Life Cycle Assessment Perspective for Sectoral Adaptation to Climate Change: Environmental Impact Assessment of Pig Production

Kennedy Ndue * and Goda Pál

Doctoral School of Regional and Business Administration Sciences, Széchenyi István University, 9026 Győr, Hungary; goda.pal@sze.hu
* Correspondence: mutua.kennedy.ndue@sze.hu

Abstract: Growing demand for sustainably driven production systems, especially pork, requires a holistic or system thinking approach. Life Cycle Thinking (LCT) offers a robust methodological background as one of the approaches to achieving system analysis for a product along its lifecycle. On the other hand, Life Cycle Assessment (LCA) can perform state-of-art system analysis characterising its sustainability fronts as a compelling set of tools. Pork, as the most consumed meat across Europe (circa 34 kg per capita per year), compounded with the sector’s contribution to global greenhouse gases (GHG) doubling over the past decade necessitated this research. Our objective was to map hotspots along the value chain and recommend the best available practices for realising the sectoral contribution to carbon neutrality and climate change adaptation. To achieve the objective, we compared organic and conventional production systems by basing our analysis on Recipe midpoint 2016 (H) V1.13 as implemented in OpenLCA 1.10.2 using AGRIBALYSE® 3.0 datasets for eleven indicators. We found that producing 1 kg of pig meat under an organic production system had almost double the environmental impact of conventional systems for land use, water consumption, acidification, and ecotoxicity. Feed production and manure management are the significant hotspots accounting for over 90% of environmental impacts associated with 1 kg pig meat Live-weight (LW) production. Similarly, efficient conventional systems were less harmful to the environment in per capita unit of production and land use compared with organic ones in ten out of the eleven impacts evaluated. Implementing increased efficiency, reduced use of inputs for feed production, and innovative manure management practices with technological potential were some of the best practices the research recommended to realise minimal impacts on the identified hotspots.

Keywords: life cycle assessment; pig production; environmental impact; sustainability; climate change; value chain

1. Introduction

Climate change remains on top of the 21st-century grand challenges list. Pig production is affected and associated with negative environmental impacts such as eutrophication, acidification, global warming, and land-use change. Several authors have investigated the effects of pork production and how to minimise them to ensure the sector remains resilient to climate change. Similarly, the desire to balance mitigation and adaptation efforts at the sectoral level has dominated discussion among stakeholders over the past decade. The dire situation has resulted in a clarion call for sectoral adoption of holistic approaches to address the problem [1,2]. The complexity of the challenge is exacerbated by the rapid-growing population exerting pressure on existing scarce resources [3]. Rapid population growth coupled with growth in income per capita has led to changes in dietary habits characterised by increased demand for animal-based protein, which researchers
have criticised for its negative contribution to the environment. One of the most demanded animal-based proteins globally, especially in Europe, is derived from pig products [4]. The conflicting interests of the sector create a complex relationship between pig production and environmental sustainability depicting an opaque future scenario for the sustainability of the sector.

The need to meet global demand for pork-based meat and its derivatives has caused production to experience rapid growth globally of 4.5 times between 1961 and 2021, from 24.8 to 109.2 Mt. Under the business-as-usual model, the Organization for Economic Cooperation and Development (OECD) projects the production to increase by 13% by 2030 in comparison with 2018–2020 levels reaching 173 Mt. Similarly, on average, global pig meat consumption between 2014 and 2017 was 117,354 kt and further projected to experience 13% growth by 2030 [5]. Although production between 2018 and 2020 declined due to the African Swine Fever (ASF) outbreak, post-covid recovery predicts a higher demand for meat that is more likely to increase production. As a result, the FAO 2020–2030 outlook highlights pig meat as the second most demanded meat after poultry, accounting for 34% of the total meat after poultry, accounting 41% [6–8].

Increased global meat production will result in a 5% increase in the emission of GHGs [9]. Low emission levels are attributed to increased adoption of innovative technologies, resulting in increased efficiency and production systems. Therefore, understanding the associated environmental impacts of the increased demand for pork and its derivatives becomes imperative. However, increased yield production as a subset of the ecological condition creates a highly complicated relationship between pig meat production and environmental conservation. Therefore, the rationale behind the emission intensity for each production unit must be tamed; otherwise, increased production would result in a proportionate GHG emission increase [10].

The production growth curve will vary across regions, with Europe expected to decline due to increasingly stringent environmental policies. As opposed to Europe, Asia, Russia, and Africa’s production is projected to grow upward to meet locally growing demand coupled with increased domestic policies supporting pig meat production locally to improve competitiveness across the sector. Furthermore, if not well regulated, the complexity associated with open markets could further shift the equation for Europe, leading to further production driven by the desire to exploit the new markets.

Globally, meat production is an essential element in agriculture. As of 2020, global pig meat stood at 109.2 million tonnes, equivalent to 33.3%. Livestock production, in general, accounts for approximately 18% of global GHGs emissions, which are a significant driver of climate change. Out of the 18% global GHG from the agricultural sector, pig production contributes approximately 11% [11].

Global pig production experienced an 8% decline during 2019–2020, as reported by FAO [7]. Although production declined, trade over the same period grew by 11%. The 2018–2019 ASF outbreak in Asia had a global impact on pig production, but the USA’s exports and Europe have risen to cover up the market. Although production decline has been prominent across Asia and the USA, FAO predicts a modest output growth in the EU, Russian Federation, UK, Brazil, and Canada. The fast-growing demand for the commodity in China has fuelled the change across the EU. Increased pig meat production to meet the market demand across the EU will cost the environment. Detecting the associated impacts forms a base for highlighting hotspots and strategies for dealing with and adapting to environmental problems [12,13].

At the continental level, FAO [7] estimated European pig meat production to grow from 29,711 Kt in 2019 to 29,987 Kt in 2020, with a remarkable decline in use from 26,281 to 26,142 Kt. The excess pig meat due to reduced utilisation increased exports from 3802 to 4176 Kt tonnes, equivalent to about 11%. The associated shift in regional consumption stabilities accelerates trade, leading to indirect land-use change if not well regulated. Indirect land-use change has been evident from increased demand for soy products for pig
feeds, resulting in forest conversion to create more land for feed production in developing countries.

The global pig sector’s total GHGs emissions intensity grew by 22% from 668 Mt CO2-eq in 2013 to 819 Mt CO2-eq and is likely to increase further by 5% by 2030 [6,9]. However, research by the Livestock Environmental Assessment Programme (LEAP) concluded that, on a per protein basis, pig meat is the second-lowest at 55 kg CO2-eq [9,14]. This scenario further ascertains that implementing good agricultural and environmental practices along the value chain could potentially reduce the product footprint.

Increasing the competitiveness and sustainability of the pig sector is a derivative of understanding the associated environmental impacts and how to reduce them. The main ecological challenges associated with pig production have been a heavy reliance on inputs for feed production, energy and water, increased production of methane, ammonia, and other emissions arising from poor manure management, storage, and waste management [4,15,16]. Over 60% of the associated environmental impacts conducted on pig production and the livestock sector, in general, are because of feed production. Thus, implementing GAECs for feed production can significantly reduce the sectoral environmental burden [17,18], necessitating a critical environmental assessment of the sector to develop its green growth or sustainability model. Averting the associated effects by ensuring production optimisation and shifting towards a greener pig sector will contribute immensely to the Farm to Fork strategy and the carbon neutrality under the EU Green Deal. An integrated approach requires identifying the hotspots/negative externalities associated with the sector and the possible adaptation pathways in Best Available Techniques (BATs).

One of the tools widely applied to analyse the environmental impacts of meat production is the Life Cycle Assessment (LCA). A tool that has been considered instrumental in holistically deciding per functional meat production unit and its associated environmental impacts. The tool has been considered important in assisting policymakers in decision-making and the development of carbon calculators for estimating environmental costs associated with meat production [11–13,15,16,19–22]. The main objective of this study is to detect the significant environmental impacts related to pig meat production. The study further aims at determining the best practices suitable and viable across the pork value chain to avert the associated environmental effects. The research applies the Life Cycle Assessment methodology to actualise the above objective, emphasising farm to gate levels and basing the environmental impact assessment using the OpenLCA 1.10.2 software and the open-access AGRIBALYSE® 3.0 database of the French Ministry of Agriculture. The analysis outcome compared existing pig LCA findings across literature comparing organic and conventional systems performance.

2. Materials and Methods

2.1. Life Cycle Assessment (LCA)

LCA methodology is a subset of the Life Cycle Thinking (LCT) philosophy [23], conceptualised in Figure 1 below. An example of a transdisciplinary approach grounded on multi-disciplines that have no specificity of boundaries. LCA is built on concepts including and not limited to system approach/system analysis, logic and mathematics, and the philosophy of science [15,20,22,24–27]. An integrated assessment methodology for assessing environmental burdens associated with the whole life cycle of any product as interpreted by Guinee et al. [24]. Therefore, we can refer to it as a tool that has the potential to offer a quantitative, manageable and verifiable modelling process for evaluating and understanding the complexity of the production process while highlighting innovative solutions and devising sustainable actions, as reported by FAO-LEAP [28]. They considered the tools’ usefulness as tripartite depending on the position along the value chain. First, it can allow pig producers to design and develop their on-farm resource inventories for assessing farm performance at the farm level. Second, the post farm level can help supply chain actors such as feed producers and processors become more aware of their
associated environmental burden. Third, beyond the value chain, it is viewed as a catalyst in implementing best practices by equipping policymakers with know-how on accounting, reporting and mitigation of environmental burdens [28].

![Figure 1](image)

**Figure 1.** Methodological diagram with both the concept and the steps for Life cycle Assessment applied in evaluating pig production; as addressed by the study: Authors constructed the image using Microsoft MS Office, free to use images and icons.

The International Standards of Organization (ISO) in ISO 14,040 on Environmental management interprets LCA as an iterative process of compiling and evaluating inputs, outputs, and the potential impacts of a product through its lifecycle [29,30]. Thus, in its simplest definition, it can be viewed as a tool for analysing the environmental burdens of any product in its lifecycle and determining possible pathways for reducing the burdens. Several descriptive terms can explain LCA, with the widely applied term “cradle to grave” analysis justifying its holistic nature. However, the tool is too complex to manage. It is characterised by a strong-intertwined network of challenges ranging from industrial, agricultural, household, and waste management activities from various parts and levels of the value chain, making it unique. Developing a model that can represent such interaction is complicated, thus necessitating the adoption of the simplicity principle.

The Joint Research Centre (JRC) presents three founding schools of thought that elaborate on how LCA methods are grounded [23]. Different approaches resulted in division among practitioners due to other results necessitating harmonisation. To reduce the criticisms and division between the three methods, in 1999, the ISO 14,042 standard on impact assessment was published. Despite the publication of ISO 14,042, conflict persisted, which led to the establishment of the Society of Environmental Toxicology and Chemistry (SETAC) [31].

To promote competitiveness and the sustainability of the agricultural sector across Europe, the European Parliament recommended to the Commission the adoption of an integrated life-cycle-oriented product policy. The potential LCA highly drives such policy holds as the basis for eco-labelling. Increased demand for the LCA tool across Europe is highly driven by its ability to facilitate avoiding trade-offs across the value chain. For
example, increasing the amount of protein content in the feed while improving the output per functional unit without increasing per-unit GHGs emissions. The EEA views LCA-based environmental management as part of a sustainable business model that has the potential for achieving the eco-efficiency concept along the value chain [22–24,32].

Although the first LCA was performed in the 1990s, the last decade has been characterised by renewed interest in LCA, resulting in different approaches. The lack of standard practice is evidence of the degree of independence in research using diverse ways to address sustainability. Furthermore, the life cycle of any product is a subset of an intertwined chain of resource extraction and substance emissions which varies in their environmental relevance. This necessitates the detection of the hotspots along the chain to ensure that any emission is addressed [33]. The ability to detect and immediately propose a plausible solution renders LCA a standalone approach for avoiding environmental burden shift along the pig value chain, bolstering its sustainability [32–34].

2.2. Methodological Design

The methodology applied was in line with ISO 14,040, which comprises the following steps as presented in Figure 1 above:

1. Goal and Scope Definition—We defined the objective, scope of the study, pork value chain system, functional units, and impact categories.
2. Inventory—We collected the relevant data for the relevant parts of the pork value chain.
3. Impact assessment—We analysed the environmental impacts of the different pig production systems.
4. Interpretation—We presented this step as the results and discussion.

2.2.1. Goal and Scope

The goal was to perform a life cycle sustainability assessment of pig production to map the associated environmental burdens (detecting hotspots) along the pork value chain. We aimed to compare the environmental impacts performance of both conventional and organic production systems per 1 kg of pork or 1000 ha of farmland to advise on improving the overall pork value chain sustainability. We focused on cradle to farm-gate as the primary system boundaries. Feed and farm inputs formed the base with system performance and management in consideration.

2.2.2. Life Cycle Inventory

We collected the Data for the LCI from two streams, with the first data set gathered from existing literature that addressed environmental performance for organic and conventional production systems starting from 2010 and computed in MS Excel to compare their performance. We further selected AGRIBALYSE® as the primary database for verification and compared existing studies calculated using OpenLCA 1.10.2 [35]. The AGRIBALYSE® 3.0 free, open access and compatibility with the latter features from the GreenDelta nexus repository [36] made it a standalone choice out of a pool of available databases.

2.2.3. Impact Assessment

The environmental impacts associated with pig production emanate from emissions arising from environmentally damaging compounds in the soil, water and air and the use of resources such as land and fossil resources. We based our analysis on Recipe midpoint 2016 (H) V1.13 as implemented in OpenLCA 1.10.2 Software [35]. Thus, we characterised the potential impacts of pig production based on the following six effects: We described global warming (KgCO₂-eq) as increased temperature due to the emission of greenhouse gases arising from the pork value chain [37]. We further described eutrophication (g PO₄-eq) as the continuous growth of biomass as a result of aquatic water systems pollution.
associated with the pig value chain, describing it by both Freshwater (FEP) and Marine water Eutrophication (MEP). Although production takes place on land, contamination of water bodies and increased pig production positively correlate [8]. This leads to the increased addition of harmful compounds into the soil due to high activities along the pig value chain described by Terrestrial Ecotoxicity [38]. Along the process, Resource depletion characterised competition for scarce resources depending on the production level. It can be in terms of land use (m² per year of crop equivalent), water consumption, and scarcity of mineral resources. In contrast, fossil resource depletion (kg oil eq), which reduces the number of available fossil resources, is described as the depletion of fossil resources [38]. Lastly, we evaluated acidification (g SO₂-eq), which changes or variations in pH values in the natural environment due to pig production, characterised as terrestrial Acidification [8,12].

Although most existing studies have focused on only Global warming, acidification and eutrophication [12,39,40], we further included ecotoxicity, fossil resource depletion and mineral resource scarcity. However, being an environmental assessment, the research excluded economic characterisation from the analysis [33].

3. Results and Discussion

The results are presented based on the different stages shown in Figure 1 to realise the research objective. Sequentially, the results and discussion start with inputs and feed impacts, followed by system production comparison, economic outcomes, and environmental and welfare of the pigs.

3.1. Inputs and Feed Production

Fewer studies have explicitly analysed pig feeds and feed inputs LCA, with three significant ones applying LCA to the traceability of feed additives (Table 1). They modelled the impacts of introducing protein feed supplements at different ratios and creating scenarios expressing the outcome per kg live swine weight. Some of the scenarios that have been developed so far reference Crude Protein content and the effects of introducing additives at varying quantities to the primary feed. Optimal performance concerning the environment from different impacts is a function of combining multiple additives. Still, the main challenge is finding an effective feed simulation that is cost-effective and has fewer negative impacts on the pigs’ welfare. For example, introducing Xylanase, 5% Benzoic, 10% benzoic, and a combination of the three compared with a feed without phytase additives [41–43] gives different outcomes, with the modest achieved when all are combined. Although it does not hold across all impacts.

Table 1. Effects of using feed additives on pig diet to reduce negative environmental impacts: data adapted from [41–43].

| Impact Category                        | Unit                  | Without Phytase | Xylanase | Benzoic Acid (5*) | Benzoic Acid (10*) | All     |
|----------------------------------------|-----------------------|-----------------|----------|-------------------|-------------------|---------|
| Climate change Excl. LUC               | kg CO₂ eq             | 0.9%            | −1.0%    | −0.7%             | 0.9%              | −0.1%   |
| Climate change                         | kg CO₂ eq             | 1.9%            | −0.2%    | −1.2%             | −0.1%             | −0.3%   |
| Acidification                          | mol H⁺ eq             | 1.1%            | 0.0%     | −8.0%             | −12.6%            | −12.7%  |
| Eutrophication freshwater             | kg P eq               | 5.4%            | 1.6%     | −1.8%             | −1.2%             | 0.4%    |
| Eutrophication marine                  | kg N eq               | −0.1%           | −2.3%    | −2.8%             | −3.1%             | −5.4%   |
| Eutrophication terrestrial             | mol N eq              | 0.7%            | 0.0%     | −8.1%             | −12.7%            | −12.8%  |
| Ecotoxicity freshwater                 | CTUe                  | 0.4%            | 1.4%     | −2.3%             | −2.3%             | −0.9%   |
| Land use                               | Pt                    | 0.4%            | −1.1%    | −2.4%             | −2.4%             | −3.5%   |
| Water scarcity                         | m³ deprived.          | 14.0%           | 2.4%     | −1.9%             | −1.4%             | 2.5%    |
| Resource, Energy Carriers              | MJ                    | 2.0%            | −1.3%    | 0.7%              | 3.8%              | 2.4%    |
| Resource use, minerals, and metals     | kg Sb eq              | 93.4%           | 1.1%     | −0.5%             | 1.3%              | −0.8%   |

5* = 5000 mg/kg DM feed intake dose, 10* = 10,000 mg/kg DM feed intake dose.
Emission reduction performance varied significantly for feed without additives compared to those with additives. The performance was modest with the introduction of xylanase additive with further reduction when combined with more additives [41]. FAO LEAP [28] in determining a typical Dutch and Belgian intensive pig farm, the carbon footprint reported 4.08 kg CO₂ eq/kg LW under the baseline scenario. They identified feed production as the primary intervention area responsible for approximately 60.1%. Excluding land-use change reduced the associated carbon footprint to 2.85 kg CO₂ eq/kg LW, with land-use change accounting for about 30%. The impact of the land-use change was attributed to the increasing demand for soybean products originating from South America, which has been highly associated with forest resource depletion to produce more feed.

In ascertaining the role played by feeds on pig supply chain GHGs, Reckmann et al. [44] assessed environmental footprint variation with changing feed components, protein type, and source in German. They calculated the impacts of global warming, eutrophication potential, and land-use change. They found that substituting the standard diets (derived from soybeans) with synthetic amino acid diets had a high potential to reduce the environmental impacts under investigation. Substituting imported inputs with locally grown legumes such as the fava beans could significantly minimise the environmental impacts, especially global warming and land use. However, in France, when amino acids were incorporated into the conventional pig feed systems, it positively reduced the effects associated with climate change, eutrophication and acidification. Based on the then practices, they recommended applying and using amino acids in the feed, such as tryptophan and valine, which could reduce climate change, eutrophication, and acidification by 1.3%, 12.5%, and 17.8%, respectively. Although reductions correlated to the production stage, feed production, housing, and manure management, substituting soybean meal with cereals and feed use acids led to a further decrease in nitrogen excretion, nitrous oxides, and ammonia by Nguyen et al. [20]. Adopting multiphase feeding can attain optimal reductions [13,20,22,45].

Monteiro et al. [42] evaluated the effectiveness of using different feed formulations to reduce the environmental impacts associated with pig production. They evaluated nine case studies where the feeds contained between 120 and 180 g/1 kg of Crude Protein (CP). They reported a negative correlation between CP level and GWP where the higher the CP, the lower the GWP was reported ranging from 1.39 when pea was used as the main feed to 3.25 under conventional feeds. There was a remarkable reduction in AP, ranging from 2 to 9% [43]. Based on their findings, we can conclude that farming is the main hotspot across the value chain, accounting for more than 90% of the three impact factors assessed.

As farming is broad, feed production dominates their interpretation, thus recommending careful feed choice selection to ensure the associated burdens are reduced [20,46,47]. Since most impacts from feed production arise from inputs and processing of the feed, increasing efficiency along the pig feed supply chain has the potential to mitigate the effects further. Evidence on adopting efficiency and its impact on environmental trade-offs across the Irish pig production systems as evaluated by Mc Auliffe et al. [4] shows that those systems where higher efficiency is implemented are more likely to reduce their GWP, EP, and AP by 6%, 15% and 12%, respectively [4,32,34,38].

3.2. System Performance

Across all the eleven evaluated environmental impacts, conventional systems were modest in ten impacts compared to organic production systems. Out of the ten impacts where conventional systems outperformed organic ones, their contribution was almost half that of organic systems (Table 2 and Figure 2). In Figure 2, we created a comparative system with a common unit to compare which system performed better than the other.
Figure 2. Pig meat environmental impact per unit production (kg) across organic, Label Rouge and Conventional systems relative performance and hotspot map identification map: Data obtained from AGRIBALYSE® database and computed using OpenLCA 1.10.2 [35,36].

Table 2. Pig meat environmental impact per unit production (kg) across organic, Label Rouge and Conventional systems: Data obtained from AGRIBALYSE® database and computed using OpenLCA 1.10.2 [35,36].

|                                | Conventional | Organic     | Label Rouge (Outdoor) | Label Rouge (Run Systems) |
|--------------------------------|--------------|-------------|-----------------------|---------------------------|
| Fossil resource scarcity (kg oil eq) | 0.178        | 0.272       | 0.185                 | 0.207                     |
| Freshwater ecotoxicity (kg 1,4-DCB) | 0.026        | 0.033       | 0.023                 | 0.024                     |
| Freshwater eutrophication (kg P eq)    | 0.000        | 0.001       | 0.000                 | 0.000                     |
| Global warming (kg CO₂ eq)            | 2.462        | 4.272       | 2.412                 | 3.343                     |
| Land use (m² a crop eq)              | 3.303        | 10.267      | 5.083                 | 3.637                     |
| Marine ecotoxicity (kg 1,4-DCB)      | 0.034        | 0.048       | 0.031                 | 0.033                     |
| Marine eutrophication (kg N eq)       | 0.003        | 0.010       | 0.005                 | 0.003                     |
| Mineral resource scarcity (kg Cu eq)  | 0.018        | 0.015       | 0.019                 | 0.018                     |
| Terrestrial acidification (kg SO₂ eq) | 0.038        | 0.079       | 0.057                 | 0.046                     |
| Terrestrial ecotoxicity (kg 1,4-DCB)  | 2.913        | 4.216       | 3.068                 | 3.117                     |
| Water consumption (litres)            | 45.253       | 87.692      | 35.628                | 34.441                    |

The results further show that organic pig production systems consume more water, with approximately 88 L. of water in organic systems required to produce one kg of pig meat as compared to efficient conventional (Label Rouge which consumed 34.5 L). On average, the water requirement for conventional systems where efficiency has not been implemented was 45.25 L (Figure 3). The outdoor nature of organic systems explains the difference in resource consumption compared to conventional systems, which are dominated by electronic feeder systems where precision watering and feeding are prioritised.
Precise watering and feeding could further reduce emission levels of GHGs, which explains the modest performance of Label Rouge (Outdoor) systems in global warming Figure 4.

**Figure 3.** Water consumption per 1 kg Pig meat across organic, Label Rouge and Conventional systems: Data obtained from AGRIBALYSE® database and computed using OpenLCA 1.10.2 [35,36].

**Figure 4.** Global warming per 1 kg Pig meat across organic, Label Rouge and Conventional systems: Data obtained from AGRIBALYSE® database and computed using OpenLCA 1.10.2 [35,36].

We further found that organic systems contributed almost twice to terrestrial ecotoxicity, terrestrial acidification and land use compared to conventional systems as presented in (Figures 5–7).
The Label Rouge (national standard outdoor system) had the best performance across all the indicators compared to the organic system. The performance can be attributed to increased efficiency and resource utilisation across the conventional system. The results
show that conventional systems require almost one-third of the land needed by organic systems to produce one kg of pork, with GWP potential half that of the organic system across France.

Several research studies (Table 3) have been conducted across Europe. Unlike our analysis, most have evaluated only three impacts (GWP, AP and EP). These studies have pointed out farming, where feed production is a primary hotspot across the pork value chain. Although the studies were conducted in different regions, Table 3 compares our analysis with existing findings, and it was observed that a declining trend over time is remarkable across the studies. This demonstrates how systems strive to reduce their unit-associated impacts over time. The declining trend across Europe, in general, is highly contributed by increased technological adoption across the sector coupled with increased awareness of environmental importance under the CAP 2014–2020.

Table 3. Pig meat production environmental impact per unit of production (kg) system performance across conventional systems in our study’s research. Data for analysis obtained from [4,8,22,28,31,33,39,48–50].

| Study                          | Fossil Resource Scarcity (kg Oil eq) | Freshwater Eutrophication (kg P eq) | Global Warming (kg CO2 eq) | Land Use (m2 a crop eq) | Marine Eutrophication (kg N eq) | Terrestrial Acidification (kg SO2 eq) |
|-------------------------------|-------------------------------------|------------------------------------|----------------------------|------------------------|-------------------------------|-------------------------------------|
| Present article (2022)        | 0.178                               | 0.003                              | 2.462                      | 3.303                  | 0.003                         | 0.046                               |
| Zira et al., 2021             | 1.3                                 | n/a                                | 7.1                        | n/a                    | 0.11                          | 0.2                                 |
| Nguyen et al., 2011, 2019     | n/a                                 | n/a                                | 2.95                       | 5.5                    | 0.2315                        | 0.0585                              |
| Sandrucci et al., 2017        | 0.0235                              | 0.025                              | 4.7                        | n/a                    | n/a                           | 0.0285                              |
| McAuliffe et al., 2017        | n/a                                 | n/a                                | 3.5                        | n/a                    | 0.321                         | 0.445                               |
| Alexandra and Morten (2016)   | n/a                                 | n/a                                | 3.94                       | n/a                    | 0.34                          | n/a                                 |
| Noya et al., 2016             | 0.0125                              | 0.0002                             | 3.42                       | 4.96                   | 0.05                          | 0.186                               |
| Winker et al., 2016           | n/a                                 | 0.364                              | 4.751                      | n/a                    | n/a                           | 0.006                               |
| Dourmad et al., 2014          | 0.01622                             | 0.019                              | 2.251                      | 4.127                  | n/a                           | 0.044                               |
| Espagnol and Demartini (2014) | 0.0162                              | 0.044                              | 2.25                       | 4.13                   | n/a                           | 0.019                               |
| Reckmann et al., 2013         | 0.0195                              | 0.0233                             | 3.22                       | n/a                    | n/a                           | 0.0571                              |
| Dolman et al., 2009           | 0.001995                            | n/a                                | 5.3                        | 9.37                   | 0.859                         | 0.093                               |

Based on the results, it was evident that efficient conventional pig production systems are more likely to have less carbon footprint than organic ones, with ten out of the eleven evaluated impacts for conventional outperforming organic systems. Similar findings are reported by Zira et al. [8] in their environmental assessment of pork organic and conventional value chains in Sweden. Their research based on two functional units (product and area) found that organic pork production outperformed the conventional system in eleven out of 20 and 18 per unit area indicators. They further found that the organic systems were likely to be less sustainable per unit product due to their less efficient nature due to the high feed requirement per kg of pork produced in organic systems. Although conventional systems tend to be more efficient in most instances, increased use of
chemicals coupled with higher welfare cost per pig to a greater extent contributed significantly to the differences. This further explains why organic systems had fewer impacts on ecotoxicity and eutrophication while for GWP, land use and resource utilisation were almost double.

In our analysis, the outcome of efficiency is represented by the Label Rouge, which represents the national defined standard practices in both indoor and outdoor systems. These systems’ performance was even better than conventional ones, where efficiency is not factored in but variation across the impacts is evident (Figures 3–7).

Organic systems only outperformed conventional systems in mineral scarcity as organic systems are less reliant on minerals as compared to conventional systems (Figure 8).

![Figure 8. Mineral resource scarcity per 1 kg Pig meat produced in different systems (kg Cu eq)](image)

3.3. Managerial Aspects across the Value Chain and their Associated Impacts

Farm management plays a pivotal role in managing systems’ environmental impacts, forming an intersection between crucial actors and policymakers to innovate actions to reduce associated burdens. All factors held constant; in most instances, there is a higher likelihood of higher returns and better environmental farm performance in well-managed farms. However, the returns come at a cost to the environment, with an inverse relationship between economic and environmental performance more likely to be the case, as is the situation across European farms. Considering the Netherlands makes it more likely to realise that the higher the Gross Value Added (GVA) a farm records, the lower its acidification and eutrophication potential. This analogy presents the best case of how efficiency across the value chain reduces environmental burdens while increasing farm output. However, the Dutch case study values were higher with a GWP of 5.3 kg CO$_2$ eq, EP of 89.9 kg NO$_3$ eq per 100 kg of slaughter weight, and AP of 9.3 kg SO$_2$ eq per 100 kg SW. They recommended the reduction in input costs as a strategy for increasing the farm outcome. The use of other feeds on the farm as an alternative could further reduce the negative impacts [48].

Dolman et al. [48] investigated the relationship between the Dutch economic and LCA indicators for fattening pigs. They applied FADN representative farms data to analyse the relationship between GVA and environmental indicators (land occupation, non-renewable energy use, GWP, EP, and AP) from a cradle-to-farm-gate perspective per 100 kg slaughter weight. They reported that the obtained results varied based on the methodology applied and concluded that there existed a negative correlation between farm performance and both eutrophication and acidification potential. This implies that low AP and EP characterise those farms with high income. The negative correlation is more likely to be caused by high efficiency in input consumption. They also recommended including
other feeds besides the dry feed in the feeding basket as a more likely possibility for reducing emissions and optimisation of the associated cost.

Hörtenhuber et al. [11] evaluated the effect of induced changes in temperature and humidity on the performance and environmental impacts of pig systems in Austria. They modelled an Austrian pig site under different temperature-humidity scenarios and found no significant differences for kg CO$_2$ eq per kg body mass. Under the four scenarios modelled, the GWP was 3.64 for a cold year and 3.69 kg CO$_2$ eq per kg body mass. Under future hot and cold scenarios, they found a higher likelihood of GWP changing to 3.71 and 3.74, respectively. This shows that even under changing climatic conditions, especially temperature and humidity, the PEF might not significantly change. This remains a crucial part as the sector grapples with variation in weather due to climate change. They recommended that total modification of pig housing systems may not be a prerequisite but adapting technical conditions to reduce the season’s impacts would be appropriate. They further highlighted the importance of ensuring good animal welfare is attained to minimise the consumption capacity of the pig and efficient resource use to reduce the impacts associated with the system [11,51,52].

Food loss and food waste management are critical managerial components today. In different parts of the world, pigs have been fed with farm waste, raising controversy about pig welfare and environmental sustainability. Heller [53], evaluating the performance of growing pigs in the US, reported that they account for 69% of the total GHG. Out of the 69%, feeding and breeding were the significant contributors accounting for 39%. They associated feed production with 27% of the cradle to grave GHGs, 96% of land occupation, and 83–86% of water use [53,54]. Although they highlighted recycled food waste (swill) as a management strategy to reduce the associated GHGs by 24%, stringent health and welfare of animal regulations limits this practice, especially in Europe, where the use of swill to feed pigs is illegal. This raises the question of health and environmental protection friction necessitating the importance of pig Social Life Cycle Assessment [55].

The adoption and implementation of efficiency along the value chain have widely been recognised as a strategy to mitigate environmental impacts. In evaluating the Danish pig production system due to the adoption of increased technological efficiency, Nguyen et al. [22] assess the environmental performance of farms using both attributional and consequential approaches by comparing the performance of conventional farms to that of 25% of highly efficient farms. They analysed GWP, AP, EP, non-renewable energy, and land use, applying both approaches reporting that GWP for a typical Danish pig farm in 2010 was 3.1–3.4 kg CO2eq while for the 25% efficient farms were between 2.9 and 3.3 kg CO$_2$ eq. The GWP contribution by the source was to a greater extent contributed by feed and on-farm emissions, accounting for 61% and 29%, respectively. As a result of high emissions from feed production, the EP was reported as 185 g NO$_3$ e per kg of pig meat produced at farms. The remaining 9–10% of GWP were from transportation and energy use. They further reported that methane from enteric fermentation is a more significant challenge accounting for more than three-quarters of the CH$_4$ and N$_2$O emissions. In terms of land use, it was reported that to produce 1kg of pig meat in Denmark, one needs 6.0–6.5 m$^2$ per year. Increased on-farm ammonia concentrations were also reported as the main contributors toward acidification potential, with AP of 38.2 to 46.3 g SO$_2$ eq per kg pig meat live weight [4,22].

Housing conditions under which pigs are raised contribute immensely to the environment. Research on environmental performance under different housing conditions with GWP ranging from 2.1–4.5 kg CO$_2$-eq/kg LW was reported by Wiedeman, McGahan and Murphy [19]. Emissions were highest from those piggeries housed in conventional housing systems characterised by open effluent ponds. It was lowest in those piggeries that housed the grower to finisher pigs on deep litter. Littering had an ameliorating effect and reduced the exposure of the effluent to the atmosphere reducing ammonia. Emissions from those farms with on-farm feed production and those that relied on locally developed feeds were
33% lower emissions than those that imported soybean meal [56]. They also found that those farms that used their manure effluent to feed their biogas digesters and heat generation reduced their GHG emissions by 33–70%. This shows how increasing the use of renewable energy from biogas derived from pig manure could reduce the associated GHGs in a farm and ensure a steady supply of cheap and clean energy. The major environmental hotspots along the Australian pork value chain were manure management contributing to approximately 50%, feed production (27%), and the rest from the other parts of the supply chain [5,15,19].

Bandekar et al. [57] evaluated the impact of alternative management strategies, i.e., the use of gestation pens versus individual stalls, on greenhouse gas (GHG) emissions, cumulative energy demand, and cumulative water consumption in the US pig industry by applying Life Cycle Assessment (LCA) methodology. They observed lower GHG emissions, and energy and water use for pens. They concluded that the use of group gestation pens rather than individual stalls resulted in a decrease in the global warming potential (GWP) and energy and water consumption. Further reductions were observed for CH4 emissions by 2.9% and N2O emissions by 2.1%. In addition, the use of gestation pens reduced overall feed consumption by 1.92%, or 37,758 kg of feed a year for a herd of 500 sows; however, due to the space requirements for sows in stalls compared to pens, the barn infrastructure requirements for pens are 65% larger. This additional infrastructure requirement increases the GWP, which, amortised over an expected 10-year life of the barn, partially offsets the lower operational GWP.

Stern et al. [58] used LCA to compare three Swedish scenarios. One focused on animal welfare and natural behaviour of the animals (sows and piglets housed outdoors with huts), the second targeted low impacts on the environment and efficient use of natural resources, and the third scenario aimed at product quality and safety. Both economic and environmental impacts were taken into account. Production costs per kg of meat produced were higher in the animal welfare scenario compared to the environmental (0.37 USD/kg) and product quality scenario (0.42 USD/kg). This was mainly attributable to higher labour costs. The environmentally friendly scenario had the lowest energy consumption, global warming potential, land use, and surplus nutrients calculated per kilogram of meat produced. The animal welfare scenario was intermediate except for land use. Building costs and labour had the highest economic impact in all three scenarios. The highest environmental impact in all three systems was generated by the pig feed production, not by factors related to housing. The majority of existing studies have compared environmental sustainability between different housing systems, ranging from conventional to organic systems, where differences in environmental sustainability are limited.

The nature and purpose determined by the raised breed and genetics of the animal affect its contribution to the environment Sandrucci et al. [4] conducted an LCA of heavy pigs at the farm to evaluate the environmental impacts of heavyweight pigs reared for producing Consortia Ham. Heavyweight pigs are highly associated with high environmental impacts due to their higher consumption than lightweight pigs. The heavyweight pig in the farms’ studied, on average, were 168 ± 33 kg for nine months. They found that the environmental impacts of heavyweight pigs are higher than those of lighter weight. They reported a GWP of 4.25 ± 1.03 kg CO2 eq/kg Liveweight. Compared to 4.42 kg CO2 eq/kg live weight for lightweight pigs in Galicia [12,13,39].

Similarly, feed production, both on-farm and bought feeds, was reported as the main hotspot across the Italian pork value chain despite the nature of the system. They further found out that there existed a negative correlation between the farm size, reproductive efficiency, and environmental factors. These findings ascertain the importance of increasing efficiency across the value chain.

4. Conclusions

Agricultural sectoral missions are not decreasing despite increased efforts in mitigating and adapting to Climate Change. As the widely consumed meat across the EU, pig
meat has resulted in growth in sectoral GHG emissions, necessitating a re-evaluation of the production methods. A total of 87% of the associated pig emissions arise from manure storage and management, while 13% are associated with feed production. Implementing the best GAECs and BATs to reach the sector emissions reduction targets concerning carbon neutrality ideals and the farm to fork strategy becomes inevitable. Attaining these ideals requires mapping the hotspots along with the pig production systems. The study identifies feeding and manure management has been identified as the main hotspots and recommends the need to adopt additional measures to reduce the emissions. Under the With added Measures (WAM) pathway, most member states are optimistic about attaining Carbon neutrality by 2050. Although the WAM Scenario is still a puzzle to policymakers and the broader scientific community, embracing increased technological adoption, circularity, and efficiency across the systems while incorporating sustainable rural development programs offers resilient pathways to reach the future for rural Europe. The greatest challenge is how to evaluate the implementation of these measures across the system.

Adopting and going by the above LCA findings, it is evident that efficient conventional pig systems are even more environmentally friendly and economically viable than organic systems. Adopting the use and application of LCA as a tool for evaluating sustainability and adaptation to climate change across pig production systems will ease performance comparison across the different adopted measures and the technological possibilities. Implementing the use of the tool will set up a pathway and an arena to ensure a resilient path to reduce per capita emissions while making the right policy direction for marketing and achieving the goals of Carbon Neutrality. However, LCA adoption and implementation along the value chain alone is not enough as policy and knowledge transfer calls for the target stakeholders and audience to ensure the smooth performance of the recommended GAECs. Therefore, a stronger drive for science-policy driven measures and advocating for preliminary stages of the LCA formulation to be driven by a holistic definition of the goal to be reached.

Attaining such a platform, especially on sectoral adaptation to climate change, prioritising strong policy-stakeholder linkages and establishments must address the harmonisation of different policies to create an enabling environment. From a futuristic perspective, the growing animal sustainability issues increased animal welfare, and the economic viability of perceived pig production systems presents a grey area for further research. Determining a middle ground for pig welfare, farm income, and environmental protection is still the critical point for striking balance across the sector.

Increasing competitiveness and sustainability of the venture to increase its adoption is a subset of economic quantification that can be achieved through a combination of Life Cycle Costing, Social Life Cycle Assessment, and Life Cycle Impact Assessment to offer a novel system approach. Combining such complex methodologies is not easy and calls for a transdisciplinary approach to producing a novel method. Furthermore, the approach must be designed in such a way that prioritises simplicity to address complexity. One criticism of LCA has been complexity, which has hindered figuring out the benefits associated with climate change adaptation to policymakers. Research has proven that the numbers do not matter, but how these numbers are derived and interpreted should matter. Therefore, adopting simplicity in methodological development and design for policymakers to give the best policy advice remains imperative.

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