Eco-efficiency assessment of pork production through life-cycle assessment and product system value in South Africa

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Abstract. The consumption of pork as a source of animal protein has increased worldwide, especially in developing countries such as South Africa. The increase in pork demand is putting pressure on the natural environment, and the costs of production are increasing. This study sought to determine what is the eco-efficiency of pork production in a South African context. It also was meant to determine which processes in the value chain have low eco-efficiencies. Lastly, it sought to find what strategies could be recommended to improve overall eco-efficiency. Eco-efficiency was assessed by following the requirements of the International Standards Organisation ISO 14045 standard, which requires that the Life cycle assessment (LCA) method and product system value be combined. The environmental life cycle costing (LCC) method was used to determine the product system value (Value Added) of pork production. The functional unit was 1 kg of pork carcass, specifically from the cradle to the abattoir gate. The findings indicated that the pig farm and abattoir were the processes that had low eco-efficiencies and eco-efficient strategic improvements could be made. Mitigation strategies could be developed to concentrate on the production of animal feed and the use of renewable energy sources at the abattoir. The use of water could be improved by automation of the abattoir processes. Therefore, this study achieved its goal as economic and environmental areas of interest were identified in this specific case study for South Africa. This framework could be extended to study the eco-efficiency of other meat production chains and other sectors.

1 Introduction

Internationally, the pork industry 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 over the possible implications of growth in the pork sector; more specifically it will increase the use and the degradation of natural resources. It will also contribute to climate change, and exhaust water supplies, affect biological diversity, and trigger ecosystem changes. Secondly, the costs of production, purchase of animal feed, labour, and utilities are increasing. Furthermore, stringent controls

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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 future demand.

Eco-efficiency, first 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 [1]. Eco-efficiency is a relative measure that addresses the relationship between environmental performance and the value of a product system [2]. Ideally, increased eco-efficiency is achieved by reducing a product system's environmental impacts while maintaining or increasing the value produced [3].

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 [4,5]. 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 [4,6]. The concept consolidates the environmental and economic pillars of sustainable development, reduces the consumption of resources, and improves environmental protection while maintaining or enhancing the manufactured product's value [4,7]. 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 [8]; wastewater [9]; sewers [10]; food [11]; agriculture [12]; automotive [13] and energy [14].

Therefore, an eco-efficiency assessment can help pork meat production systems since it is a tool that decision-makers can use to measure and move towards sustainability [4 & 5]. Eco-efficiency encourages companies to become more competitive while being more environmentally responsible at the same time. 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 occur 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 the pork meat production's environmental and economic costs; and
- Use these results for strategic decision-making processes to attain sustainable development goals for pork meat production systems.

2 Methods

This research's eco-efficiency assessment was performed according to the principles established by the ISO 14045 framework. The framework firstly requires that the environmental performance of the product system be analysed using the LCA methodology according to the ISO 14040 and 14044 specifications [16,17]. The second requirement of the framework is the determination of the economic performance of the product system. The methodological procedures of this eco-efficiency assessment study were made through the following steps based on a four-step methodology aligned with ISO 14045 standard [2]:

(i) Goal and Scope definition.

(ii) Environmental and Product System Value Assessment.
(iii) Quantification of Eco-efficiency; and
(iv) Interpretation.

The system boundary covered two subsystems of the pork food chain from farm to abattoir. It covered not only processes from feed production to electricity and other raw material productions (called the "foreground system" in the study), but also its background system (which accounts for all related material flows, such as energy, transport of resources, and production of chemicals). The functional unit (FU) of this study was 1 kg of pork meat.

An exhaustive Life Cycle Inventory (LCI) was drawn up to gather inventory data for the pork production processes. This included costs 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. Whereas the eco-efficiency assessment was standardised in 2012, as per [2], many hurdles are still to be overcome to implement the standard fully to assess pork systems. The challenges included securing relevant primary and secondary data from an actual plant. Secondary data, therefore, had to be used to supplement the environmental indicators to calculate eco-efficiency.

SimaPro 9.0 software and the ecoinvent 3.5 database were used with the ReCiPe 2016 Midpoint (H) 1.03 and Endpoint as a suitable life cycle impact assessment (LCIA) method. In the LCIA, the choice was first made to use the 18 indicators at the mid-point level to determine the environmental indicator, understand which processes contributed to the production system, and identify environmental hotspots. The second choice was to quantify the LCIA results at end-point categories. The impact categories reported included: global warming potential, acidification potential, eutrophication potential, land use, water consumption, terrestrial ecotoxicity, and freshwater ecotoxicity. Additionally, non-renewable energy consumption was modelled using the Impact 2000+ method. The damage to Human Health was expressed by Disability-Adjusted Life Years (DALY), considering the years lost to premature death and expressing the reduced quality of life due to illness in years as well.

The damage to the ecosystem quality was expressed by an aggregated unit, 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 expressed by US dollars in 2013 (USD2013), which denoted the additional costs required for mineral or fossil resource extraction in the future.

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

As detailed earlier, eco-efficiency is measured as the ratio of economic and environmental performance or the ratio between environmental and economic performance [15]. The most common mathematical expression for eco-efficiency (Equation 1) is:

$$\textit{Eco-efficiency} = \frac{\textit{product or system value}}{\textit{environmental performance}} \tag{1}$$

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.

3 Results

Table 1 shows the economic performance of pork production. The contributions of the main input materials and resources are shown in this table. The study shows that rearing pigs for slaughter is a costly exercise. The feed cost was the highest in the farm subsystem, specifically for maize, R10.27 /FU (49%), and wheat bran, at R 4.24 /FU (19%). Barley bran and soya bean meal were R1.54 /FU (7%) and R1.24 /FU (6%), respectively. The Rapeseed and local fish contributed R0.63 (3%) and R0.45 (2%). The electrical and Operations &Maintenance, costs R0.54 (2%) and R0.36 (2%). The costs of feed production accounted for more than 70% of all the costs at the farm. The costs of feed also affected the costs of purchasing the pig at the abattoir. This amounts to R 26.00/FU and is responsible for more than 73% of the abattoir's costs.

Natural resources used to produce these raw materials are also a significant issue of concern for this study. Energy costs at the abattoir were the second-highest costs at R 1.98/FU (6%). Abattoirs have critical energy-using equipment such as refrigeration systems and cooling towers.

Table 1. Major Economic input of Pork Production

Subsystem	Operation	Cost (R/FU)	% of total subsystem cost	% of total pork production system cost
Farm	Maize	10.77	49	19
	Wheat bran	4.24	19	7
	Barley grain	1.56	7	3
	Rapeseed	0.63	3	1
	Soybean meal	1.24	6	2
	Electricity	0.54	2	1
	Operation and maintenance	0.36	2	1
	Local Fish	0.45	2	1
Abattoir	Purchasing pig	26.00	73	45
	Electricity	1.98	6	3
	Cleaning Products	0.97	3	2
	Water	0.74	2	1
	Packaging	0.87	2	1
	Natural Gas	0.87	2	2
	Operations and Maintenance	0.75	2	1
	Boiler	0.78	2	1
TOTAL		57.74	100	100

It is necessary to keep temperatures low at the facility to keep meat free from pathogen risks. As a result, electricity costs are incredibly high as more energy is required to run these systems. These were followed by the cleaning chemicals, which were at R 0.97 /FU (3%). Abattoirs need a thorough cleaning regime to mitigate the enormous risks associated with food safety. Therefore, chemicals are used to clean the surfaces to eliminate any potential for the growth of pathogens, viruses, and bacteria that might impact human life. Consequently, it 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 R0.87 /FU (2%) and R 0.78 /FU (2%), respectively. The use of natural gas was at a high cost of R 0.87 /FU (2%). Interestingly, the boiler's running at the abattoir also attracted R 0.78/FU (2%) costs by purchasing wastewater treatment chemicals. The O&M costs contributed R0.75 (2%). The Value-Added for the whole pork product system was determined to be R17, 16/FU.

Table *2* below shows the environmental performance of pork production at mid-point and end-point levels.

Table 2: Environmental characterisation indicators for the production-midpoint and endpoint values

Impact category	Unit	Total
Midpoint		
Non-renewable energy	MJ primary	36.5
Terrestrial ecotoxicity	kg 1,4-DCB	6.56
Land use	m2a 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}

Regarding environmental performances, the feed was recorded to be responsible for the highest environmental impacts in the overall pork production system. The environmental performance results show that the production of pork contributed 36.46 MJ of non-renewable energy use. The electricity needs contributed 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 other 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%).

The farm production system contributed 4.01 kg $CO_{2\text{-eq}}$ to the overall GWP score regarding climate change. The highest contributors were feed production (growing of maise, soya, wheat, and barley). The electricity usage and maise production were responsible for 20%, whereas the soya meal and wheat grain contributed 10%. 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 $CO_{2\text{-eq}}$.

For the abattoir contributions, electricity usage contributed around 68%, plastic packaging 28%, and coal usage at the boiler 7%. The electricity use 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 to 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 $SO_{2\text{-eq}}$. The electricity used at the abattoir contributed 88% of terrestrial acidification, with the packaging contributing less than 10%. 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 $N_{\text{-eq}}$ was attributed to the farm production subsystem. 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 m2a was required. The feed producing process was the most significant contributor to land use, with wheat (40%), maise (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% of water use, which shows that 0.365 m^3 was used in animal production, with maise responsible for 15%, wheat, 8%, and barley grain 2%. In terms of end-point results, the pork produced in South Africa contributed 9.63×10^{-6} DALY to human health impacts. The ecosystem diversity was 4.87×10^{-8} species. yr. and the resource availability impact were 0.18 USD2013.

For the human health environmental impact indicator, the pork meat production system eco-efficiency was 5.61×10^{-7} DALY/R, the ecosystem quality impact indicator was 2.84×10^{-9} species.yr./R and the resource availability was 1.05×10^{-2} USD 2013/R. The farm is credited for the most considerable environmental impacts, based on findings (solely because of on pork feed production process), for all impact categories evaluated in the assessment. These are primarily attributable to several products (grains, maise, barley, and soybean).

4 Discussion

The ISO 14045 framework was applied successfully in this research to quantify the baseline eco-efficiency of a South African pork production system from cradle to abattoir gate. 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 that the economic hotspots were both animal feed and the abattoir at the farm. There is extensive use of natural resources 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.

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.

Eco-efficiency assessment is a tool for the relative evaluation of different systems [2]; thus, these results could be used only as a reference point for the assessment of various suggested measures for eco-efficiency improvement or cross-comparison with the eco-efficiency of pork meat production system. As can be seen, these results are essential to the decision-makers in the pork meat industry. 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.

The eco-efficiency concept has some strengths and weaknesses associated with it. The strengths of the concept [18], are based on its potential to provide a clear operational action strategy for a policy on sustainable development, as well as a variety of indicators of its direction. The weakness of the concept is based on its multidisciplinary theoretic basis, the nature and uncertainties of environmental problems, and other measurement difficulties. This means that the eco-efficiency concept, though it falls under the industrial ecology concept, also uses economic thinking. In this study, it was difficult to get economic data as companies do not feel comfortable sharing sensitive information.

5 Conclusions

The methodology addressing eco-efficiency has enabled us to identify the primary areas of concern in pig processing's environmental and economic performance. According to the author's knowledge, this study is the first in South Africa to use for pork meat production. The research demonstrated that an assessment like this might enable pork farmers, and local government agencies, to introduce sustainable pork meat processing options. An appealing strategy could be to use eco-efficiency as a viable tool to compare the performances of various pork producers.

To ensure the competitive development of goods and services, balancing economic and environmental indicators is essential, and this research accomplished that. Another recommendation is that it could also be valuable to consider a socio-economic scenario for the same framework proposed within an eco-efficiency assessment. Considering the socio-economic strategy would allow for a complete assessment of the pork meat sector's sustainability by determining all pillars of sustainable development. The values of the calculated eco-efficiency indicators could serve as reference values in further research work and for decision-makers. As demonstrated in this study, the eco-efficiency framework developed helps accommodate an increasing requirement from society for industries to report on topics such as environment, climate, and societal costs.

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