business economics: income minus costs. It might be the willingness to pay minus costs for customers, which is also called surplus value. The costs might include size, leasing costs, and running fees. These principles are difficult to determine on a life cycle basis because some supply chain players cannot reveal their operational costs. Nevertheless, changes in such factors can be calculated, either by functional value (technical value) or by financial cost (monetary value).

Rebitzer *et al.* (2008) suggest eLCC to be a good match for LCA. LCC assesses costs related to a system's life cycle with costs covered by one or more actors. Swarr *et al.* (2011) state

that LCC adopts ISO 14040's structure, importance, scope, and defined functional unit in structuring the analysis. ELCC is considered an approach to estimate sustainability's economic dimension (Swarr *et al.*, 2011). LCC was not initially developed to comply with an LCA because LCC is older than the first definitions of sustainability and LCA (Hunkeler *et al.*, 2008). The idea of combining LCA and LCC arose along with the development of eco-efficiency and similar terms aiming at economic and environmental sustainability (Swarr *et al.*, 2011). Different versions of LCC exist today. In this case, the most relevant LCC is eLCC, which refers to an LCC that aims to be consistent with LCA's methods and principles (Hunkeler *et al.*, 2008).

ELCC may well be a mature tool to assess a product or a system's life cycle costs and was utilised during this study. LCC studies are conducted for varied end goals. This research used LCC to follow the requirements of ISO 14045. LCC is appropriate for use as a tool to plan, optimise, identify hotspots or, finally, aid decision-making concerning investments. In literature, three different LCC kinds are found: standard LCC, eLCC, and social LCC. As per Swarr *et al.* (2011), the difference between eLCC among the various LCC is that eLCC analyses are solely connected to the environmental LCA approach because it follows the standards that govern the LCA perspective. The eLCC utilises a functional unit's view, regards the cradle-to-grave approach, and includes all actors within the whole life cycle. Unlike the standard LCC, eLCC came to be a method to support LCA because it covers the economic dimension and is employed to spot opportunities in terms of economic and environmental impacts (Niero *et al.*, 2017). To this effect, Swarr *et al.* (2011) state that generally, eLCC aims to:

- Assess the costs related to actual money flows and the physical life cycle of a product, which is to be borne directly by the actors along the life cycle.

- Compare the life cycle costs of alternatives products, including associated processes and services.
- Record the improvements made by a firm regarding a given product.
- Estimate improvements of the planned product system, including process changes within the life cycle, innovations, supplier development, or taxation changes.
- Identify win-win situations and trade-offs in the life cycle once combined with LCA (and ultimately with social LCA).

Therefore, as the objectives of this research demand, the monitory unit was fixed as the life cycle cost of producing pork meat at the pork value chain (farm to abattoir). Miah, Koh, and Stone (2017) define LCC as an economic analysis tool to directly assess decision makers' costs and benefits across an investment's life cycle.

ELCC is characterised by three distinct steps, which are:

- Goal and scope definition: This is like the LCA and eco-efficiency step and must be done following LCA's same standards.
- LCI: Similar to the LCA step of LCI. The same challenges are experienced in this step regarding the collection of relevant data.
- Interpretation and sensitivity analysis: This is done following the standardised LCA, except for a few essential differences, making data analysis easier or difficult. There is no characterisation of this method, unlike the LCA.

There are multiple critical incentives in using LCC assessments, which might improve cost savings opportunities during operations and investment savings where necessary. The LCA and eLCC integration represent two out of three sustainable development elements: environmental and economic (Müller, 2015).

Therefore, to meet this study's objectives, the product system value was determined through eLCC. A product system's functional value represents real and achievable opportunities for users and others. The functional value is simply a numeric value reflecting the functional efficiency or desirability of a product system and enhanced. However, the functional value is distinct from the functional unit in the eco-efficiency assessment. The product system performance quantification should assess the functional value and attach it to the functional unit. The product system's functional value demonstrates a measurable and meaningful benefit for consumers and other stakeholders.

The functional unit provides a reference to which the input and output data are normalised mathematically. Therefore, within an eco-efficiency assessment, the functional value may change – possibly because of product improvement – whereas the functional unit remains the same. The functional value of the eco-efficiency assessment is different from that of the functional unit. In quantifying product system performance, the functional value should be calculated and related to the functional unit.

Quantification of eco-efficiency

The ISO 14045 standard requires that the eco-efficiency indicator, a measure relating the product system's environmental performance to its product system value, be determined according to the goal and scope definition. As per the requirements of ISO 14045, the eco-efficiency indicator for this assessment was quantified by connecting the environmental assessment results to the results of the financial costs as per the goal and scope definition using Equation 1. The outcome was the eco-profile of the baseline pork meat production system. For eco-efficiency assessments to be communicated to the public, an eco-efficiency profile had to be determined by relating the LCIA profile to the product system value. The

pork meat production system's eco-efficiency was calculated for each environmental impact as the value-added ratio's environmental impact, as per Equation 1.

The LCA impact scores can be broken down depending on the research's objective and scope, indicating that each impact category represents an autonomous environmental impact that must be integrated or added into a single score with the economic impact on interpretation. Engineers and designers favour this assessment method since it eases the interpretation of results when a single environmental and economic aspect are coupled (Kicherer *et al.*, 2007; Michelsen, 2006; Weiss *et al.*, 2011), which was not done in this research.

Sensitivity and uncertainty analysis

Sensitivity analysis is a systematic procedure for estimating the effects of the choices made regarding methods and data on a study's outcome. Sensitivity analysis was not done in this study to ascertain whether data and methodological approaches influence the eco-efficiency assessment results.

Uncertainty analysis is another step in this assessment. The uncertainty step was not done to check how the uncertainty of the collected data and presumption affected the degree to which the eco-efficiency assessment results can be dependent upon accuracy.

Interpretation

The eco-efficiency assessment interpretation phase includes the following characteristics depending on the study's purpose and scope:

- Identification of significant issues depending on the environmental and product system's performance evaluation results.

- Assessment of the aspects of completeness, sensitivity, uncertainty, and accuracy.
- Formulation of conclusions.

The interpretation is the last step of this assessment. The interpretation of eco-efficiency clearly defines and identifies critical issues based on the LCC and LCA phases' outcome. This detail provided the conclusion, recommendation, and limitations of this research study.

2.5 Case studies on the use of the eco-efficiency methodology under the ISO 14045 framework

The eco-efficiency principle applications have proved to be remarkably diverse. They spanned from the individual to contrast product, eco-design, end-pipe treatment assessments. The case studies below show how this principle has been implemented in different sectors.

2.5.1 Water sector

The eco-efficiency concept has been applied extensively in the water sector, with LCA being used for different end goals in conjunction with other related methods in the process. The conventional approach of selecting wastewater treatment technologies depends on techno-economic factors (Popovic *et al.*, 2013). Currently, there is a move to use sustainable development tools to determine which technology will deliver the best economic and environmental performance. Social and environmental issues need to be integrated to decide what to do regarding the eco-efficiency of WWTPs (Chhipi-Shrestha, Hewage & Sadiq, 2017). Hence, determining a range of sustainable and eco-efficient WWTP alternatives could be a complicated and challenging activity, consistent with Castillo *et al.* (2017), who has notably given the variability of connected aims and competing criteria that have to be considered (Gémar *et al.*, 2018).

Treating the sludge from abattoirs poses severe challenges to the pig industry as pig slurry from farms and abattoir waste in the form of sludge are the final waste that results in wastewater treatment (Fytili & Zabaniotou, 2008; Ren & Liang, 2017). Eco-efficiency has further been used to determine the best form of sludge treatment. The management and treatment of this inevitable waste material are essential to decrease sludge volumes and mitigate risks to human health and the environment in compliance with the sludge process (Appels *et al.*, 2008). Accordingly, handling of sludge is of international concern (Singh & Agrawal, 2008), and any lack of proper treatment could result in detrimental consequences to the environment and health problems for humanity.

The possible best available strategy and technique for treating sludge abattoir has become a much-talked-about subject. There are several possible methods for treating sludge, including incineration (Li *et al.*, 2014), disposal to landfill sites (Koenig, Kay & Wan, 1996), putting sludge on soil (Fang & Wong, 1999), and anaerobic digestion for energy recovery (Karagiannidis & Perkoulidis, 2009). It should be noted that the social, environmental, and economic performance of these technologies may differ. For example, one technology may perform better economically than another but perform poorly environmentally and cause unintended environmental issues. This raises challenges for decision-makers to choose the most environmentally efficient strategies. Hence, this research will provide decision-makers with relevant data.

Petit-Boix *et al.* (2018) carried out a study in Spain that compared sewer case studies with different sewer settings, populations, climate, and urban topography. The objective was to evaluate sewer eco-efficiencies by incorporating LCA and LCC techniques to determine economic and environmental performances. The functional unit delivered 1 m^3 of urban wastewater from households to the WWTP through a sewer network in medium-size cities

(namely, Calafell and Betanzos). The study aimed to determine hotspots in the entire sewer network stages for users to provide evidence for decision-making.

Throughout this research, LCA and LCC were used as tools to evaluate the system's economic and environmental performance. Results revealed that both cities had identical profiles. However, they had different characteristics, with operation and maintenance being the critical environmental impacts (50% to 70% of impacts), and pipe installation showed the most considerable use of economic capital (70% to 75%) due to labour. The research identified the WWTP location as an essential factor due to the topographical impact (for example, the annual pump energy in Calafell was 13 times greater than the pumping energy in Betanzos. Using the principle of eco-efficiency, the researchers observed that sewers may be less eco-efficient than WWTPs and that their layout needs to be considered in the sense of integrated WWTP sewer management to improve sewer performance. In terms of the methodological approach, the two-dimensional nature of eco-efficiency enabled comparisons of these sewer systems.

Lorenzo-Toja *et al.* (2016) carried out a study that used the two sustainability assessment tools, namely LCA and eLCC, to calculate the eco-efficiency of WWTPs through the framework described in ISO 14045. The study used 22 WWTPs to attain their goals. This research was intended for decision-makers in the field of wastewater. Another trend for evaluating the connections between LCA and LCC was the research methodology. Two midpoint impact categories, namely GWP and eutrophication potential, were selected in the study: an endpoint single score indicator was used for the environmental assessment, while LCC was used for product value. The findings showed that there were differences between the eco-efficiencies of the various WWTPs.

Stanchev and Ribarova (2016) conducted a study using the ISO 14045 framework. The study found that the ISO 14045 concept could be applied to study urban water systems, including identifying their environmental impact and economic value. The study was conducted using the urban water system of Sofia, Bulgaria.

Ribarova *et al.* (2014) conducted research to show how the ISO 14045 (2012) standard requirements were considered for an eco-efficiency assessment of technology improvements to Sofia's urban water system. Key elements such as product system, system boundary, system value, and environmental performance were described. Tools for system value measurement and environmental impact assessment were proposed, and LCA was used to determine environmental impacts. The research employed 'willingness to pay as a suitable product system value for water customers. Notably, there were variations from the standard LCA studies because the number of households was used as the system's functional unit, unlike regular units (1 m^3) as usually used. Two types of indicators were proposed based on the LCI and impact assessment. The researchers implemented a scientific approach following the standard's concepts to adapt the general design structure to an existing urban water system (ISO 14045).

Petit-Boix *et al*. (2017) conducted research that used eco-efficiency as a strategic tool to help prepare for flood damage, flood prevention, and harm avoidance. The research was done in Maresme (Catalonia, Spain). The study's objective was to assess the viability of post-disaster emergency measures employed after a significant flooding event using a comprehensive hydrological and eco-efficiency strategy. In order to assess the eco-efficiency of such practices, LCA and LCC tools were used. Researchers found that, relative to reported water flows and storm frequencies, interventions significantly decrease harm.

The emergency measured eco-efficiency resulted in a CO_2-eq of 1.2 kg per euro spent. Negative net impacts were reported when the prevented harm was absorbed into the initial investment, which implied that all these interventions contributed economic and environmental gains to the community. Financial expenditure was regained within two years. Furthermore, the development might be improved to boost its environmental effects, which can be recovered within 25 years. Their approach and results demonstrate the consequences of combining the environmental and economic impact of decision-making in an urban environment. This may help authorities and insurance companies develop preventative strategies and adapt to climate change.

In another study, Georgopoulou *et al.* (2017) performed a systematic review of eight alternative water management schemes. To determine these frameworks' eco-efficiency, the authors used the meso-level framework generated by the Eco Water Project. The cases identified opportunities for enhancing water resources' environmental performance by implementing advanced technologies in resource efficiency, emission management, and circular economy for each of the eight case studies. The authors concluded that the Eco Water Methodological Framework's systemic approach provides for the practical, extensive economic, and environmental performance of assessing the water use system. However, some drawbacks were identified, and further studies are required to confirm the method and establish a cross-sectoral technology performance improvement method.

2.5.2 Agriculture and food industries

Mehmeti *et al.* (2016) used eco-efficiency to study opportunities for increasing the eco-efficiency of irrigation in the south-east Italian region of Apulia. To completely comprehend the relations between the different processes in an agricultural water system, the researchers introduced a unique scientific framework that used the various measurement and modelling

techniques as described in the Eco Water Project. These methods included weather patterns of precipitation, the procurement of fertilisers and energy use (including carbon emissions), costs of farm products, and the use of emerging innovations. The eco-efficiency improvement strategy was based on the structural approach of implementing multiple innovative technologies to identify environmental consequences, reasonable costs, and added value of adopting such technologies throughout three irrigation zones and 14 administrative areas in the Apulian region.

Mehmeti *et al.* (2016) used the Environment and Venue Assessment Tool of the Eco Water Project to establish a baseline eco-efficiency assessment for the area based on historical rainfall data. After consultations with local stakeholders, four technical scenarios were identified, and the economic impacts of these scenarios were considered using ISO 14040–14044 LCA tools. The scenarios were contrasted with the baseline year, and their impact on a range of factors such as climate change, depletion of fossil fuel, human toxicity, and mineral depletion was considered. The whole method allowed the researchers to evaluate alternative technological solutions throughout the entire life cycle and identify the potential impact of the various scenarios on the region's environment and economic productivity.

Rodrigo *et al*. (2016) investigated the mesoscale eco-efficiency assessment of water efficiency in the Monte Novo agricultural irrigation perimeter in southern Portugal. They researched the possible benefits of transitioning from rain-fed farming to irrigation-based farming through new economic activities, innovation, and technology standards. A full eco-efficiency assessment with five stages phases was undertaken: (i) goal and scope definition; (ii) environmental assessment using LCA; (iii) value assessment considering the complete life cycle of the system calculated in monetary terms; (iv) quantification of eco-efficiency, which was estimated as the ratio between the value of the product/service and the

environmental impacts identified; and (v) interpretation. The evaluation factors included using resources (chemicals, energy) and raw materials (fertilisers, electricity). A baseline scenario was established against which the various eco-efficiency improvements in agriculture were assessed.

There are several possibilities for incorporating different eco-efficiency improvements (including financial costs such as investment, maintenance, and operating cost) in the basic scenario. Rodrigo *et al.* (2016) described every scenario graphically with 11 eco-efficiency indicators, and the baseline scenario and eco-efficiency improvement scenarios were compared to optimise economic productivity and minimise environmental impacts. In the Monto Novo irrigation perimeter, overall proposals were made to enhance eco-efficiency, including crop type and agricultural practices changes.

Laso *et al.* (2018) carried out an eco-efficiency study for the canning industry through a two-stage eco-efficiency evaluation system that blended environment and economic performance. The environmental performance was calculated using the ISO 14040 and ISO 14044 specifications (ISO, 2006a; 2006b). The economic performance was calculated through the LCC methodology based on the approaches outlined in Hunkeler *et al*. (2008) and Swarr *et al.* (2011). The whole study's primary purpose was to introduce a framework for evaluating canned anchovy goods' eco-efficiency through an approach to a life cycle perspective.

The functional unit in Laso *et al.* (2018) study was 1 kg of fresh anchovy captured during the fishing phase. The environmental impact indicators were GWP, acidification potential, eutrophication potential, and the ReCiPe single score endpoint. The calculated eLCC results were used to determine the economic value add. The value add was used as an economic indicator of the canned anchovy. LCA–eLCC were coupled with linear programming tools

to define an eco-efficiency index of composites. This strategy allowed the environment-induced damage for a specified option to be converted into economic terms.

This cradle-to-gate method specifically analysed the different origins of the anchovy species (South American vs Cantabrian) and related waste management alternatives (landfill, incineration, and valorisation). Results indicated that substantial differences could be observed depending on the origin of the fish. Anchovies that arrived in Cantabria had a higher value-added score at the cost of more significant environmental impacts, mainly due to the rate of fuel usage. Therefore, as fish residues were converted into saleable goods, their environmental scores reduced while the added value increased. The study showed the environmental and economic advantages of implementing a circular economy. Accordingly, the cradle-to-cradle idea can be implemented in the canned fish industry. The suggested approach is intended to be beneficial to decision-makers in the anchovy-canning field and could be applied to other regions and sectors of industry.

2.5.3 Textile sector

Alexandratou *et al.* (2016) determined the eco-efficiency of a water use system for the textile industry in the northern Italian region of Biella by relating the Eco Water Project's empirical method to an industrial water use system. Using this method, the researchers analysed two model units of the textile industry, namely, a unit with an in-house WWTP that used conventional chemical approaches in the dyeing phase and a unit that used both conventional chemical and natural herbal colours in different production lines, but that was also linked to the municipal wastewater network. These were listed as representing the region's more than 500 small- and medium-sized manufacturing units. Eight environmental midpoint indicators that reflected the specific system and applied to the textile industry were used to determine the selected units' environmental performance.

A cost assessment was conducted for each unit's economic costs in conjunction with an eco-efficiency assessment. Six emerging technologies were chosen for deployment within the current system, which evaluated two different technology scenarios that would improve resource efficiency, freshwater uptake, pollution prevention and control, and water effluent treatment. Such scenarios tackled the critical regional issues of the depletion of freshwater resources and wastewater toxicity in the river. The researchers established that all innovations could improve the system's environmental performance under both conditions. Notwithstanding this, the pollution prevention and control scenario was deemed not financially sustainable due to high investment, while the resource efficiency scenario needed additional economic incentives and support from the government for industrial stakeholders to be considered feasible.

2.5.4 Automotive and aeronautic sector

Levidow *et al.* (2016) examined options for eco-efficiency improvements in Volvo and Arla Foods, two large manufacturing firms. This was also undertaken under the Eco Water Project. The endeavour evaluated the entire water-service value chain using relationships between diverse actors (process water users, suppliers, and wastewater treatment companies) at the meso-level. The initiative established a framework for collecting the relevant information, engaging the stakeholders in the assessment, and encouraging their consideration of alternative options. Each study stimulated internal company discussions on the need and means to evaluate whole-system effects of investment decisions. Inter-organisational co-operation helped to anticipate how meso-level resource efficiency related to lower burdens in wastewater treatment. The authors state that the assessment method can be extended to any water-service system. By comparing options, the approach can facilitate better decisions, thereby improving meso-level resource efficiency.

Mami and Rev (2017) conducted a study to compare aircraft door stops produced using three-dimensional (3D) printing and conventional machining techniques based on the eco-efficiency system ISO 14045. The study integrated life cycle costs and life cycle environmental assessment to promote eco-design programmes in the aeronautics industry that meet specific reduction targets. The research was intended to compare aircraft door stops produced by 3D printing and conventional machining techniques based on the established eco-efficiency metric. The environmental LCA was carried out to adhere to ISO 14040 and ISO 14044.

The value of the product system was calculated using environmental LCC as defined in Swarr *et al.* (2011). The main objectives were: (i) to evaluate the environmental impacts of an aircraft doorstop made by additive manufacturing and machining over the entire life cycle; (ii) to assess the life cycle costs of the processes; and (iii) to find optimum alternatives by applying the suggested eco-efficiency framework and contrasting the manufacturing methods. Eco-efficiency findings relating to the aircraft doorstop production revealed that 3D printing has a higher cost and environmental impact than traditional machining. Nevertheless, the cost of 3D printing technology was found to be high, and a sensitivity analysis demonstrated that the best scenario depended on the preferred trade-off between environmental consequences and reducing costs for lower productivity levels.

2.5.5 Energy and coal industry

Czaplicka-Kolarz *et al.* (2015) recommend a framework for performing an eco-efficiency assessment of the mining processes within hard (or anthracite) coal mines, ensuring economic and environmental convergence performances. The researchers indicate how their framework uses the life cycle methodology to evaluate environmental performance and operating activities to determine economic performance. Their methodology suggests a key

performance indicator for the systematic method of assessing mining production processes in Poland's hard coal mines. This approach is intended to promote decision-making in mining companies in the sense of a multivariate evaluation of coal mining operations and investment processes and promote selecting the best costly variant of coal production that has a minimal effect on the natural environment.

Burchart-Korol *et al.* (2016) studied the eco-efficiency of an underground coal gasification (UCG) system using the ISO 14045 method. The system boundaries were established for the UCG process, from the mining deposit preparation of gasification agents, gasification process, gas cleaning, and electricity generation to resource utilisation and energy and pollution emissions considerations. The measurement results were calculated for a functional unit of 1 MWh of net electricity generated. An LCA was conducted in four stages following the ISO 14044:2006 standard: determining research purpose and scope, gathering data from LCI, performing LCIA, and interpreting the study results. SimaPro 8 software and ecoinvent 3 database were used for the LCA analyses.

An LCIA method, namely ReCiPe 2008 H/A (Hierarchist/Average Perspective), was used to evaluate the different damage categories. LCC was used to calculate the economic value of the product system. The assessment included the cost of the investment phase (investment and pre-investment expenditure), operation phase (production phase), and liquidation phase (especially the costs of managing demolition waste and reclaiming the land). The LCA findings addressed environmental damage categories such as the impact on human health, ecosystem quality, and resource use. The most significant impact on environmental damage was attributable to CO_2 emissions from burning syngas and electricity consumption.

According to the LCC findings, enhancing the installation size while improving electricity produced is essential for cost-effective electricity generation with UCG. Transmission fees

are prevented by burning UCG syngas in existing power plants, combining heat and power/heat plants, and generating power for a mine's own needs, which are actions that improve UCG technology's competitiveness. The sensitivity analysis found that the critical factors of electricity generation's eco-efficiency with UCG are infrastructure capacity to produce electricity and coal seam thickness.

Lee *et al.* (2011) did research in South Korea under the eco-efficiency framework ISO 14045. The study's purpose was to determine whether hydrogen and fuel cell buses could compete with conventional fuels used in buses in terms of the eco-efficiency method, which focuses on economic viability and environmental performance. This study assessed the economic and environmental consequences of hydrogen systems using practical production methods and capacity and transportation choices in Korea using LCA and LCC approaches.

The following hydrogen production methods were addressed throughout this research: naphtha steam reforming (Naphtha SR), natural gas vapour reforming (NG VR), and water electrolysis. Therefore, traditional fuels (diesel and compressed natural gas) were included as focus fuel pathways to determine which hydrogen pathway had the most extensive environmental benefits against traditional fuels. The research concluded that hydrogen pathways, Naphtha SR[C] and NG SR[S], are much more sustainable from an eco-efficiency point of view than standard fuels. Consequently, transitioning from traditional transport fuel to these proposed hydrogen pathways is expected to give a more eco-efficient transport mode – both economically and environmentally. Based on the evidence provided in this study, it might be sensible for decision-makers to start spending on more cost-effective and environmentally friendly fuels by building an optimum hydrogen infrastructure.

Muradin, Joachimiak-Lechman and Foltynowicz (2018) undertook eco-efficiency research on the efficient use of waste from the agro-food industry for water-to-energy applications in

biogas plants. The main aim was to evaluate two biogas plants' eco-efficiencies based on the type of raw material used, their transportation, and the probability of using the heat produced. Using the LCA approach, the environmental impact of the studied installations was evaluated. The LCA framework was based on ISO 14040–14044 and the Impact 2002+ method. The functional unit was specified as the biogas combusted amount, which allowed for the production of 1 MWh of electricity with standard requirements in the biogas plant. The biogas plants' primary function is supplying electricity to the national grid or directly to the agro-food sector. The by-products of the process are heat and digestate. Environmental impact evaluations were based on actual data from operators of biogas plants. Data from the ecoinvent database was used to assess emissions attributed to truck manufacturing, operation stage, and the quantity of pollution from diesel-burning. Data on the cultivation of energy crops were gathered based on scientific data and literature data and values used in the ecoinvent database.

Muradin *et al.* (2018) retrieved the eco-balance data for the different unit processes as applied within a modern mesophilic fermentation system. The system boundaries covered energy crops and feedstock availability, including transportation, energy generation, storage, and distillation. The construction and dismantling of biogas plants and the generation of waste substrates were omitted from the studies.

The cost estimate was performed using the levelled cost of electricity (LCOE) method. Muradin *et al.* (2018) selected the LCOE approach since the feed-in tariff system is used widely in European Union countries. This allowed a comparison of all energy generation expenses from multiple sources, generated throughout their whole life cycle by various technologies. The LCOE method reflects the current technological and financial burden; it

reflects the actual costs aligned with electricity generation in controlled electricity monopoly economies with legislated prices.

The LCA results showed that a biogas plant with a reduced level of waste heat utilisation and that transports substrates by wheeled transport negatively impacts. The distributed energy production cost structure showed a significant share of the feedstock supply costs in the overall value of the LCOE ratio. Therefore, the factor affecting the attainment of high eco-efficiency is the location of the biogas plant. This study is an agro-food processing plant where the transmission pipeline provides the primary feedstock to produce biogas. In contrast, heat is transferred in a processing plant or farm for the production processes' needs.

Valente *et al.* (2019) researched to benchmark the eco-efficiency performance of renewable hydrogen generated by indirect biomass gasification and traditional steam methane gas reformed hydrogen by the ISO eco-efficiency standard. The eco-efficiency indicator for each device – connected to an environmental indicator and a product system value indicator – was calculated separately for three different environmental life cycle indicators: GWP, acidification potential, and cumulative non-renewable energy demand.

Furthermore, from the other end, the specific value indicator for the calculation of eco-efficiency was centred on the levelised cost of hydrogen, which was measured with two external and non-external variations. In a study by Valente *et al.* (2019) on the eco-efficiency assessment of hydrogen energy systems, the ISO-based methodological methodology developed showed that it supports and enriches decision-making by firmly integrating economic and environmental aspects combining both. These developments in the energy systems analysis sector may support decision-makers and policymakers to find suitable alternatives in the journey toward renewable and sustainable energy within the SDG framework.

The proposed methodology concluded that renewable hydrogen generated using indirect biomass gasification is a life cycle eco-efficiency viewpoint, an acceptable alternative to standard hydrogen from steam reforming gas. Therefore, the eco-efficiency assessment performed in this study was able to resolve the inconsistencies in decision-making that occur when environmental and economic life cycle indicators are separately evaluated.

2.6 Conclusion

The above studies are but some of the work that has been carried out in different sectors in the world. Based on the author's knowledge, there is no known published work in the local literature regarding a pork meat product system. This study seeks to close this gap in South Africa. It is, therefore, imperative that this study be carried out for the South African context.

CHAPTER 3 MATERIALS AND METHOD

This chapter describes the methods followed in conducting this research and the assumptions that were made to achieve the research's intended objectives. This chapter starts by defining the goal and scope of this study and presents the means and the stages used to achieve them. In general, the study method comprises a logical and rigorous investigation process to achieve study goals. In this case, a combination of quantitative and qualitative research methods had to be employed to answer the research questions posed.

Since an eco-efficiency assessment relies on LCA quantitative studies, the quantitative methods dominate, and actual measured values were preferred. However, in the absence of various measurements for the different processes involved, calculations based on literature and qualitative methods had to be used. The methods used in this study follow the ISO standards procedural framework. The methods employed for the impact assessment phase (or stage) used the ReCiPe methodology for impact category definition, classification, and characterisation.

3.1 Eco-efficiency assessment framework

This research's eco-efficiency assessment was performed according to the principles established by the ISO 14045 framework (ISO, 2012). Thus, the environmental impacts were analysed using the LCA methodology according to the ISO 14040 and 14044 specifications (ISO, 2006a; 2006b). The methodological procedures of this eco-efficiency assessment study were made through the following steps based on a five-step methodology (Figure 3.1) aligned with ISO (2012): (i) goal and scope definition; (ii) LCA; (iii) product system value assessment; (iv) quantification of eco-efficiency; and (v) interpretation with sensitivity and uncertainty analysis.

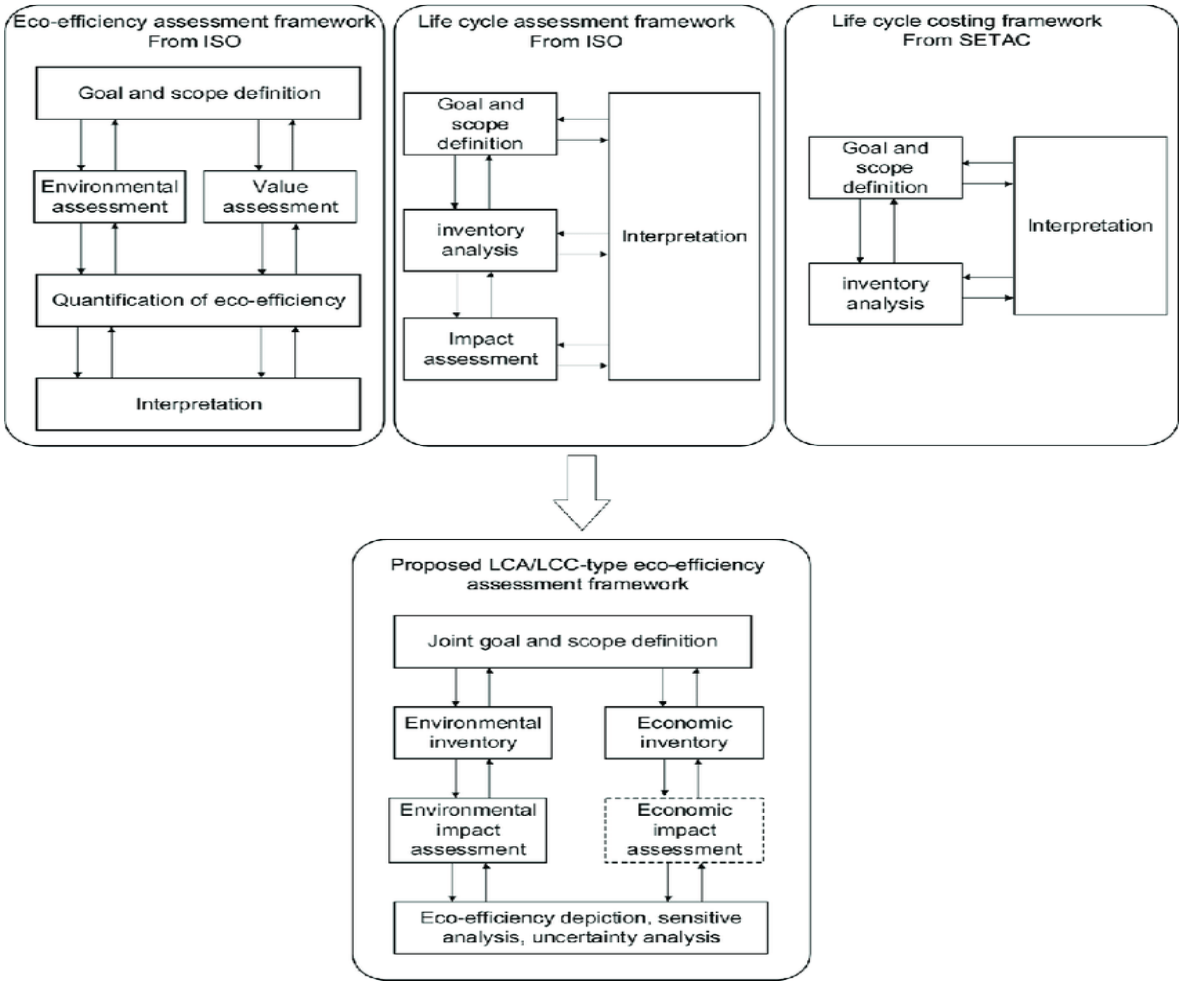


Figure 3.1: Envisaged eco-efficiency assessment model LCA/LCC [Source: Zhang et al. (2019)]

The production system's value was estimated as the sales price minus the operation costs (gross benefit), not including the investment and its amortisation, which was determined as the value-added. There were consistent system boundaries to ensure that for both assessments, the aim was to directly link the LCA and value-added.

As described in Section 2.4.3, eco-efficiency is measured as the ratio of economic and environmental performance or the ratio between environmental and economic performance (Huppes & Ishikawa, 2005). The most used mathematical expression of eco-efficiency is shown in Equation 1:

$$Eco\text{-}efficiency = \frac{product\ or\ system\ value}{environmental\ performance} \qquad (Equation\ 1)$$

The main hotspots were identified as a basis for recommending alternative approaches that might minimise the environmental and economic consequences and increase the South African pig sector's eco-efficiency performance from a circular economy point of view. Due to the increased costs of meat production and the demand for sustainable consumption of finite resources in the industry, there was a requirement to assess both the overall environmental value and the product system value of the meat production processes through an eco-efficiency assessment. Therefore, the product life cycle focused on these subsystems: agriculture, feed production, and abattoir.

3.2 Eco-efficiency framework for integrating LCC and LCA

The ISO 14045 (2012) framework for the eco-efficiency concept, as detailed in Chapter 2, required that the assessment followed the LCA methodology combined with a product system value.

The research project commenced with the main steps: (i) goal and scope; (ii) LCI; (iii) LCIA; (iv) economic assessment; and (v) eco-efficiency depiction, sensitivity analysis, and uncertainty analysis as depicted in Figure 3.2. The proposed framework integrating the LCA and LCC results allowed critical linkages and trade-offs in base scenarios to be established, which improved decision-making. A thorough assessment was performed for each of the four stages involving LCA and LCC.

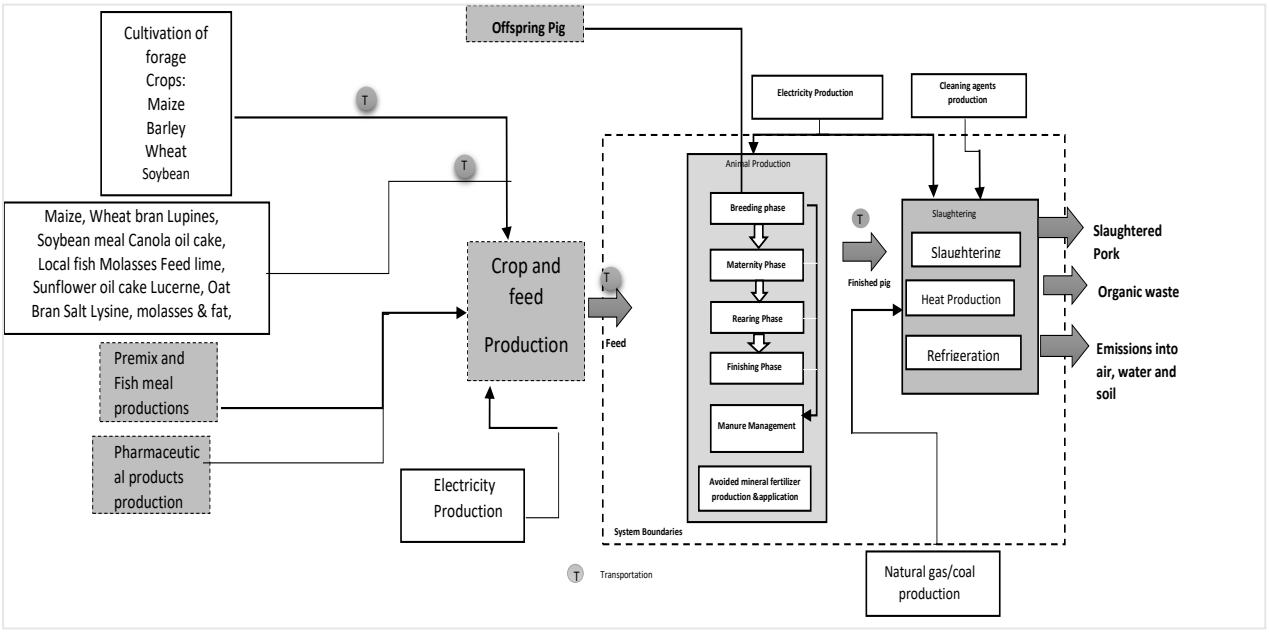


Figure 3.2: Scope and system boundary of the pork meat product system of a South African pork meat production system (scenario base)

The LCA was structured following the four stages per ISO 14040 (2006) and ISO 14044 (2006). However, the typical stages for goal and scope definitions fall under the ISO 14045 standards framework. The typical stages of LCA used in an eco-efficiency assessment are LCI and LCIA. In this study, ELCC was conducted using the guidelines set by Hunkeler *et al*. (2008) and Swarr *et al.* (2011) that classify LCC into three types, namely: conventional LCC, eLCC, and societal LCC.

Throughout the research, the economic value-based value was added and calculated from the LCC data and price of 1 kg pork meat and was linked to the LCA-based LCIA indicator (Swarr *et al.*, 2011). ELCC has three stages, namely: (i) description of function and scope; (ii) evaluation of the LCI; and (iii) interpretation of the eLCC costs.

3.3 Goal and scope definition

3.3.1 Purpose of the eco-efficiency assessment

In this study, an eco-efficiency assessment related to a pork meat product system in South Africa was evaluated through a life cycle perspective. Therefore, the main hotspots were identified as a basis for recommending alternative approaches that might minimise the environmental and economic consequences and increase the South African pig sector's eco-efficiency performance from a circular economy point of view. Due to increased meat production costs and the demand for sustainable consumption of finite resources in the industry, there was a requirement to assess the meat production processes' overall environmental and product value through an eco-efficiency assessment.

The present study's main objective was to use an eco-efficiency framework to assess a conventional pork meat production system's baseline sustainability performance using LCA and eLCC tools. The aim was to give a final volume of pork meat at appropriate meat quality levels for various end uses.

When designing quantifiable strategies for creating sustainable future economic and environmental mitigation plans, sustainability performance evaluation is hugely critical for sustaining and improving society's socio-economic status (Park *et al.*, 2015). This evaluation could provide a quantitative understanding of a system's environmental and socio-economic performance at any time. In this context, eco-efficiency is a valuable tool used in business to measure sustainable performances of engineered and socio-economic systems, defined as economic gains to environmental impacts among different sustainability assessment metrics (Kuosmanen & Kortelainen, 2005; Park *et al.*, 2015).

3.3.2 Scope and boundary of this study

The system boundary defines the processes and systems to be included or eliminated in an eco-efficiency study. The study included all significant processes that entail pork production from the farm right to the abattoir. The transportation of pigs from the farm to the abattoir was excluded based on the unavailability of data. Furthermore, final products' transportation to retailers, consumption, and final disposal of pork by-products by consumers were excluded. All significant economic costs incurred from the farm to the abattoir were included. The environmental impacts caused by the provision of energy, raw materials, and operating resources and transport emissions and waste and wastewater directly generated because of these processes were included. Not included were the emissions related to waste/wastewater treatment beyond the pork cutting stage or emissions caused by setting up the infrastructure.

Furthermore, the provision, maintenance, and disposal of capital goods were not considered. The study focused on South African pork production, and thus the geographic border reflects the South African border. The imports and exports of livestock or pork meat were excluded from the LCA. Data were derived from a South African production system as characterised by a model pig farm. The reference period for the process data covered the period from 2016 to 2017 as data from different sources were not always available for identical years.

The research was based on the baseline eco-efficiency assessment of the pork meat production from the cradle (farm) to the abattoir gate, which made the study a cradle-to-gate study (Figure 3.2). Also, comprehensive inventory data was recorded in this research, which might support the public concentrating on measuring food-derived processes' environmental consequences– especially meat, a fundamental human nutrition component.

In this research, the production chain's economic and environmental hotspots were calculated per mass in kilograms of pork. The system boundary with associated processes, as depicted in Figure 3.2, were chosen based on the LCA ISO standard specifications. The study was delineated to the operational phase stage of the farm and abattoir. Since the construction phase contributes little to environmental and economic performance, the research focused solely on the usage phase.

3.3.3 The function of the product system and functional unit

The functional unit of the studied production systems was pork meat production to a level where it can meet legal quality requirements for different uses and discharge wastewater that meets legal limits for the financial year 2016–2017. In this study, the financial year accounted for seasonality in the volumes of production processes.

The functional unit was based on 1 kg of pork meat produced (carcass weight) at a South African pig abattoir gate for 2016–2017. Moreover, the functional unit relies on the function product, and the primary purpose of livestock products is to meet a need for protein in the human body. Given the various functional units widely used in pork meat production systems, a review of the LCIA results obtained from this research was undertaken.

3.3.4 The intended audience

The results will be used by stakeholders who are owners of pig farms, abattoir operators, and decision-makers within the pork meat sector who want tools that link both the subsystems' ecological and financial performance.

3.3.5 Allocation

Allocation is a significant concern throughout LCA research. It is described as assigning the environmental burden for each functional input or output of a multi-function system (González-García *et al.*, 2014; Noya, Aldea *et al*., 2017). Nevertheless, the ISO standard suggests avoiding the unit cycle's allocation to be divided through subsidiary processes or extending system limitations to include additional functions of the co-products in principle (ISO, 2006a). Since more than one product is produced widely in livestock systems, different co-products global environmental costs can be allocated (Nguyen *et al.*, 2011; Noya, Aldea *et al.*, 2017). This research did not consider an allocation to avoid giving emission factors to pork co-products. The allocation was only done for core pork products (feed, live weight pork, carcass weight pork, and cut pork) as they were deemed to be the only ones accountable for all the life cycle stages impacts. The reason was the lower production of most of these non-products instead of other significant outputs and their non-profitable market value. As a result, the assessment of management practices and further disposal of all co-products and wastes were omitted from the study's scope.

The following cut-off criteria were excluded from the study as they are generally not included in the LCAs of agricultural products, goods, and services owing to their negligible impacts: capital, equipment, buildings, infrastructure, and repair and maintenance materials. Impacts that contribute less than 1% individually and collectively as various components or component operations or more than 3% in total as a group of components or processes to the overall value chain are generally excluded from LCAs. For this study, these impacts included office and administrative impacts, switching of employees, veterinary medicines for pork, and the retailer and consumer use of cleaning compounds. In terms of the control of pig slurry, pig slurry recovery as an agricultural fertiliser was excluded. Other exclusions were

veterinary medicines, defoamers, flocculants, disinfectants, coagulants, spices, antioxidants, and additives.

3.4 Life cycle inventory

The LCI inventory analysis comprised gathering economic and environmental data and drawing up equations as part of the second phase of the eco-efficiency principle so that the flows to and from the system could be quantified. Data of material flows (inputs and outputs) derived from the material flow balances (energy and materials) of the researched system were documented throughout the LCI inventory phase.

In case of missing data, assumptions were made. As mentioned earlier, this step is the longest in the LCA and LCC as it is affected by data availability and is time-consuming. In this process, the amount of energy used, raw materials usage, atmospheric emissions, and the number of wastes and costs created were quantified systematically. By including all the impacts at each life cycle stage, the LCA and LCC provide a true reflection of the potential trade-offs in selecting products and processes.

3.4.1 Data collection

The inventory collection process was the most time-consuming activity for this specific study. In the LCI phase, an inventory of all flows that enter and leave each process in the foreground system was made. The inventory flows included inputs and outputs of the generic ‘materials and their costs. This helped obtain an accurate representation of the product’s life cycle from the cradle to the grave by methodically measuring the amounts of energy used, raw material usage, emissions to the atmosphere, and the amount of energy produced. By including all the impacts at each life cycle stage, the LCA and LCC provided a true reflection of the potential trade-offs in selecting products and processes.

The pig production process uses a feed vendor for all the feed required throughout the farm subsystem. When the farm receives the feed, it has already been mixed at the feed vendor's plant (Müller, 2015). Throughout this research, this data was used to measure the feed volumes needed for the abattoir to raise 100 kg, from which 1 kg of pork would be obtained. The pig production chain does have livestock within which piglets are conceived, bred, and raised to an age from which they attain the required weight to be sent to the abattoir. There is no slaughter facility in the production chain. The processes end where live pigs are purchased as input material to the abattoir.

The slurry method is made of a slatted floor that moves the liquid slurry to a filtering facility where liquid or fluid is separated. In the surrounding area, crop growers extract the solids at their own expense. The liquid is transferred into two holding tanks, namely anaerobic and aerobic dams. The anaerobic dam is used for fermentation, and the aerobic dam has nitrogen-rich water. This water is used to irrigate sheep and cattle grass fields for grazing. The solids are transferred in the surrounding areas to vegetable producers. The total volumes, input materials and resources, and outputs from the pig production system are shown in Table 3.1.

Table 3.1: LCI inventory of pork production

	Value	**Units**
Inputs		
Water	24.12	ℓ
Maize	1.732	kg
Wheat bran	0.683	kg
Barley grain	0.251	kg
Soybean meal	0.199	kg
Rapeseed	0.102	kg
Local fish	0.072	kg
Sugar beet molasses	0.039	kg
Fodder beet	0.027	kg
Sunflower oil cake	0.025	kg

	Value	Units
Soybean oil	0.021	kg
Oat bran	0.018	kg
Salt	0.01	kg
Mineral feed mix	0.048	kg
Cardboard	0.12	kg
Polyethylene (low density)	0.011	kg
Electricity	0.64	kWh
Diesel burned in building machine	0.68	MJ
Coal burned in industrial process	0.006	MJ
Liquefied petroleum gas (LPG) burned in building machine	26.45	MJ
Natural gas, burned in building machine	0.002	MJ
Outputs		
Pork – abattoir	1	kg
BOD5, biological oxygen demand	3.73	g
tCOD, chemical oxygen demand	3.60	g
Nitrogen	0.085	g
Phosphorus	0.079	g
Oils, biogenic	0.018	g
Suspended solids, unspecified	0.447	g
Wastewater, municipal treatment plant	2.98	ℓ
Cardboard	2.982	g
Municipal waste, unsanitary landfill	0.334	g
Plastic packaging waste	1.338	g
Scrap metal	37.2	g

LCC recognises initiatives to reduce costs, allowing decision-makers to choose a cost-effective alternative project (Escobar *et al.*, 2015). The cost of production, maintenance and repair, electricity, and servicing costs were included. According to Swarr *et al.* (2011), the eLCC assessment has a similar system boundary to LCA. Zhang *et al.* (2019) state that LCC assesses costs for running the same production systems measured in the LCA. The assessment costs were expressed in South African currency: ZAR. However, it concerned that specific economic values fluctuate with time, like the market rates, that change with

market forces in the marketplace. Hence, previously collected data from multiple sources were used and modified afterwards with specific participants as per their verification. In the eLCC study, the significant cost contributions associated with a parameter cost database were investigated using Microsoft Office Excel 2016.

To model the farm product system, this study used primary and secondary data from a South African study by Müller (2015) that evaluated three case studies on pig farms in South Africa. This study was crucial to meet the objectives of this research as it went into detail and highlighted the South African context of pork meat production's environmental performance at a farm level.

A lack of access to primary data for the farm subsystem necessitated gathering secondary data from literature studies conducted in South Africa as case studies for pork meat production. As per the LCA standards requirement, both economic and environmental primary data was made available for the abattoir. The economic costs were obtained from the cost inventories of the production system. As previously discussed in detail, the eco-efficiency evaluation involves estimating LCA impacts and LCC. The secondary data was sourced from literature and the eco-invent 3.5 database.

Specific data collection and modelling approaches are outlined in the following sections. The primary data was sourced from the plant, and where it was not available, literature and data from the eco-invent 3.5 database were used. The total quantity of slurry per pig in a year was found in literature, and the slurry was determined based on some assumptions. Literature was used to assume the number of pigs that are produced at the farm. The calculation yielded a total volume of sludge produced by the number of pigs (657 742.33 pigs). The pigs produced 733 070 023 kg of slurry, which amounted to 14.33 kg/FU.

Furthermore, calculations were done to calculate the LCC of this phase of the case study, as shown in Table 3.2. Another South African research informed the economic assessment approaches' estimations by Roelofse (2013), which used a functional unit of 1 kg live weight at the farm level. The LCC costs were used to determine the value add of pork meat production. Table 3.2**Error! Reference source not found.** depicts the LCC inventories for both animal production and abattoir subsystems. A functional unit of 1.29 kg pig was used for the animal production subsystem. The pig's cost at the abattoir was subtracted from the product system's final LCC to avoid double-counting. It must be noted that the pig's cost was the highest input cost at the abattoir.

Table 3.2: Cradle-to-abattoir gate – LCC inventory for pork meat production

Inputs from technosphere: Materials	**Cost per 1 kg functional unit (ZAR)**
Maize	10.77
Wheat bran	4.24
Barley grain	1.56
Soybean meal	1.24
Rapeseed	0.63
Local fish	0.45
Sugar beet molasses	0.24
Fodder beet	0.17
Sunflower oil cake	0.16
Soybean oil	0.13
Oat bran	0.11
Salt	0.06
Mineral feed mix	0.30
Water	0.02
Electricity	0.54
Diesel burned in building machine	0.20
Coal burned in industrial process	0.19
Operation and maintenance	0.36
Labour	0.02

Veterinary costs	0.32
Waste	
Wastewater	0.32
Total LCC cradle	22.04
Input abattoir	**1 kg functional unit (ZAR)**
Carcass weight of 1 kg	26.00
Water used per year	0.74
Electricity	1.98
LPG gas consumed	0.22
Coal consumed	0.21
Natural gas consumed	0.87
Ammonia	0.38
Chlorine	0.10
Cleaning chemicals	0.97
Boiler – WWTP	0.78
Truck washing	0.39
Cardboard	0.87
Plastic	0.35
Labour cost	0.44
Lab analysis	0.13
Maintenance and operation	0.75
Fines for chemical oxygen demand for 2016/17	0.07
Output abattoir	
Pork meat produced per year	1 kg
Water used per year	0.20
Effluent generated per year	0.26
Waste disposal	
Total LCC abattoir gate	35.70
Total $LCC_{cradle\text{-}to\text{-}gate}$ (R35,70 + R22,04 − R26)	31.74
Price	48.91
$VA = P - LCC_{total}$	ZAR17.17

3.4.2 Data validation

Data validation was carried out for all processes deemed significant. In the SimaPro model, South African data was used in the case of energy consumption. For the eLCC, Microsoft

Excel was used to do data validation. The case studies listed in Table 4.4 were used to compare the input data's validity for farm production. It was found that there were no significant differences between the data used in this study for a South African context and the international and local studies reviewed.

3.4.3 Life cycle impact assessment and indicator selection

Meat production consumes natural resources such as water, land, energy, and other materials and generates waste and environmental emissions. The impacts on the environment can be explained using various impact categories: acidification, eutrophic treatment, and climate change. The potentials of photochemical oxidant production are significantly affected by CO_2, CH_4, ammonia (NH_3), and N_2O pollution. Several studies are available in literature on the environmental performance of the pork meat sector (Dalgaard *et al.*, 2007; Devers *et al.*, 2012; González-García *et al.*, 2015; Müller, 2015; Nguyen *et al.*, 2011; Noya, Aldea *et al.*, 2017; Noya, Villanueva-Rey *et al.*, 2017; Pelletier *et al.*, 2010; Reckmann *et al.*, 2012; 2013; Weidema *et al.*, 2008).

As discussed in Section 2.4.4, the eco-efficiency standard framework requires that the environmental assessment be based on the ISO 14040 and ISO 14044 LCA methods. In this study, the LCA of a single pork product system (farm and abattoir) in South Africa was calculated following the ISO 14040 and 14044 (ISO, 2006; 2009) and FAO (2016) principles and guidelines. The stages followed in this study included: goal and scope definition, inventory data collection, LCIA, and the interpretation of the results (ISO, 2006).

The LCI inventory analysis comprised gathering economic and environmental data and drawing up equations as part of the second phase of the eco-efficiency principle so that the flows to and from the system could be quantified. The LCI involves collecting data and

doing calculations to quantify the relevant input and outputs of a product system, including material and energy flows (ISO, 2009; Winkler *et al.*, 2016).

The most significant feed ingredients in this study and their percentage contributions were maize meal (53.7%), wheat bran (21.2%), barley grain (7.8%), soybean meal (6.2%), rapeseed (3.2%), local fish (2.2%), sugar beet molasses (1.2%), fodder feed (0.8%), sunflower oil cake (0.8%), soybean oil (0.7%), oat bran (0.5%), salt (0.32%), and mineral mix (1.5%) (Müller, 2015).

A structured questionnaire was developed to collect the data required for the calculations. It was forwarded to the chosen meat producer. The abattoir provided data for the 2016–2017 financial year, the foreground LCI data's main constituent. The foreground system consisted of processes under the control of the decision-maker for whom the eco-efficiency study was carried out. In this study, these were processes where access to data was readily available at the abattoir and pig farm systems.

The background system consisted of processes where no or, at best, indirect influence could be exercised by the decision-maker for whom the LCA was carried out. These were the processes where all the input resources for this study originated, such as energy generation, chemical, and fertiliser manufacturing. Such processes are called ‘background processes.

The processing of data to a product basis, mass allocation of inputs and outputs (water consumption, waste, wastewater discharge, use of chemical cleaners, electricity consumption and thermal energy) were used. The inventory data was determined annually and divided by the overall annual 1 kg of final product generated (water usage, cleaning agent, electricity, waste disposal, and discharge). Data on the inventory of pork products were shown for each kilogram of the final product.

The inventory collection process was the most time-consuming activity for this specific study. An inventory was made of all the flows that entered and left each process in the foreground system. The inventory flows included inputs and outputs of the generic materials and their costs. The inventory helped obtain an accurate representation of the product's life cycle from the cradle to the grave by methodically measuring the amounts of energy used, raw materials used, emissions to the atmosphere, and the amount of energy produced.

In the case of missing data, assumptions were made during this step. In this process, the amount of energy used, raw materials used, atmospheric emissions, and the number of wastes and costs created were quantified systematically. By including all the impacts at each life cycle stage, the LCA and LCC provided a true reflection of the potential trade-offs in selecting products and processes. This study's LCI inventories are shown in Table 3.1 (for LCA) and Table 3.2 (LCC).

SimaPro 9.0 software and the ecoinvent 3.5 database were used with the ReCiPe 2016 Midpoint (H) 1.03 and ReCiPe endpoint methods. The impact categories reported included: GWP, acidification potential, eutrophication potential, land use, non-renewable energy consumption, water consumption, terrestrial ecotoxicity, and freshwater ecotoxicity. The non-renewable energy consumption impact category was modelled using the Impact 2000+ method.

The damage to the ecosystem's quality was expressed by an aggregated unit, namely, species. yr, which represented the local relative species loss or potentially disappeared fraction of species in terrestrial, freshwater, and marine ecosystems. Finally, the resource scarcity potential was represented by US dollars [the reference year 2013 (USD2013)], which denoted the additional costs required for mineral or fossil resource extraction in the future.

The LCA was performed from a farm-to-gate perspective since the production system included the pork processing at the plant, electricity production, different chemicals, and the treatment of liquid effluents.

ISO standards point out that the use of aggregated single scores will lead to different results due to their normalisation and weighting being centred on presumptions with a bit of scientific foundation. Nevertheless, this research tried implementing a ReCiPe single score, which consisted of a single aggregate score comprising 16 separate categories of impact (Laso *et al.*, 2018; Lorenzo-Toja *et al.*, 2016). Moreover, the single endpoint ReCiPe promoted the decision-making process.

3.4.4 Building the basic model in SimaPro

The inventory analysis culminated in an inventory table being created. This is attributable to the Analyse function in SimaPro, which calculates the system inventory using a reduced matrix by building an operating network and tracing the material movement from stage to stage. The software shows the table as an alphabetical, detailed list. The list is used to explain the various processes' relation to the total environmental impact throughout the preceding step to the impact assessment phase.

SimaPro defines seven types of process types: materials, energy, transport, processing, use, waste scenario, and waste treatment. These can either be in the form of unit processes like describing a single operation or a system process or one process containing a set of unit processes. The primary purpose of all the processes is to quantify the flow of resources, products, co-products, and emissions in and out of the system.

Once processes have been modelled, product stages can be constructed. Such stages allow the definition of processes that are to be included in the different stages of the product. By

default, SimaPro has five product stages: assembly, disposal scenario, disassembly scenario, reuse, and life cycle. The assembly stage describes the production stage of the process, while the disposal scenario defines what could occur with the product if reused or disassembled.

The disassembly scenario details which parts of the total product are being disassembled and their destination, while the reuse stage provides information about the processes required to reuse parts of the product. As the name suggests, the life cycle stage links the various stages to describe the entire life cycle. For this study, a cradle-to-gate analysis focused on the assembly and life cycle stages of the process.

Table 3.3: Common environmental impact categories prominent in the pig sector [Source: Müller (2015); Noya, Aldea et al. (2017); Reckmann et al. (2012)]

Impact categories	**Units**	**Indicators**
GWP	kg CO_2-eq	Emissions of CO_2, CH_4, and N_2O
Stratospheric ozone depletion	kg CFC-11-eq	Emissions of chlorofluorocarbons (CFCs)
Eutrophication potential	kg P-eq	Nitrogen discharge into watercourses [nitrate (NO_3) and NH_4]; phosphorus losses through erosion and interflow, and surface runoff
Use of resources	kg oil-eq	Use of primary energy; use of other resources (like fertiliser)
Ecotoxicity	kg 1,4-DCB	Pesticides discharged into the ecosystem; discharges of antibiotics and feed additives into the ecosystem
Terrestrial eutrophication	kg NO_x-eq	Emissions of nitrogen oxide (NO_x) and NH_3
Aquatic eutrophication	kg P-eq	Nitrogen discharge into watercourses (NO_3 and NH_4); Phosphorus losses through erosion and interflow, and surface runoff
Acidification potential	kg SO_2-eq	Emissions of SO_2, NH_3, and NO_x
Freshwater depletion	m^3	Water consumption
Marine toxicity	g N-eq	Nitrogen discharge into watercourses (NO_3 and NH_4)

3.5 Economic indicator selection

The most crucial aspect of the eco-efficiency assessment focuses on defining a product value expressed as a functional, productive, or economic factor. Annexure B from ISO 14045 provides various examples of how to apply the eco-efficiency assessment methodology.

As discussed in Section 2.4.4, eLCC is a good match for LCA because LCC assesses costs related to a system's life cycle with costs covered by one or more actors (Rebitzer *et al.*, 2008). LCC adopts ISO 14040's structure, importance, scope, and defined functional unit to structure the analysis (Swarr *et al.*, 2011). Based on the definition that LCC is the total cost incurred in the life cycle of pork production, Equation 2 was adopted to calculate the total LCC of pork production systems (Table 3.2).

$$LCC_{cradle\text{-}to\text{-}gate\ (pig\ production)} = C_{RM} + C_U + C_V + C_M + C_{WM} \qquad \textit{(Equation 2)}$$

Where:

- C_{RM} is the raw materials' cost, including feed and pigs for slaughter at the abattoir, including packaging (ZAR/kg).
- C_U is the cost of all utilities such as electricity, water, coal, diesel, natural gas, and LPG (ZAR/kg).
- C_V is the cost of veterinary services at the farm, including vaccinations and all medical costs needed for pig farming (ZAR/kg).
- C_M is the production cost, including the operation and maintenance of equipment and labour costs (ZAR/kg).
- C_{WM} is the cost of waste management, including safe waste disposal to the landfill (ZAR/kg).

Value-added was estimated based on LCC, as shown by Equation 3:

$$VA = P - LCC_{cradle\text{-}gate} \quad \textit{(Equation 3)}$$

Where:

- P is the sales price of the product.
- $LCC_{cradle\text{-}gate}$ is the life cycle costs from cradle (farm-to-abattoir gate) to the gate.

Throughout this research, value-added was chosen as the economic indicator, commonly used in eco-efficiency research to assess eco-efficiency (Konstantas *et al.*, 2020). The LCC was conducted through the guidelines set by Hunkeler *et al*. (2008) and Swarr *et al.* (2011) that classify LCC into three types: conventional LCC, eLCC, and societal LCC.

Throughout the research, the economic value-based value was added and calculated from the LCC data and price of 1 kg pork meat, and it was linked to the LCA-based LCIA indicator (Swarr *et al.*, 2011). The eLCC has three stages: (i) description of function and scope; (ii) evaluation of the LCI; and (iii) interpretation of the eLCC costs.

3.6 Conclusion

This chapter gave a detailed account of the methods followed in conducting this study. As a result of a lack of data, assumptions were made in some instances, and literature data were used. According to the eco-efficiency guidelines detailed in the ISO 14045 document, eco-efficiency assessments must be done in line with the LCA guidelines (ISO 14040; ISO 14044) and the product system value must be determined as well. The eco-efficiency standards state that based on the stakeholder's objectives and goals of the study, it shall be described which stakeholder's value(s), type of value(s), and methods used to determine the product system value(s) are to be used in the assessment. The product system value can be

functional, monetary value, or other values. The monitory value was used in this study in the form of LCC and was determined by following the guidelines set up by Hunkeler *et al*. (2008) and Swarr *et al.* (2011).

CHAPTER 4 RESULTS AND DISCUSSION

This chapter characterises the life cycle stages and describes the search for possible reasons for poor environmental and economic results. Such measurements are compared, and the effects on eco-efficiency in the pork life cycle are addressed.

The interpretation phase of the eco-efficiency assessment comprised the following elements according to the goal and scope of the study:

- The identification of significant issues based on the results of the environmental and product system value assessment.
- An evaluation that considers aspects of completeness, sensitivity, uncertainty, and consistency.
- Formulation of conclusions, limitations, and recommendations.

This chapter describes how the requirements of the eco-efficiency standard apply to the interpretation of an eco-efficiency assessment. Also, the interpretation considers the relationship between the environmental results and the product system value results.

4.1 Environmental and economic characterisation of the pork meat

This study was conducted at three levels, namely: midpoint, endpoint, and a single score. Single score results were calculated to help decision-makers who do not need to identify each midpoint indicator's environmental relevance. Table 4.1 shows the characterised midpoint, endpoint, and single score results at these different levels.

Table 4.1: Midpoint, endpoint, and single score results per 1 kg of pork meat production

Impact category	Unit	Total
Midpoint		
Non-renewable energy	MJ primary	36.5
Terrestrial ecotoxicity	kg 1,4-DCB	6.56
Land use	m^2a crop-eq	5.38
Global warming	kg CO_2-eq	4.03
Water consumption	m^3	1.98
Terrestrial eutrophication	g P-eq	0.87
Fossil resource scarcity	g oil-eq	0.75
Terrestrial acidification	g SO_2-eq	0.16
Stratospheric ozone depletion	kg CFC-11-eq	2.73×10^{-5}
Ionising radiation	kBq Co-60-eq	1.22×10^{-2}
Ozone formation, human health	kg NO_x-eq	1.16×10^{-2}
Fine particulate matter formation	kg $PM_{2.5}$-eq	8.26×10^{-3}
Ozone formation, terrestrial ecosystems	kg NO_x-eq	1.18×10^{-2}
Marine eutrophication	kg N-eq	4.55×10^{-3}
Freshwater ecotoxicity	kg 1,4-DCB	1.75×10^{-2}
Marine ecotoxicity	kg 1,4-DCB	1.27×10^{-2}
Human carcinogenic toxicity	kg 1,4-DCB	2.35×10^{-2}
Mineral resource scarcity	kg Cu-eq	1.10×10^{-2}
Endpoint		
Human health	DALY	9.63×10^{-6}
Ecosystem	species. yr	4.87×10^{-8}
Resources	USD2013	1.81×10^{-01}
Single score		
Human health	mPt	162.25
Ecosystems	mPt	53.86
Resources	mPt	1.29
Total	**mPt**	**217.40**

The ecological performance results show that the production of pork contributed 36.46 MJ of non-renewable energy use. The electricity needs contributed approximately 34% and maize 31%, which is over half the total contributions from the two inputs for non-renewable energy use in terms of contribution. The following highest contributors were wheat grain (15%), barley grain (5%), rapeseed (3%), and soybean (2%), all of which were under 15%. Additionally, plastic packaging from the abattoir contributed 6% to non-renewable fossil fuel use. The abattoir subsystem had a high use of electricity (51%), followed by coal (4%) and LPG (4%).

Table 4.2 shows the base scenario's environmental performance with all the identified impact categories for the various subsystems' overall impact.

Table 4.2: Eco-efficiency characterisation indicators for the production-midpoint values

Impact category	Unit	Total	Units	Value
Non-renewable energy	MJ primary	36.463633	MJ/ZAR	2.12
Terrestrial ecotoxicity	kg 1,4-DCB	6.557957	kg1,4-DCB/ZAR	0.38
Land use	m^2a crop-eq	5.3847424	m^2a crop-eq/ZAR	0.31
Global warming	kg CO_2-eq	4.0308316	kg CO_2-eq/ZAR	0.23
Water consumption	m^3	1.9815173	m^3/ZAR	0.12
Terrestrial eutrophication	g P-eq	0.86902385	g P-eq/ZAR	$5.06x10^{-02}$
Fossil resource scarcity	g oil-eq	0.75098645	g oil-eq/ZAR	$4.37x10^{-02}$
Terrestrial acidification	g SO2-eq	0.16048731	g SO_2-eq/ZAR	$9.35x10^{-03}$
Stratospheric ozone depletion	kg CFC-11-eq	2.72809E-05	kg CFC-11 eq/ZAR	$1.59x10^{-06}$
Ionising radiation	kBq Co-60-eq	0.012172182	kBq Co-60-eq/ZAR	$7.09x10^{-04}$
Ozone formation, human health	kg NOx-eq	0.011620411	kg NO_x-eq/ZAR	$6.77x10^{-04}$
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.008264123	kg$PM_{2,5}$-eq/ZAR	$4.81x10^{-04}$
Ozone formation, terrestrial ecosystems	kg NO_x-eq	0.011841718	kg NO_x-eq/ZAR	$6.90x10^{-04}$
Marine eutrophication	kg N-eq	0.00455166	kg N-eq/ZAR	$2.65x10^{-04}$

Impact category	Unit	Total	Units	Value
Freshwater ecotoxicity	kg 1,4-DCB	0.017536711	kg 1,4-DCB/ZAR	$1.02x10^{-03}$
Marine ecotoxicity	kg 1,4-DCB	0.012734081	kg 1,4-DCB/ZAR	$7.42x10^{-04}$
Human carcinogenic toxicity	kg 1,4-DCB	0.02347336	kg 1,4-DCB/ZAR	$1.37x10^{-03}$
Mineral resource scarcity	kg Cu-eq	0.01102688	kg Cu-eq/ZAR	$6.42x10^{-04}$

The farm production system contributed 4.01 kg CO_2-eq to the overall GWP score regarding climate change. The highest contributors were feed production (growing of maize, soya, wheat, and barley). The electricity usage and maize production were responsible for 20%, whereas the soya meal and wheat grain contributed 10%. At the farm, farm electricity, which contributed 13%, is used to prepare and mix feed, provide lighting and heating, and cool the pig enclosures. The overall GWP for this study was determined to be 4.03 kg CO_2-eq.

For the abattoir contributions, electricity usage contributed around 68%, plastic packaging 28%, and coal usage at the boiler 7%. The use of electricity at the abattoir is driven by the demand for cooling the product through refrigeration and operating energy systems such as motors, fans, and compressors. The other contributor in the abattoir is the production of packaging plastic used to package the finished product to the market. The terrestrial ecotoxicity results were 2.85 kg 1,4-DCB, while the total terrestrial acidification score was 0.190 g SO_2-eq. The electricity used at the abattoir contributed 88% of terrestrial acidification, with the packaging contributing the next highest at less than 10%.

The different environmental impact categories of importance in the meat-producing sector are shown in Table 4.3. The table shows the normalised results for South Africa. The world normalisation factors were used to calculate these normalisation results.

Table 4.3: Normalised impact categories of the entire life cycle

Impact category	Total
Global warming	5.05×10^{-4}
Stratospheric ozone depletion	4.56×10^{-04}
Ionising radiation	2.53×10^{-05}
Ozone formation, human health	5.65×10^{-04}
Fine particulate matter formation	3.23×10^{-04}
Ozone formation, terrestrial ecosystems	6.67×10^{-04}
Terrestrial acidification	6.77×10^{-04}
Freshwater eutrophication	1.20×10^{-03}
Marine eutrophication	9.88×10^{-04}
Terrestrial ecotoxicity	6.33×10^{-03}
Freshwater ecotoxicity	1.43×10^{-02}
Marine ecotoxicity	1.23×10^{-02}
Human carcinogenic toxicity	8.47×10^{-03}
Human non-carcinogenic toxicity	1.28×10^{-03}
Land use	8.72×10^{-04}
Mineral resource scarcity	9.19×10^{-08}
Fossil resource scarcity	7.66×10^{-04}
Water consumption	7.43×10^{-03}

In pork production, eutrophication is mainly driven by fertiliser feed production due to fertiliser use (Müller, 2015). Pork production contributes to freshwater and terrestrial eutrophication because of fertiliser used to grow feed and waste management at the pig farm. Terrestrial eutrophication of 0.86 g P-eq was recorded. The marine eutrophication of 4.55 g N-eq was attributed to the pig production subsystem. The feed production showed the highest share with more than 52%, followed by pig housing with a share of 36%. Eutrophication during the slaughtering stage originated from organic pollutants and nitrogenous and phosphorous compounds in the wastewater.

For 1 kg of pork, 5.38 m^2a was required. The feed producing process was the most significant contributor to land use, with wheat (40%), maize (23%), oat bran (8%), soybean feed (17%), and rapeseed (8%) all contributing.

The production of 1 kg of pork consumed 1.98 m^3 of water, with the abattoir and feed production being significant contributors to water consumption. The abattoir subsystem is responsible for 74% water use, which shows that 0.365 m^3 was used in animal production, with maize being responsible for 15%, wheat, 8%, and barley grain 2%.

In terms of endpoint results, the pork produced in South Africa contributed 9.63×10^{-06} to human health impacts of DALY units. The ecosystem diversity was 4.87×10^{-08} species. yr, and the resource availability impact was 0.18 USD2013.

In terms of single score indicator values, pork production's contribution to human health was determined to be 162.24 mPt. The contribution of pork production to ecosystem diversity was determined to be 53.86 mPt, and resource availability was 1.29 mPt. The pig feed and production (farm) had the highest impacts on this, and the reviewed studies' environment.

Figure 4.1 shows that the pig feed and production (farm) had the highest impacts on the environment as per this study and the reviewed studies. The feed production process comprises all feeds and by-products in the production system for all the various feeding cycles. Although animal feed inputs can be sourced from far away, they can still outweigh other locally generated alternatives due to agricultural subsidies, different tax charges, scarcity of resources, and infrastructure. For example, as described in a study by Reckmann *et al.* (2013), soya was shipped from Brazil to the port of Rotterdam in the Netherlands (9 700 km) and afterwards trucked to its intended location in Germany (412 km). In a study by Müller (2015), the pig production subsystem grains, such as maize, barley, and wheat, were trafficked inside South Africa from different regions where the pigs were based.

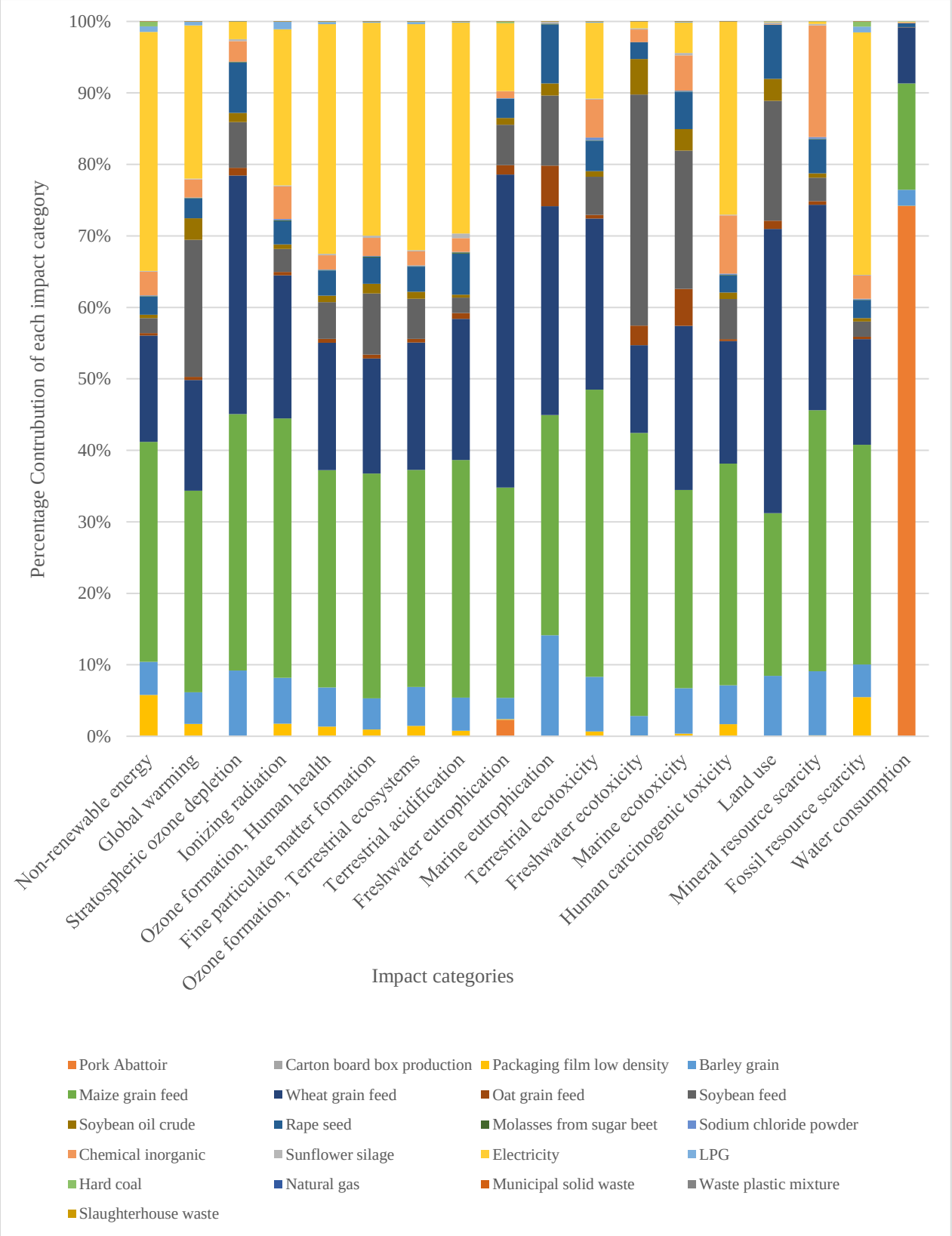


Figure 4.1: Characterisation LCIA of pork production

The normalised values for pork meat production in Figure 4.2 show that freshwater toxicity had the highest environmental indicator caused by feed production.

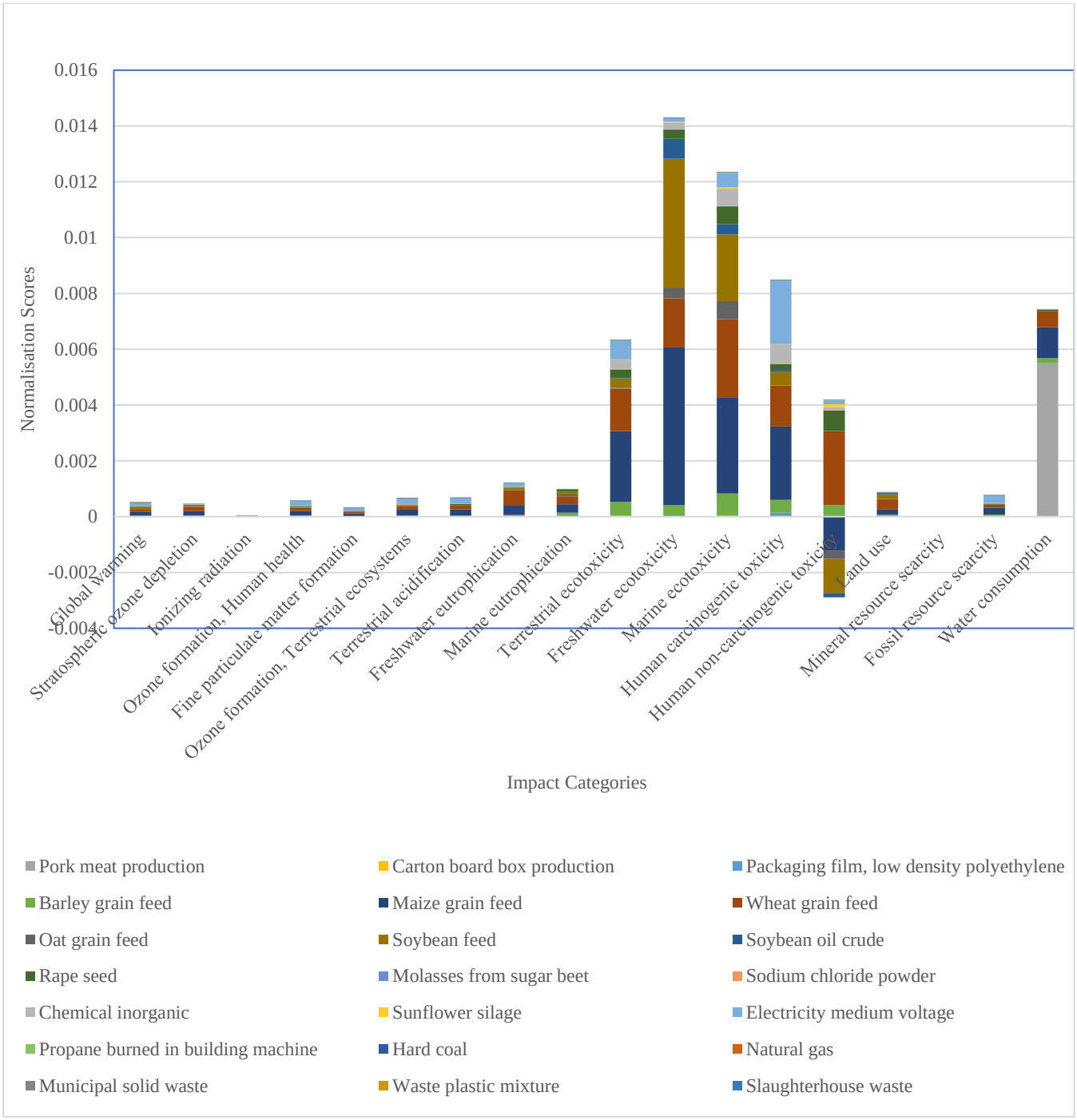


Figure 4.2: The normalised values for the pork meat production

4.2 Comparison of this South African case study LCIA results with past studies.

Chapter 2 described some studies conducted in the pork sector and summarised the literature review in Table 2.1. A contrast had to be conducted on the outcomes of this case based on South African conditions. Table 4.4 shows the results of the comparison. As shown in the previous research results, and with the cradle-to-gate perspective, the findings reported in

this research corresponded with other LCA research that examined various pork products. The findings of this research study enabled the identification of inputs with the highest environmental burdens. It is clear from these findings that the production of feed for pig nourishment contributed massively to the impact on the environment of the subsystem of livestock production. The feed is the principal input for pork production.

The results of all the reviewed studies confirm that the primary process stage accountable for the highest environmental impact is livestock feed production (values ranging from 20% to 90% depending on the category). Around 30%, 40%, and 75% of the emissions contributing to global warming, eutrophication, and acidification, were jointly responsible for pig production activities, primarily on-farm and slurry emissions.

There were minor variations between such studies, and this study's research: the environmental profile was identical except for acidification emissions irrespective of the impact assessment method (see Table 4.2). Greenhouse gas emissions at the farm gate in this study were 4.01 kg CO_2-eq/kg carcass weight. Results ranged from 1.89–9.08 kg CO_2-eq/1 kg live weight and 1 kg carcass weight.

Further essential findings of organic agriculture systems were found (Basset-Mens & Van Der Werf, 2005), adding up to 4.3 kg CO_2-eq/1 kg carcass weight at the farm gate. Noya, Villanueva-Rey *et al*. (2017) also reported a high value for climate change (5.9 kg CO_2-eq/kg carcass weight at the farm gate) related to feed production and transport activities. It is further essential to reiterate that using different databases introduces errors into the comparisons (Reckmann *et al.*, 2013). Moreover, emissions on-farm and related to the slurry application were calculated considering emissions factors.

A critical factor in those variations seems to be the measuring process, which further relies on the region. Although emission variations, such as eutrophication and energy

consumption, were found in certain areas, these were in limited ratios. In the case of eutrophication, the characterisation findings in g PO^{4-} are reported in three case studies (Basset-Mens *et al.*, 2005; De Vries & De Boer, 2009; Reckmann *et al.*, 2013). When eutrophication outcomes are contrasted irrespective of the system's boundary and functional unit, the discrepancy is less than 6%.

Concerning energy use (expressed in MJ-eq), this study's research findings align with many of those in the literature. The research analysis showed an attribution assessment of 5.39 m^2a/kg carcass weight concerning land use. That is the same value as the 5.8 m^2a/kg carcass weight reported in Denmark in a cradle-to-slaughterhouse gate study (Nguyen *et al.*, 2011).

4.3 Completeness, sensitivity, and consistency checks

A completeness check was carried out by comparing the impact results of this study with the impact results for previous LCAs of pork chains. No statistical sensitivity check could be performed because the data was primarily qualitative. The system boundaries for the pork supply chain were effective because a relevant comparison could be made. Functional units are included in Table 4.2.

Table 4.4: The reviewed LCIA literature results for pork meat production

Reference	Functional unit	System boundary	Country	Non-renewable energy use	GWP (CO_2-eq)	FE (g P-eq)	Water use (m^3)	Land use (m^2a)	Terrestrial acidification (SO_2-eq)
(Nguyen *et al.*, 2011)	1 kg LW	Cradle-to-gate	Denmark	21.0 MJ	3.40 kg	23.3 g		4.4	56 g
(Dalgaard *et al.*, 2007)	1 kg CW	Cradle-to-gate	Denmark		3.6 kg	232 g (NO_2-eq)			45 g
(Cerberg & Flysjo, 2004)	1 kg bone and fat-free	Cradle-to-gate	Sweden	9.3 MJ	2.06 kg	183 g			34 g
(Devers *et al.*, 2012)	1 kg CW	Cradle-to-gate	South Africa	30.7 MJ	4.5 kg	34 g			63 g
(Basset-Mens & Van der Werf, 2005)	1 kg SW	Cradle-to-gate	France	15.9 MJ	2.3 kg	28 g			45 g
(Stone *et al.*, 2012)	1 kg SW	Cradle-to-farm gate	USA		3.37 kg	42 g			
(Pelletier *et al.*, 2010)	1 kg LW		USA	11.45 MJ	2.91 kg	17 g			
(Müller, 2015)	1 kg LW farm gate	Gate-to-gate	South Africa (NW)	5.55 MJ	1.886 kg	3.46 g			15.6 g
(Müller, 2015)	2 kg LW farm gate	Gate-to-gate	South Africa (KZN)	8.44 MJ	1.964 kg	3.23 g			14.7 g
(Müller, 2015)	3 kg LW farm gate	Gate-to-gate	South Africa (WC)	11.66 MJ	2.059 kg	3.08 g			14.7 g
(Reckmann *et al.*, 2013)	1 kg CW	Cradle-to-gate	Germany	19.5 MJ	3.2 kg	23.3 g			57.1 g
(Noya, Aldea *et al.*, 2017)	1 kg LW farm gate	Cradle-to-farm gate	Spain	12.5 MJ	3.42 kg	200 g		4.96	186.0 g
(Noya, Aldea *et al.*, 2017)	1 kg cut pork	Cradle-to-gate	Spain		4.96 kg	1.37 kg	0.18	9.37	94.0 g
(Winkler *et al.*, 2016)	1 kg CW	Cradle-to-cradle	Austria		4.8 kg	381.4 g (NO^{3-}eq)			61.5 g
(Lukić *et al.*, 2015)	1 kg of pork products	Cradle-to-cradle	Serbia		9.0392 kg	15.1 g			9.874 g
(Pirlo *et al.*, 2016)	1 kg of body weight	Cradle-to-farm gate	Italy		3.3 kg	3.4 g			6.18 g
(González-García *et al.*, 2015)	1 kg CW	Cradle-to-gate	Portugal		3.3 kg	558 g	3.07	4.12	22.8 g
(This Study, 2021)	1 kg CW	Cradle-to-gate	South Africa	36.6 MJ	4.01 kg	400 g	1.44	3.51	2.17 g

Legend: *CW: carcass weight; KZN: KwaZulu-Natal; LW: live weight; NW: North West; SW: slaughter weight; WC: Western Cape.*

4.4 Results for product system value

According to Devers *et al.* (2012), LCC takes the cost factors relating to a product's operational life into account. The feed costs were the highest in the farm subsystem, specifically for maize, ZAR10.27/FU, and wheat bran, at ZAR4.24/FU. Barley bran and soya bean meal were ZAR1.54/FU and ZAR1.24/FU, respectively.

The costs of feed production accounted for more than 70% of all the costs at the farm. The feed was recorded to be responsible for the highest environmental impacts in the overall pork production system. The costs of feed further affected the costs of purchasing pigs at the abattoir. This amounted to ZAR26.00/FU. The pigs' purchase price at the farm was responsible for more than 90% of the abattoir's costs.

Natural resources to produce these raw materials were further a significant issue of concern to this study. Energy costs at the abattoir were the second-highest costs at ZAR1.98/FU. Abattoirs have significant energy-using equipment such as refrigeration systems and cooling towers. These are necessary to keep the facility's temperatures low to keep meat fresh and free from pathogens risks. As a result, electricity costs are very high as more energy is required to run these systems.

These costs were followed by cleaning chemicals, which were ZAR0.97/FU. Abattoirs need a thorough cleaning regime to mitigate the enormous risks associated with food safety. Chemicals are used to clean surfaces to eliminate any potential for the growth of pathogens, viruses, and bacteria that might affect human life. This results in an enormous volume of water being used in the process. In terms of the water balance of the abattoir operations, cleaning is responsible for most water use. The costs of water and packaging were ZAR0.87/FU and ZAR0.78/FU, respectively. The use of natural gas was high at the cost of

ZAR0.87/FU. Interestingly, the boiler running at the abattoir also attracted a cost of ZAR0.78/FU due to the purchase of wastewater treatment chemicals.

The value-added for the whole pork product system was determined to be **ZAR17.16/FU**. This is in line with literature stating that electricity, labour, water, and veterinary costs are among the costs that affect the South African pork sector (BFAP, 2013).

4.5 Identification of environmental hotspots

4.5.1 Fossil (non-renewable) energy use

This impact category was modelled using the Impact 2000+, an essential indicator of food production systems' sustainability. It comes from finite resources that will eventually be exhausted beyond the level that can be extracted economically. As shown in the overall calculation, this impact category was the highest for both subsystems, with the feed production stage being the main contribution. Electricity and maize contributed around 64% to the high non-renewable use of fossil energy use. The electricity generation and usage alone contributed around 34% and maize 31%.

The third highest contributors were wheat grain (15%), barley grain (5%), rapeseed (3%), and soybean (2%). The other contributor that was not linked to the pig farming activity was the overall plastic packaging from the abattoir (6%). The 36.46 MJ of non-renewable energy use at the pig farm is shown in Table 4.1 and Figure 4.1. The highest contributors were stated above for the animal production subsystem. Similarly to the abattoir, non-renewable energy use of 5.41 MJ was reported for the abattoir subsystem, with high electricity use being responsible for 51%, coal for 4%, and LPG for 4%. The packaging plastic production was responsible for 38% of non-renewable energy use, as shown in Figure 4.1.

4.5.2 Global warming potential

GWP refers to the increase in temperature caused by the emission of greenhouse gases into the atmosphere. The results were expressed in terms of CO_2-eq, which represents a 100-year time horizon. The pig production system contributed 4.01 kg CO_2-eq overall to the GWP. The highest contributors were feed production (growing maize, soya, wheat, and barley) and electricity usage.

In a pig production system, slurry management contributes to 0.132 kg of CO_2-eq (Lopez-Ridaura *et al.*, 2009). Figure 4.1 and Table 4.3 shows how much of each material is used to produce the feed. As previously mentioned, maize is responsible for 20% of GWP, and soya meal with wheat grain contributing 10%. Electricity usage at the farm to prepare and mix feed and lighting and heating or cooling the pig enclosures contributed 13%.

For the abattoir contributions, electricity usage contributed around 68%, plastic packaging 28%, and coal usage at the boiler 7%. The abattoir's electricity usage is driven by the demand for cooling of the product using refrigeration and driving energy systems such as motors, fans, and compressors. LPG is also used in the abattoir during the singeing process to remove hair from pigs. With the volumes of pigs slaughtered, more gas is required to process more pork carcasses. The other contributor to GWP in the abattoir is packaging plastic packaging used to package the finished product.

4.5.3 Eutrophication potential

The elevated levels of nitrogen and phosphorus, primarily caused by wastewater from agricultural activities and waste disposal, constitute eutrophication. The water system absorbs those runoff components, which alter the environment. Emissions to the air of these components are taken seriously when determining the eutrophication potential. These

elements have one thing in common, namely the consumption of oxygen in their surroundings. Reducing oxygen causes lower levels of oxygen in the water, which affects aquatic ecosystems. This contributes to the uncontrolled growth of aquatic plants, such as algae blooms, and a significant decline in the overall quality of water and aquatic ecosystems. Algae prevent sunlight from entering low water depths, which reduces photosynthesis and resulting in less oxygen being released.

The eutrophication potential reflects the number of nutrients released into the environment (Müller, 2015). In pork production, the eutrophication potential is mainly driven by feed and urine production (Müller, 2015). The results of this impact category were expressed in g P-eq per kg of pork. The feed production showed the highest share of this impact category, namely more than 52%, followed by pig housing with a share of 36%.

Table 4.2 shows that the contribution of the slaughtering stage was comparatively small. Eutrophication during the slaughtering stage originated from organic pollutants, nitrogenous and phosphorous compounds in the wastewater.

4.5.4 Water consumption

The other significant impact category considered in the pork production system was water depletion/consumption. Water is a vital resource in both subsystems. As shown in Figure 4.1, the most significant contributor in overall port meat production was the abattoir that contributed 74%, and the second was maize (15%), followed by wheat (8%).

Table 4.2 shows that 1.98 m^3 of water was consumed to produce 1 kg of pork meat. The pork production subsystem was responsible for 99% of water use. Animal production consumed 0.365 m^3, with maize being responsible for 62%, wheat 32%, and barley grain 4%.

4.5.5 Land use

According to Nguyen *et al.* (2011), land use refers to the land area occupied and temporarily unavailable for other purposes. Table 4.2 shows that 5.38 m^2a is required for producing 1 kg of pork meat carcass. The feed producing process is the most significant contributor, with wheat contributing 40%, maize 23%, oat bran 8%, soybean feed 17%, and rapeseed 8%.

4.5.6 Terrestrial acidification

The acidification potential computes the decline of the nutrient base (calcium, magnesium, and potassium) in the ecosystem and the substitution of acidic elements caused by atmospheric pollution. The key contaminants triggering the acidification potential include SO_2, NO_x, HCl, and NH_3. The fact that all those contaminants attract acidifying H^+ ions is a standard feature. Acid gases such as SO_2, NO_x, and NH_3 can react with air to form acids such as H_2SO_4 and HNO_3 in the atmosphere. Acid deposition occurs via rain, fog, snow, and dew.

Dry acid particles can be broken down when exposed to moist tissue (for example, in the lungs). The soil and water that is exposed to the acid cause their pH levels to decrease. Low levels of pH damage habitats and ultimately destroy them. The degradation of construction materials, including metals and natural stones, has other harmful consequences. The effect varies depending on the region in which acid deposition occurs and the acid system's buffering ability.

Acidification potential is measured in kg SO_2-eq. A total of 0.190 g SO_2-eq of acidification potential with power contributes to this analysis. In the abattoir, electricity contributed 88% to terrestrial acidification, whereas the packaging contributed less than 10%. Lopez-Ridaura *et al.* (2009) found that animal production, specifically slurry management, contributed

0.0023 kg of SO_2-eq to terrestrial acidification. This research study found the value to be 0.03 SO_2-eq.

4.6 Identification of economic hotspots

The feed cost was the highest in the farm's subsystem, maize specifically was ZAR10.27/FU, and wheat bran was ZAR4.24/FU. Barley, bran, and soya bean meal were ZAR1.54/FU, and for the latter, it was ZAR1.24/FU. The costs of feed accounted for more than 70% of all the costs at the farm. The feed was recorded to be responsible for the highest environmental impacts in the overall pork production system. The feed costs further affected the costs of purchasing the pig at the abattoir, which amounted to ZAR26.00/FU.

The purchase of a pig to meet up with the functional unit makes the pig responsible for more than 90% of the abattoir's costs. Natural resources used to produce these raw materials were also a significant issue of concern to this study. Energy costs at the abattoir were the second highest at ZAR1.98/FU. Abattoirs have significant energy-using equipment such as refrigeration systems and cooling towers. These are necessary to keep temperatures low to keep meat fresh and free from pathogens. As a result, electricity costs were incredibly high as more energy is required to run these systems.

These costs were followed by cleaning chemicals, which were ZAR0.97/FU. Abattoirs need a thorough cleaning regime to mitigate the enormous risks associated with food safety. Therefore, a large volume of chemicals is used to clean surfaces to eliminate any potential for the growth of pathogens, viruses, and bacteria that might affect human life. This results in an enormous volume of water being used in the process. In terms of the water balance of the abattoir operations, cleaning is responsible for the most water use. The cost of water and packaging were noted as ZAR0.78/FU and ZAR0.87, respectively. The use of natural gas

was also noted as being a high cost at ZAR0.87/FU. Interestingly, the abattoir's boilers also attracted ZAR0.78/FU costs by purchasing wastewater treatment chemicals.

4.7 Assessing the eco-efficiency of pork production

At this stage, this research study has applied the eco-efficiency portfolios to integrate the environmental and product system results and facilitate the decision-making process. Because the production system results were based on an LCC and subsequently value-added, the study showed the environmental effects of pork meat production and the eco-efficiency type called environmental intensity (Huppes & Ishikawa 2005; Konstantas *et al.*, 2020).

The eco-efficiency analysis was performed by following the ISO 14045 standard (ISO, 2012). For this purpose, the LCC results obtained in this work were combined with the LCA results reported. According to Zhang *et al.* (2019), two methods are used in most literature to express eco-efficiency, namely via numeric value or via a two-dimensional diagram. Although using a diagram is the most frequently used method, providing a unified numeric value is convenient for decision-making. For this research, numeric values and graphs were used to interpret the eco-efficiency results. The pork meat production system of eco-efficiency for the human health environmental impact indicator was $5.61x10^{-7}$ DALY/ ZAR/units; the ecosystem quality impact indicator was 2.84×10^{-9} species. yr/ZAR/unit and the resource availability were 1.05×10^{-2} USD 2013/ZAR.

Table 4.2 shows the characterised eco-efficiency of pork meat production at the midpoint level. As shown from these results, the pork meat production system results of eco-efficiency were non-renewable energy impact category at 2.12 MJ/ZAR. The eco-efficiency observed for terrestrial ecotoxicity was 0.38 kg 1,4-DCB/ZAR. The eco-efficiency observed for land use was 0.31 m^2a crop-eq/ZAR. Global warming for pork meat production demonstrated an

eco-efficiency value of 0.23 kg CO_2-eq/ZAR. These figures followed the LCA results' calculations regarding water consumption and eco-efficiency of 0.1154 ZAR/m^3.

The farming subsystem was credited for the most considerable environmental impacts based on the findings (solely because of the pork feed production processes) for all impact categories evaluated in the assessment. These were primarily attributable to several products (grains, maize, barley, and soybean). Agricultural practices, in conjunction with pork processing, have a significant role in global environmental issues. The research examined the economic and environmental consequences of pork processing in South Africa from a cradle-to-abattoir gate context, thereby providing the pork industry's first eco-efficiency analysis.

Table 4.2 shows the calculated eco-efficiency indicators. Equation 3 was used with environmental performance and value-added as calculated above. The values represent the baseline eco-efficiency performance of the South African pork meat system. According to the standard (ISO 14045, 2012), eco-efficiency assessment is a tool for the relative evaluation of different systems. Thus, these results could be used only as a reference point for assessing different suggested measures for eco-efficiency improvement or cross-comparison with the pork meat production system's eco-efficiency.

For other representations of the calculated results in Figure 4.3, this research study used a single score indicator to aggregate the environmental impacts into a single unit. With this approach, the study could identify the pathway toward eco-efficiency in each life cycle stage. The pork meat single score results are shown in Figure 4.3 and tabulated in Table 4.5. These results show the eco-efficiency of the baseline for the South African pork system. As can be seen, these results are essential to decision-makers in the pork meat industry.

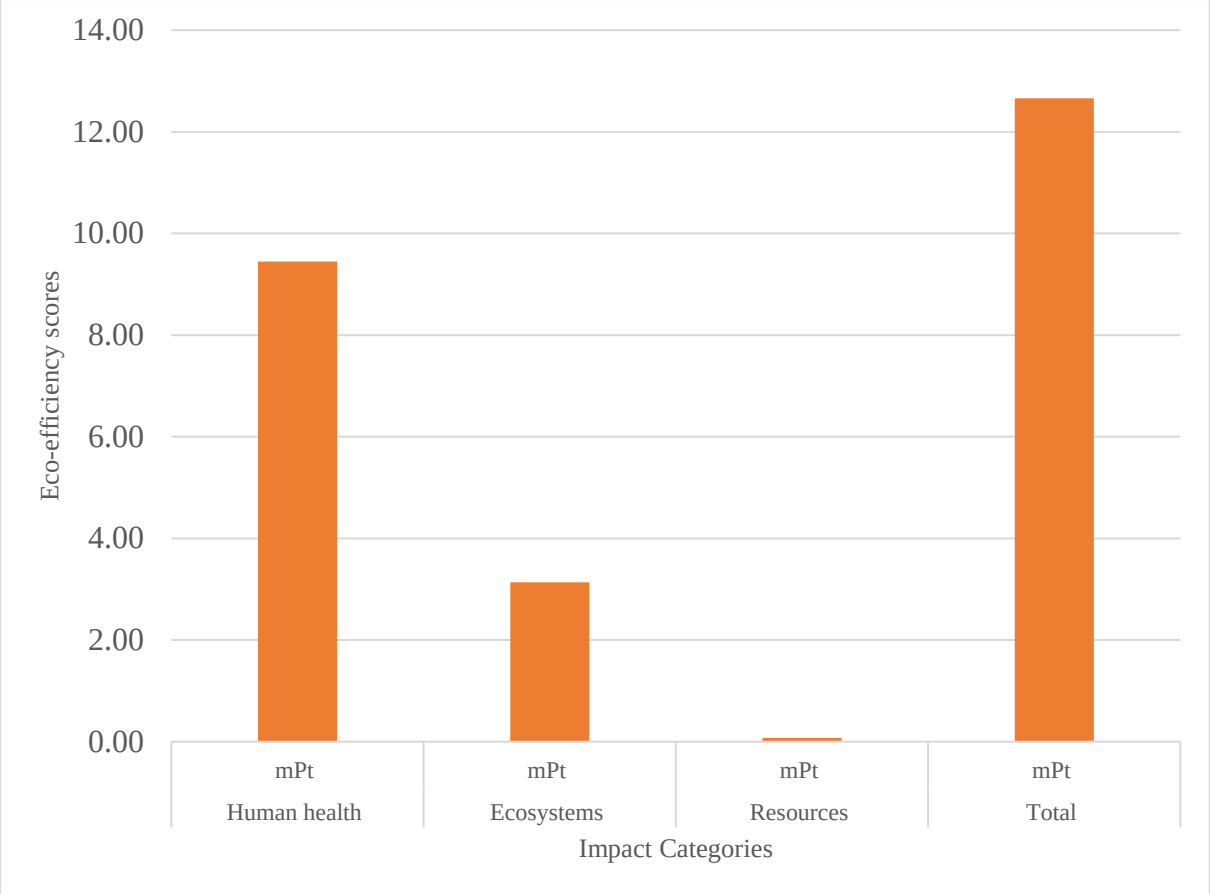


Figure 4.3: The eco-efficiency single score results for significant impacts

Table 4.5: Normalised single score results for eco-efficiency analysis

Single score	Unit	Total	Eco-score	Value-added
Total	mPt	217.40282	12.66178296	17.17
Human health	mPt	162.24794	9.449501456	
Ecosystems	mPt	53.862203	3.136994933	
Resources	mPt	1.2926704	0.07528657	

Table 4.6 below shows the eco-efficiency of pork meat production at the endpoint level. As shown from these results, the pork meat production system of eco-efficiency for the human health environmental impact indicator was 5.61×10^{-07} DALY/ZAR/unit. The ecosystem quality impact indicator was 2.84×10^{-09} species. yr/ZAR/unit. Lastly, the eco-efficiency result for the resource availability environmental indicator was 1.05×10^{-02} USD2013/ ZAR/unit.

Table 4.6: The eco-efficiency indicators for the production of per functional unit

Endpoint	**Eco-scores**	**Units**	**Value-added**	**Eco-efficiency scores**	**Units**
Human health	9.63×10^{-06}	DALY	R17.16	5.61×10^{-07}	DALY/ZAR
Ecosystem	4.87×10^{-08}	species. yr	R17.16	2.84×10^{-09}	species. yr/ZAR
Resources availability	1.81×10^{-01}	USD2013	R17.16	1.05×10^{-02}	USD2013/ZAR

4.8 Conclusion

The chapter gave details about the results of this study. As per the aims and objectives of this thesis, a South African pork product system's eco-efficiency was determined. Both the economic and environmental hotspots were defined for pork production. To improve pork production's eco-efficiency, Chapter 6 details what decision-makers in the meat sector must do.

CHAPTER 5 DISCUSSION AND INTERPRETATION

This research presented a study of the eco-efficiency of a pork meat production system in South Africa. This study combined an environmental performance through an LCA and a product system value assessment through value add. This was done by applying the LCA and LCC methodologies from the cradle to the gate for the pork meat production system. An exhaustive LCI was drawn up to gather inventory data for the pork production processes. This LCI included financial information and data concerning the input and output flow of material and energy of the pork meat production subsystems for each stage of their life cycle, from the farm to the abattoir gate, and all the raw materials needed.

Although the eco-efficiency assessment was standardised in 2012, according to ISO 14045, many hurdles must still be overcome to implement the standard fully to assess pork systems, such as securing relevant primary and secondary data from an actual plant. Challenges were faced with securing a plant that was willing to share its financial and production data. Secondly, there had to be an agreement regarding the use of relevant economic indicators to supplement the environmental indicators to calculate eco-efficiency.

The system boundary covered two subsystems of the pork food chain from farm to abattoir. It covered the foreground system, which included all production processes to electricity and other raw materials productions and the background system, which accounted for all related material flows, such as energy, transport of resources, and chemicals production.

Concerning the economic evaluation method, the study showed that the LCC is an appropriate monetary metric for assessing a pork meat production system's product system value, as is it congruent to the LCA method. Its calculation requires the economic costs of producing the product to be determined.

The ISO 14045 framework was applied successfully in this research to quantify the baseline eco-efficiency of a South African pork production system from the cradle-to-abattoir gate. In the LCIA, the first choice was to use the 18 indicators at the midpoint level to determine the environmental indicator and understand which processes contribute to the production system and identify environmental hotspots. The second choice was to quantify the LCIA results at endpoint categories. The results showed that the animal production system's higher negative environmental impact is attributable to the background system, which accounts for energy production, feed, and fuels for transport.

In the product system assessment, all costs linked to the production of pork were calculated. The LCC calculations showed the economic hotspots to be both the farm in animal feed and the abattoir. Natural resources are used extensively to produce pork meat. South Africa generates most of its electrical energy used in this study from coal. There is a potential to install renewable energy resources such as biogas technology by valorising the pig value chain’s wastes. Valorisation of waste could help the production system drive a circular economy and improve the non-renewable energy value.

The reviewed European studies by González-García *et al.* (2015), Nguyen *et al.* (2011), Noya, Villanueva-Rey *et al.* (2017), and Reckmann *et al.* (2013) show that valorisation can be applied in the South African context to offset the carbon footprint of the facility. The farm already uses slurry water to irrigate grazing land and apply solids to vegetable farms. There are advantages and disadvantages to these strategies as it is reported that the introduction of nitrates and phosphates from agricultural activities can negatively affect the soils and result in emissions of ammonia to the atmosphere, causing acidification. The runoff from the irrigated farms can result in eutrophication of the receiving water bodies. Meat products can be used as animal feed, which is not currently happening at the abattoir as organic meat is

sent to the landfill. More detailed work on the benefits of valorisation of pork production waste is found in González-García *et al*. (2015) and Noya, Villanueva-Rey *et al*. (2017). South Africa is a water-scarce country; thus, the feed responsible for most of the negative environmental performance needs to be reviewed. Maize and wheat are staple foods in South Africa, but their production requires enormous water and land volumes. Although water prices in South Africa are lower than in other countries globally, freshwater usage must be addressed. Throughout the pork life cycle production, freshwater is used in a wide range of process stages. On the farm, subsystem water is used to irrigate for feed farming, provide drinking water for animals, and clean the facilities. The abattoir subsystem is used for scalding and cleaning carcasses; manufacturing respective pork products, disinfecting and sterilising knives, machinery, and facilities; and providing water for workers' hygiene.

As far as water efficiency projects are concerned, there are various ways to reduce use in the pig supply chain, such as improving the flow of water levels, managing to process efficiently, reusing clean wastewater from refrigeration systems, and using appropriate vacuum pumps for pig processing. Continuing to improve wastewater quality could be a top priority task. The bulk of the water used in abattoirs becomes wastewater. Because of manure, urine, blood, and fat, abattoir wastewater has a high organic material strength. The pollution load in the abattoir wastewater is primarily reduced by preventing blood, fat, and manure from mixing with the effluent. Small investments could strengthen basic housekeeping practices. Highly energy-efficient appliances, including heat recovery systems, could be used to achieve further savings. Recovering methane to supplement the fuel from anaerobic digesters of high-strength effluent streams (mainly manure) could be a problem for most pork producers.

CHAPTER 6 CONCLUSION

The methodology addressing eco-efficiency enabled the study to identify the main hotspots in pig processing's environmental and economic performance. More than 75% of environmental impact scores were from farm activities such as producing feed and generating electricity. Abattoir and feed production had significant impacts on the use of water and energy. These two processes were found to have the highest contribution to global warming.

The impacts of slurry management include emissions such as CH_4 and N_2O. The significant environmental impacts with the abattoir's highest scores were non-renewable energy use, water depletion, and eutrophication. The findings indicated that the pig farm and abattoir were the processes where eco-efficient strategic improvements could be made. Mitigation strategies should be developed to concentrate on animal feed production and the use of renewable energy sources at the abattoir. The use of water could be improved by automating abattoir processes.

The economic hotspots were mainly feed costs at the farm and energy costs at the abattoir. The abattoir operation uses energy-intensive units such as refrigeration and cooling towers and coal for heating generation.

To ensure the competitive development of goods and services, balancing economic and environmental indicators is essential, as accomplished by this research. A further recommendation is that it could be valuable to consider a socio-economic scenario for the same framework proposed within an eco-efficiency assessment. Considering a socio-economic scenario would allow for a complete evaluation of the pork meat sector’s sustainability by determining all sustainable development pillars. The calculated eco-efficiency indicators' values could serve as reference values in further research work and for

decision-makers. The developed method is not case study specific and has been applied successfully to another product system with quite different characteristics.

Based on the case study's eco-efficiency and the findings that provided valuable information on baseline eco-efficiency of pork production, it was agreed that an eco-efficiency framework should be developed to assist companies in making decisions. As demonstrated above, the eco-efficiency framework created helps accommodate an increasing requirement from society for industries to report on topics such as the environment, climate, and societal costs. According to the author's knowledge, these assessments may enable pork producers and local governments to use more sustainable approaches for strategic pork production.

This study is the first in South Africa to use the ISO 14045 (ISO 2012) for pork meat production. It is believed it is a system with excellent communication potential, even though it should consider additional social issues. The whole research demonstrated that an assessment like this might well enable pork farmers, including local governments, to introduce sustainable pork meat-processing options. An appealing strategy could be to use this tool as a viable tool for comparing their performances, as seen in Lorenzo-Toja *et al.* (2016).

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APPENDICES

Appendix A- Pork Production Data

Pig production Data from the Farm

Number of pigs raised with live weight of 100kg each: 657,742.00

Description	Units	Total Quantity per year per WC study	Unit Cost - R	Total Costs - R	Quantity per 100kg Pig	Price per kg/unit for a 100kg Pig	Total cost per 100kg Pig	% of Cost of 100kg Pig
Feed	kg	165,082,883.00	R 6.22	R1,026,058,281.24	250.98	R 6.22	R 1,559.98	87%
Water	kL	963,297.07	R 31.29	R 30,141,565.19	1.46	R 31.29	R 45.83	3%
Electricity	kWh	32,870,915.40	R 0.84	R 27,611,568.94	49.98	R 0.84	R 41.98	2%
Veternary costs	R	60,205,213.33	R 1.00	R 60,205,213.33	1.00	R 91.53	R 91.53	5%
Fuel	L	916,452.77	R 11.32	R10,370,854.48	1.39	R 11.32	R 15.77	1%
Coal	kg	12,138.44	R 800.00	R 9,710,752.00	0.02	R 0.90	R 0.02	0%
Waste water /slurry	kg	733,070,022.67	R -	R -	-	R -	R -	0%
Labour	R	1,265,747.45	R 1.00	R 1,265,747.45	1.00	R 1.92	R 1.92	0%
Operation and Maintenance	R	18,561,479.24	R 1.00	R 18,561,479.24	1.00	R 28.22	R 28.22	2%
Total costs				R1,183,925,461.87			1,785.25	100%

Data on Pork Abattoir and Processing

Description	Units	Total Quantity per year	Unit Cost - R/kg	Total Costs - R	Units per kg	Quantity per Functional Unit	Cost per Functional Unit (R/kg)	% of per Functional unit cost
Input Materials								
Number of 100kg pig slaughtered	pigs/year	657747.2033						
Carcass weight of a 100kg pig	kg/year	51,153,000.00	26	R1,329,978,000.00		1.298	R 26.00	93%
Water								
Water used per year	L/year	211,086,000.00	0.02	R 3,765,193.85	L/kg of pork	4.126561	R 0.07	0%
Energy								
Electricity	kWh / year	9,660,058.17	1.05	R 10,126,033.32	kWh/kg	0.19	R 0.20	1%
LPG Gas Consumed	kg/year	275,051.15	4.05	R 1,115,148.53	GJ/kg of pork	0.26	R 0.02	0%
Coal Consumed	tons/year	1,182.30	898.11	R 1,061,841.14	kg/kg of pork	0.02	R 0.02	0%
Natural Gas Consumed	GJ/year	92,713.19	4.80	R 445,214.04	GJ/kg of pork	1.81	R 0.01	0%
Chemicals								
Ammonia	kg/year or litres			R 1,950,600.00			R 0.04	0%
Chlorine	kg/year or litres			R 50,000.00			R 0.00	0%
Cleaning chemicals	kg/year or litres			R 4,942,677.00			R 0.10	0%
Boiler-WWTP	kg/year or litres			R 400,000.00			R 0.01	0%
Truck washing	kg/year or litres			R 20,000.00			R 0.00	0%
Other chemicals	kg/year or litres			-			R -	0%
Packaging								
Cardoards	tons/year	109.35		R 445,140.62	kg /kg of pork	2.14E-03	R 0.01	0%
Plastic	tons/year	1,189.30		R 1,804,577.96	kg /kg of pork	2.32E-02	R 0.04	0%
		1,298.65	1,732.35	R 2,249,718.58				
Labour Cost								
Labour Cost				R 22,423,846.00			R 0.44	2%
Lab Analysis				R 6,480,000.00			R 0.13	0%
Other Cost								
Maintanance+ Operation				R 38,188,957.00			R 0.75	3%
Fines for COD for 2016/17				R 360,590.00			R 0.01	0%
Total Costs				R 1,425,807,538.04			R 27.87	100%
Output								
Pork Produced								
Pork Meat produced per year	kg/year	51,153,000.00	27.87	R 1,425,807,538.04			27.87	99.833%
Waste Water generated								
Cardboards	tons/year	17.10			kg/kg of pork	3.34E-04		
General waste	tons/year	68.43			kg/kg of pork	1.34E-03		
Plastic	tons/year	19.01			kg/kg of pork	3.72E-04		
Scrap Metal	tons/year	155.10			kg/kg of pork	3.03E-03		
Other	tons/year	650			kg/kg of pork	1.27E-02		
Landfill (Safe disposal)	tons/year	155			kg/kg of pork	3.03E-03		
Boiler Ash	tons/year	177.57			kg/kg of pork	3.47E-03		
Waste Disposal	tons/year	1,242.09	835.09	R 1,037,259.25	kg/kg of pork	2.43E-02	R 0.02	0%
Output Water Quality								
Effluent Generated per year	kL/year	152,559.73		R 1,345,209.40	kg/kg of pork	0.00298242	R 0.03	0.094%
BOD5, Biological oxygen demand	mg / L / year	1,250.00		-	mg / kg	1.2500E-03		
tCOD, Chemical oxygen demand	mg / L / year	1,207.77		-	mg / kg	1.2078E-03		
Total Kjheldahl Nitrogen	mg / L / year	28.67		-	mg / kg	2.8667E-05		
Total Phosphorus	mg / L / year	6.00		-	mg / kg	6.0000E-06		
Fats, oil and grease Total	mg / L / year	150.00		-	mg / kg	1.5000E-04		
Total suspended solids	mg / L / year	218.69		-	mg / kg	2.1869E-04		
pH		7.00		-				
Total costs				R 1,428,190,006.69			R 27.92	100.00%

To calculate LCC= Utilities cost+ labour costs+O&M costs+ fines+taxes+material costs

To callculate eco-efficiency = LCC/LCA = with LCC being the overall costs of producing 1 kg of pork meat over an environmental impact/perfomace

APPENDIX B- Life Cycle Assessment Inventory Data

SimaPro input for on-farm production				
Products			Farm FU	657,742.00
Pork production - On-farm	51,153,000	kg	1.285832698	
Inputs from nature				
Water - Unspecified natural origin	963,297	m3	1.46	
Inputs from technosphere: materials				
Feed	Mass contribution	kg	Total kg FU (100KG)	1kg FU
Maize	88,616,491.59	kg	134.73	1.73
Wheat bran	34,915,029.75	kg	53.08	0.68
Barley Grain	12,850,051.61	kg	19.54	0.25
Soybean meal	10,175,708.91	kg	15.47	0.20
Rapeseed	5,201,761.64	kg	7.91	0.10
Local fish	3,689,602.44	kg	5.61	0.07
Suger BeetMolasses	1,999,153.71	kg	3.04	0.04
Fodderbeet	1,363,584.61	kg	2.07	0.03
Sunflower oil cake	1,277,741.51	kg	1.94	0.02
Soybean oil	1,080,467.47	kg	1.64	0.02
Oat Bran	900,362.04	kg	1.37	0.02
Salt	534,868.54	kg	0.81	0.01
Mineral Feed Mix	2,478,059.16	kg	3.77	0.05
Total	**165,082,883**	kg	**250.98**	**3.23**
Water	963,297.07		1.46	0.02
Inputs from technosphere: energy				
Electricity	32,870,915	kWh	49.98	0.64259995
Diesel, burned in building machine	34,916,851	MJ	53.08593725	0.68259634
Coal, burned in industrial process	294,964	MJ	0.448449532	0.00576631
LPG, burned in building machine	33,794,528,045	MJ	26448.64213	26.4490489
Natural gas, burned in building machine	92,713	MJ	0.001812468	0.00181247
Waste				
Slurry	733,070,023	kg	1,114.53	14.3309292
SimaPro input for abattoir				
Products			FU-1kg carcass weight	
Pork production - Abattoir	51,153,000	kg	1	
Inputs from nature				
Water - Unspecified natural origin	211,086	m3	4.126561492	
Inputs from technosphere: materials				
Pork production - On-farm	51,153,000	kg	1.298	
Cardboard	6,211,351	kg	0.121426907	
Polyethylene (low density)	583,831	kg	0.011413426	
Inputs from technosphere: energy				
Electricity	9,660,058	kWh	0.188846366	
LPG, burned in building machine	12,679,858	MJ	0.247881024	
Coal, burned in industrial process	28,730	MJ	0.000561646	
Natural gas, burned in building machine	92,713	MJ	0.001812468	
Emissions to water				
BOD5, Biological oxygen demand	190,700	kg	0.003728025	
tCOD, Chemical oxygen demand	184,257	kg	0.003602075	
Nitrogen	4,373	kg	8.5496E-05	
Phosphorus	-	kg	0	
Oils, biogenic	915	kg	1.78945E-05	
Suspended solids, unspecified	22,884	kg	4.47E-04	
Waste				
Wastewater, municipal treatment plant	-	m3	0.0000000	
Cardboard	152,560	kg	0.0029824	
Municipal waste, unsanitary landfill	17,100	kg	0.0003343	
Plastic	68,430	kg	0.0013378	
Scrap Metal	19,010	kg	0.0003716	
Municipal waste, unsanitary landfill	155,100	kg	0.0030321	
Municipal waste, unsanitary landfill	649,780	kg	0.0127027	
Municipal waste, unsanitary landfill	155,100	kg	0.0030321	

APPENDIX C-Life Cycle Costing Inventory

LCC Inventory of Pork Meat Production		
Inputs from technosphere: materials	**Cost per 1kg FU**	**Cost per 100kg FU**
Maize	R10.77	R837.39
Wheat bran	R4.24	R329.93
Barley Grain	R1.56	R121.43
Soybean meal	R1.24	R96.16
Rapeseed	R0.63	R49.15
Local fish	R0.45	R34.87
Sugar Beet Molasses	R0.24	R18.89
Fodderbeet	R0.17	R12.89
Sunflower oil cake	R0.16	R12.07
Soybean oil	R0.13	R10.21
Oat Bran	R0.11	R8.51
Salt	R0.06	R5.05
Mineral Feed Mix	R0.30	R23.42
Water	R0.02	R45.83
Electricity	R0.54	R41.98
Diesel, burned in building machine	R0.20	R15.77
Coal, burned in industrial process	R0.19	R0.90
Operation and Mantanance	R0.36	R28.22
Labour	R0.02	R1.92
Veterinary Costs	R0.32	R91.53
Waste		
Wastewater	R0.32	R25.18
Total LCC cradle	R22.04	R1,811.28
Input Abattoir	1kg FU	100kg FU
Carcass weight of a 100kg pig	R26.00	R2,022.02
Water used per year	R0.74	R5.72
Electricity	R1.98	R15.40
LPG Gas Consumed	R0.22	R1.70
Coal Consumed	R0.21	R1.61
Natural Gas Consumed	R0.87	R0.68
Ammonia	R0.38	R2.97
Chlorine	R0.10	R0.76
Cleaning chemicals	R0.97	R7.51
Boiler-WWTP	R0.78	R0.61
Truck washing	R0.39	R3.04
Cardoards	R0.87	R0.68
Plastic	R0.35	R2.74
Labour Cost	R0.44	R34.09
Lab Analysis	R0.13	R9.85
Maintenance+ Operation	R0.75	R58.06
Fines for COD for 2016/17	R0.07	R0.55
Output Abattoir		
Pork Meat produced per year		
Water used per year	R0.20	R1.58
Effluent Generated per year	R0.26	R2.05
Waste Disposal		
Total LCC, abattoir gate	R35.70	R2,171.61
Total LCC cradle-to-gate	R31.75	R3,982.89
Price	R48.91	
VA= P-LCCtotal	R17.16	