Evaluating Sustainability in Pork Production

Zur Erlangung des akademischen Grades eines

Doktors der Ingenieurwissenschaften
(Dr.-Ing.)

von der KIT-Fakultät für Wirtschaftswissenschaften
des Karlsruher Instituts für Technologie (KIT)

genehmigte

Dissertation

von

Nina Treml, M.Sc.

Tag der mündlichen Prüfung:	14.04.2026
Referent:	Prof. Dr. Frank Schultmann
Korreferent:	Prof. Dr. Simon Glöser-Chahoud

Acknowledgements

As we know, the only part of this document that receives the attention it deserves, given its scope and ambition, is the *Acknowledgements* section. Therefore, I would like to use this opportunity to take a step back and remind everyone that holistic sustainability affects not only nature, but also our lives in terms of how we treat each other and respect our environment. Now, it's time for the real acknowledgements.

I would first like to thank my colleagues and friends at the IIP. Your constant availability for discussions, problem-solving, and new perspectives greatly enriched my work. Thank you, Thorben, Max, Paul, Alex, Elias, Flo and Joris, for broadening my horizon with your valuable insights and for putting up with the jokes at your expense. Very important were the people who became close friends during this formative phase of my life. Thank you, Uwe, for your unwavering support, especially during difficult times. I was particularly grateful to pursue my dissertation in a group largely consisting of women. Special thanks go to Sandra for her openness and willingness to share knowledge, and to Sonja, who was always there with a helping hand whenever questions arose. I would also like to thank Simon for offering me this opportunity and for being a motivating group leader who kept spirits high—even during the challenging period of starting at the institute in full home office—and for serving on the examination committee of this dissertation.

My thanks also go to Prof. Schultmann, my doctoral supervisor, for his continuous support as well as for granting me considerable freedom in conducting my research, project work, and teaching activities. Of course, I would like to thank Prof. Dr. Kay Mitusch and Prof. Dr. Martin Klarmann for reviewing my dissertation and participating on the examination committee.

Beyond the institute, within the KIT environment, I would like to acknowledge Steven. It was a pleasure collaborating with you on the protein comparison paper that forms part of this dissertation.

A significant part of my life during these years was shaped by handball. My team and the sport itself have been essential sources of strength, balance, and resilience, helping me through both highs and lows. A special thank you goes to my team and to the love of the game.

My deepest thanks go to my closest friends: Marlene (Kindy 1), Regina, Julia, Philipp, Chris, Jonas, Matti, Hannah, Jens, Moritz, Flo, Britta, Rebecca, Laura, and Shirin. I am equally grateful to my family—my parents, my brother Niklas, Ines, Renate, Felix and Paul, Beppo, and Angelika—for their constant support and encouragement.

I would like to conclude these acknowledgements with a touch of humor, inspired by the wise words of Snoop Dogg:

“Last but not least - I wanna thank me.
I wanna thank me - for believing in me.
I wanna thank me - for doin’ all this hard work.
I wanna thank me - for having no days off.”

Abstract

The transformation toward sustainable food systems requires a comprehensive understanding of the environmental, economic, social, and ethical implications of livestock production. Pork, as one of the most consumed meats globally, exerts significant environmental pressures through greenhouse gas emissions, nutrient losses, and land use. Conventional life cycle assessment provides a robust framework for quantifying environmental impacts but fails to capture economic viability, social consequences, and animal welfare—dimensions essential for holistic sustainability assessment. This dissertation addresses these gaps by developing and applying integrative methods for evaluating and optimizing sustainability in the pork value chain.

The basis builds an environmental life cycle assessment of seven German case studies conducted to identify hotspots across farming, slaughtering, and processing stages (Paper A). Results confirm feed production as the dominant contributor to global warming, acidification, and eutrophication, while slaughtering and processing impacts are primarily driven by energy use and waste treatment. Scenario analyses reveal that targeted interventions, such as feed optimization and renewable energy integration, can substantially reduce burdens. Extending environmental considerations, animal welfare is introduced as a quantifiable sustainability dimension (Paper B). Using the analytic hierarchy process, expert judgments are employed to weight pre-selected animal welfare indicators, enabling the creation of an aggregated impact category for integration into life cycle assessment. The findings highlight the importance of animal-centered indicators, such as animal losses and fitness condition, for reliable animal welfare assessment. Merging all sustainability dimensions, a multi-objective optimization model is developed to simultaneously address environmental, economic, social, and animal welfare objectives within a pork supply chain network (Paper C). The model generates Pareto-efficient configurations, revealing synergies between economic, environmental and animal welfare improvements and trade-offs with social objectives such as affordability and employment. Complementing these analyses, an evaluation is performed that encompasses a consideration of a possible substitution in terms of protein delivery (Paper D). A comparative life cycle assessment evaluates pork against microbial protein as an alternative protein source. Results indicate that mycoprotein significantly reduces land and water use but entails higher energy demand, underscoring the potential for future improvements through low-impact feedstocks and renewable energy integration.

Overall, this dissertation advances sustainability assessment by integrating animal welfare as a quantifiable dimension into established frameworks and coupling them with optimization-based decision support. Through the integration of environmental, economic, social, and ethical aspects within a unified model, the research moves beyond descriptive assessments toward actionable, preference-sensitive solutions. These innovations enable a more holistic evaluation of livestock systems and provide a foundation for strategic decision-making that aligns sustainability objectives across stakeholders. Furthermore, the comparative analysis of pork and microbial protein highlights forward-looking opportunities for diversifying protein supply chains, underscoring the potential and the challenges for transformative developments beyond traditional livestock production.

List of included articles

1. Treml N, Rudi A, Schultmann F (2025b) Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany. Journal of Cleaner Production 503(145408). https://doi.org/10.1016/j.jclepro.2025.145408.

2. Treml N, Naber E, Schultmann F (2025a) Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming. Sustainability 17(10):4677. https://doi.org/10.3390/su17104677.

3. Treml N, Rudi A, Schultmann F (2026b) Assessing sustainability in the pork value chain: A multi-objective approach. *Submitted to a Scientific Journal*.

4. Treml N, Minden S, Grünberger A, Volk R, Rudi A, Schultmann F, Kaster A (2026a) Meat versus microbial protein—a life cycle assessment of present-day value chains. The International Journal of Life Cycle Assessment 31(5):65. https://doi.org/10.1007/s11367-026-02637-w.

Table of contents

List of figures

List of tables

List of abbreviations

AHP	Analytic hierarchy process
AW	Animal welfare
FU	Functional unit
GHG	Greenhouse gas
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
MADM	Multi-attribute decision making
MCDA	Multi-criteria decision analysis
MODM	Multi-objective decision making
MOO	Multi-objective optimization
MP	Microbial protein
SLCA	Social life cycle assessment

Part I
Overview

1 Introduction

In 2024, the agricultural sector accounts for more than 8% of Germany's total greenhouse gas (GHG) emissions, representing a reduction of 27% compared to 1990 (Umweltbundesamt 2024). Despite this progress, agriculture remains the sector with the lowest relative decline in emissions, whereas energy-related emissions have decreased by more than half during the same period. As food production is indispensable to human survival, the transformation of agriculture toward environmental sustainability represents a central societal challenge.

Within this sector, livestock production occupies a particularly critical position due to its complex environmental, social, and economic implications. Globally, animal-based foods—particularly meat products from pork and beef—exert disproportionately high pressures on the environment compared to plant-based commodities (Halpern et al. 2022). Pig meat ranks among the most environmentally burdensome food types, contributing significantly to GHG emissions, nutrient discharges, land use, and water demand. Life cycle assessment (LCA) provides a well-established methodological framework to quantify such environmental impacts across all stages of production. However, conventional LCA focuses exclusively on environmental dimensions and does not account for the economic viability, social implications, or animal welfare (AW) aspects that are essential to a holistic understanding of sustainability.

In recent years, the concept of Life cycle sustainability assessment (LCSA) has expanded LCA to include economic and social dimensions, offering a broader view of product and process sustainability. Nevertheless, LCSA applications in livestock systems often remain descriptive, focusing on comparative assessments of farming systems without providing decision-support mechanisms for system optimization. Furthermore, AW—although an increasingly central ethical and societal concern—has rarely been integrated quantitatively within LCSA frameworks. The trade-offs among environmental, economic, social, and AW objectives in livestock production therefore remain poorly understood. While organic systems tend to perform better in AW-related and social indicators, they often exhibit higher environmental impacts and lower economic profitability due to lower productivity and longer rearing times. These interactions illustrate the inherent complexity of achieving sustainability in livestock production and underscore the need for methods that can evaluate and optimize such trade-offs across multiple dimensions.

The evaluation presented in this thesis represents a first and essential step toward transforming livestock production systems. Identifying environmental, economic, social, and AW hotspots is a prerequisite for designing targeted mitigation strategies that address the most critical leverage points across the value chain. Without such knowledge, sustainability measures risk missing their intended effects. A comprehensive understanding of where and how impacts arise enables more efficient use of resources and guides policy and management actions toward the areas with the highest potential for improvement. The transformation of the livestock sector must ultimately aim for a more sustainable use of natural resources and a better life for animals, workers, and society as a whole. Livestock production affects everyone—directly through food consumption and employment, and indirectly through its global resource dependencies. For instance, the import of soy-based feed from South America contributes substantially to deforestation, biodiversity loss, and GHG emissions, thereby pushing several planetary boundaries beyond safe operating limits. Similar linkages can be observed in nutrient cycles, water use, and land degradation, illustrating the global interconnectedness of local production systems. Addressing these challenges requires not only improved efficiency but also structural changes in production and consumption patterns. By providing a detailed assessment framework and integrative modeling approaches, this thesis contributes to understanding these interdependencies and lays the groundwork for transformative change in the livestock sector for the case of pork.

To date, existing optimization models in agricultural sustainability considering meat production have primarily addressed economic efficiency and GHG emissions, thereby neglecting the broader range of sustainability criteria. Integrated models that capture the full spectrum of environmental, social, economic, and AW dimensions are largely missing. Bridging this gap requires both methodological innovation and empirical grounding in real-world production data to ensure that optimization reflects realistic sustainability constraints and opportunities within the livestock sector.

To overcome the above needs, this thesis contributes to existing research by developing a life cycle assessment of seven case studies from the German pork value chain (Paper A). Alongside, a framework is developed to include AW into sustainability assessment by weighting indicators against each other with expert judgements using the analytic hierarchy process (AHP) (Paper B). Further, the findings of Paper A and B are enriched to fulfill four sustainability objectives that are modeled and optimized in a multi-objective optimization (MOO) of a pork value chain network constructed from the aforementioned case studies (Paper C). Finally, to gain a broader perspective on future developments, an alternative protein source, namely mycoprotein, is examined environmentally in comparison to pork production (Paper D).

Thereby, the following research questions are answered:

- What are the environmental hotspots in the German pork value chain? (Paper A)
- How can animal welfare indicators be weighted to combine them into an impact category? (Paper B)
- How can environmental, economic, social and animal welfare objectives be optimized simultaneously in a multi-objective model for the pork value chain to identify a Pareto-efficient configuration? (Paper C)
- What are the environmental benefits and trade-offs of mycoprotein as an alternative protein source in comparison to pork? (Paper D)

This thesis is organized in two parts. Part I provides the framework of the four papers included in the thesis. Part II contains the manuscript versions of Papers A-D.

Part I is structured as follows. First, chapter 2 explores the evolution and current status of methods for sustainability assessment of pork production, delivers the associated theoretical and methodological background, identifies hotspots, introduces animal welfare, and takes a look at the status-quo of mitigation strategies comparing environmental impacts from meat to microbial protein sources. Chapter 3 summarizes the four papers and presents their key findings. Chapter 4 critically reflects the limits of the proposed approach and provides suggestions for further research. Finally, Chapter 5 summarizes the key findings and the novelty of this work and derives conclusions.

2 Background

The following chapter introduces the theoretical and methodological background relevant for the cumulative studies of this dissertation. It combines conceptual foundations of sustainability assessment with methodological frameworks such as LCA, multi-attribute decision making (MADM), and MOO, which form the analytical basis for the subsequent research papers.

2.1 Sustainability assessment of pork

This section establishes the conceptual and methodological foundation for the sustainability assessment of pork production. It begins by introducing LCA as the primary approach for evaluating environmental impacts, followed by a general description of the pork value chain. Subsequently, an overview of the current state of LCA applications in pork production is provided, including approaches for extending the assessment toward a holistic perspective through LCSA. Finally, the integration of animal welfare as an additional sustainability dimension is discussed.

2.1.1 Principles of life cycle assessment

LCA, as defined in the international standards ISO 14040/44 (2009; 2018), follows an iterative framework consisting of four phases to assess environmental impacts of systems, processes or products: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The goal and scope definition phase establishes the purpose of the study, its system boundaries, and the chosen LCIA method. In the LCI phase, data from multiple sources is collected, validated, and aligned with the functional unit (FU) to form a consistent dataset, supplemented by assumptions where necessary. The LCIA phase applies characterization factors from impact assessment methods to the inventory data to calculate environmental impacts. Finally, the interpretation phase relates the results back to the initial goal and scope, addressing uncertainties, limitations, and insights emerging during the assessment.

2.1.2 Characteristics of the pork value chain

When assessing the pork value chain, the general understanding of associated steps in scientific literature covers primary pig production and the processing steps including slaughter and processing to retrieve final meat products. Figure 1 represents an overview of simplified steps of the value chain and important accompanying structures. For evaluation and reflecting operational purposes, the pig farming stage is separated into several steps. Starting with the breeding stage, followed by the rearing of the pigs and their fattening. Primary pig production farms integrate one stage or combinations of them alongside the value chain in one location.

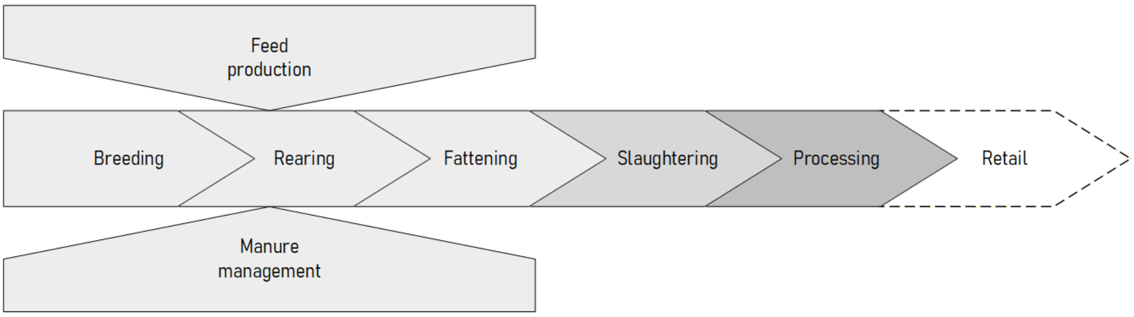


Figure 1. Simplified visualization of the pork value chain. The primary pig production is separated into breeding, rearing and fattening accompanied by feed production and manure management as essential aspects. The slaughtering and processing stages follow, ending with retail. For this dissertation, the steps highlighted in gray are of relevance.

The production cycle begins with insemination and a gestation period of roughly 115 days, followed by farrowing and a lactation period of about three to four weeks. After weaning at approximately 8 kg, piglets enter the rearing phase, where they are raised for several weeks until they reach a weight of around 30 kg. At this point, animals intended for breeding undergo an extended rearing period to develop into gilts, whereas piglets destined for meat production move into the fattening stage. The fattening phase typically lasts around four months, during which pigs grow from roughly 30 kg to a market-ready live weight of 120-140 kg.

Farms differ in size and housing conditions influenced by the farming system and its characteristics. While organic production has completely different legally binding requirements in terms of feed and housing than conventional farming, there are also shades or mixtures of systems further complicating the classification of systems. The comparison of environmental impacts of these systems are the focus of most assessments (Gislason et al. 2023). Despite the system, the characteristic on-farm activities are comparable – comprising feed production and manure management (see Figure 1). For slaughtering and processing, there are no explicitly influencing factors that are as system dependent as for the farming stages. However, the size of the facilities affects not only their environmental performance. Many large slaughter facilities also include processing procedures under one roof diversifying their product portfolio.

Slaughterhouses convert live animals into carcasses through a sequence of standardized steps. After arrival and a short resting period, pigs are stunned—using electrical stunning—before being slaughtered and bled. The carcasses then undergo scalding to remove bristles, followed by evisceration and thorough cleaning to prepare them for further processing. Meat-processing facilities refine these carcasses into a variety of pork products. Typical operations include cutting, trimming, cooling, curing, or smoking, depending on the product portfolio of the facility. Slaughtering and processing plants range from small artisanal operations to large-scale industrial factories, and handle multiple types of meat. Despite differences in scale and product range, the core purpose of these facilities is to transform pigs into carcasses into consumer-ready products through a sequence of mechanical and thermal processing steps.

2.1.3 Environmental impacts of pig production

Given the substantial influence, a scientifically robust evaluation of pork's environmental impact is essential. LCA provides an effective framework for analyzing complex environmental issues associated with processes, systems, or products. Gislason et al. (2023) offer the most comprehensive up-to-date review on LCAs of primary pig production in examining 74 studies. While this overview is an essential step to picture the landscape of LCAs for pig and pork, differences in implications must be emphasized. The problem in comparability of LCA studies already starts with the methodological choices before the actual data collection and assessment (Andretta et al. 2021; Gislason et al. 2023). The system boundaries, the FU, the considered LCIA method and impact categories and the handling of multifunctionality are decisive methodological factors influencing comparability. Furthermore, the covered production stages must align to compare results. For example, a study conducted on a breeding farm is barely comparable to a complete primary pig production study. Further distinguishing factors affect the geographical scope, the background data base, the data type/source and the inclusion of piglets and sows into the assessment.

The assessed studies in Gislason et al.'s (2023) review face some of these challenges and focus on selecting studies that match methodologically to enable a resilient comparison. These characteristic predefinitions comprise the FU of 1 kg live weight, the system boundary from cradle to farm gate, as well as the consideration of an integrated pig production than solely one stage. This includes an important restriction: the exclusion of slaughter and processing stages from the system boundary. The review results display the emphasis on specific impact categories that are used most frequent when evaluating agricultural processes with LCA—these are global warming (or climate change), acidification, eutrophication, non-renewable energy use and land use/occupation. The pattern identified for category use must be reviewed in front of the differing LCIA methods implemented for the calculation. Mainly the impact assessment for more than one category is based on the common LCIA methods CML baseline and ReCiPe 2016 (CML 2016; Huijbregts et al. 2017). Figure 2, Figure 3 and Figure 4 present the results for the predominant impact categories—global warming, acidification, and eutrophication—derived from methodologically comparable studies. Where multiple scenarios were calculated, the figures indicate the corresponding minimum and maximum values.

Overall, the results of LCAs of pig and pork reveal one distinct hotspot alongside the value chain—the feed production (Gislason et al. 2023). For livestock production many feed types are required to meet the nutrients needed to achieve an optimal feed conversion rate. For pigs, these contain crops, food production by-products, special amino acids as well as minerals. As breeders continuously try to improve feed conversion rates of pigs, the needed mass of feed transforming into 1 kg of pig is typically more than three times higher but constantly changing over the growth period. The exceptional environmental impact of feed in pig production arises from the combination of the production's impacts paired with the bad conversion rate.

Global warming is reported in nearly all studies, with attributional results ranging from 1.16 to 7.12 kg CO_2-eq/kg LW presented in Figure 2 (Basset-Mens and van der Werf 2005; Cederberg et al. 2005; Williams et al. 2006; Halberg et al. 2010; Pelletier et al. 2010; Nguyen et al. 2011; Dolman et al. 2012; Reckmann et al. 2013; Dourmad et al. 2014; Cherubini et al. 2015; González-

García et al. 2015; Mackenzie et al. 2015; Winkler et al. 2016; Bava et al. 2017; Bava et al. 2017; McAuliffe et al. 2017; Noya et al. 2017; Bandekar et al. 2019; Makara et al. 2019; Djekic et al. 2021; Pazmiño and Ramirez 2021; Sun et al. 2022; Savian et al. 2023; Dorca-Preda et al. 2023; Hietala et al. 2024). The comparison of global warming values across the reviewed studies reveals substantial variability in the carbon footprint associated with producing one kilogram of live weight. This spread highlights both methodological differences among LCAs and the heterogeneity of production systems, including factors such as feed composition, management practices, and regional conditions. Overall, the dataset emphasizes the importance of context-specific assessments when evaluating the environmental impacts of livestock production.

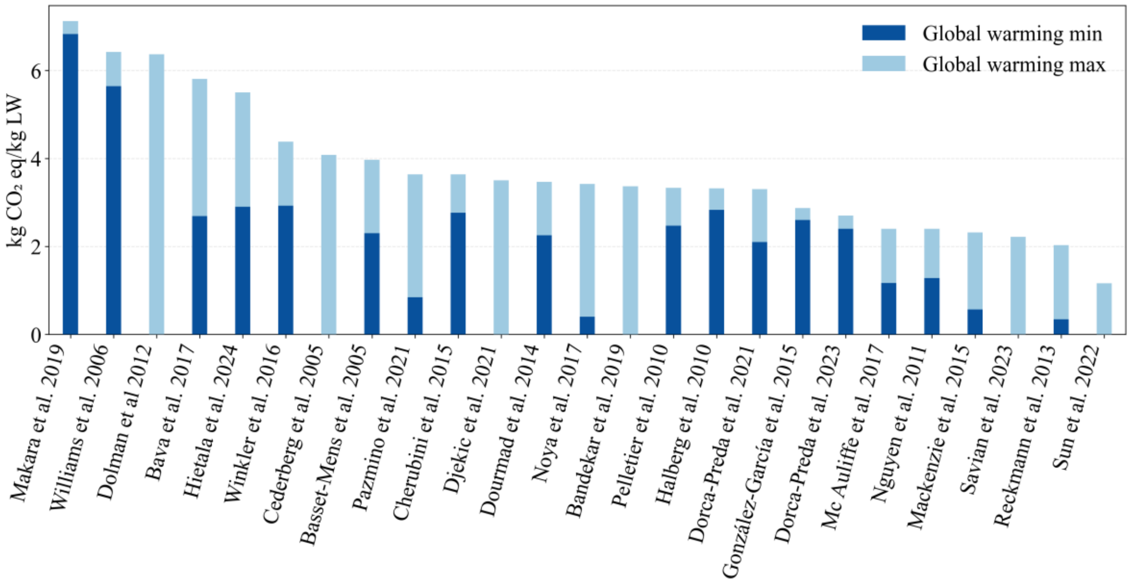


Figure 2. Global warming expressed in kg CO_2 eq per kg of live weight for methodologically comparable studies. The visualizations of the 25 studies are retrieved from own calculations based on data from Gislason et al. (2023) and enriched with newer literature sources.

Acidification (5.58-77.53 kg SO_2-eq/kg LW) and eutrophication (2.88-55.03 kg PO_4^{3-}-eq/kg LW) are frequently assessed, driven largely by ammonia emissions and nutrient leaching. Figure 3 and Figure 4 are based on the studies presented in Figure 2. Effective mitigation requires integrated strategies combining optimized feeding, housing and manure technologies, and anaerobic digestion, which can reduce climate impacts by up to 64%. The systematic review by Gislason et al. (2023) synthesizes 74 cradle-to-farm-gate LCAs of primary pig production across 27 countries, highlighting substantial methodological heterogeneity and impact variability. In this review, no study from Germany is listed, whereas Germany is one of the biggest pork producers globally (FAO 2023). Beyond this, the latest study assessing German pig production is from 2013 (Reckmann et al. 2013). Addressing this offers the possibility to close the gap with an up-to-date assessment.

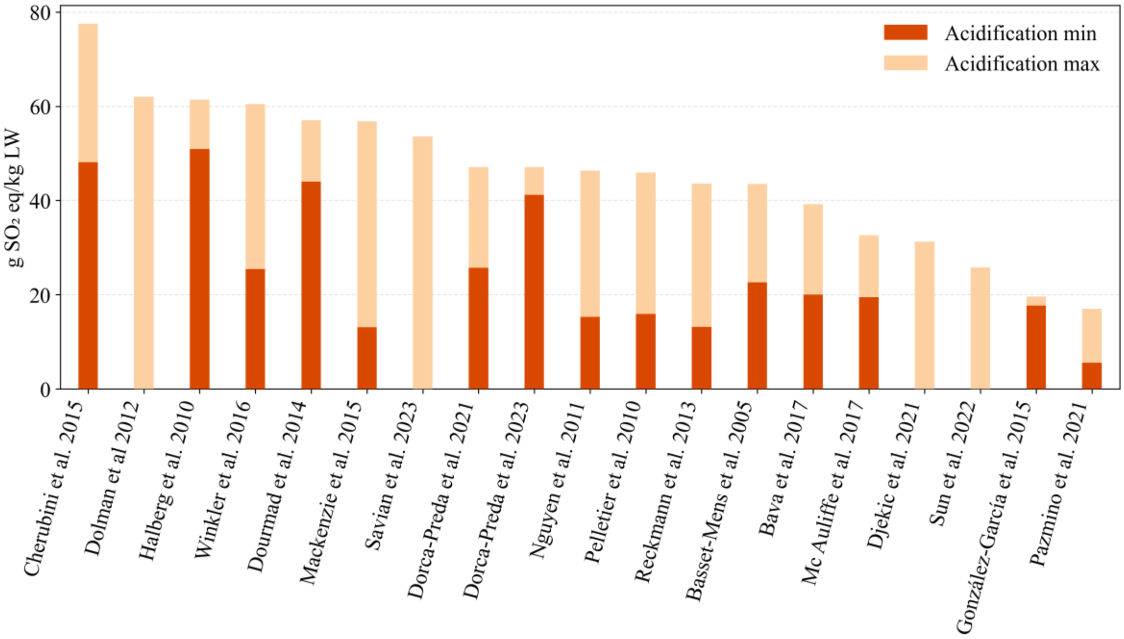


Figure 3. Acidification expressed in g SO_2 eq per kg of live weight for methodologically comparable studies. The visualizations of the 19 studies are retrieved from own calculations based on data from Gislason et al. (2023) and enriched with newer literature sources.

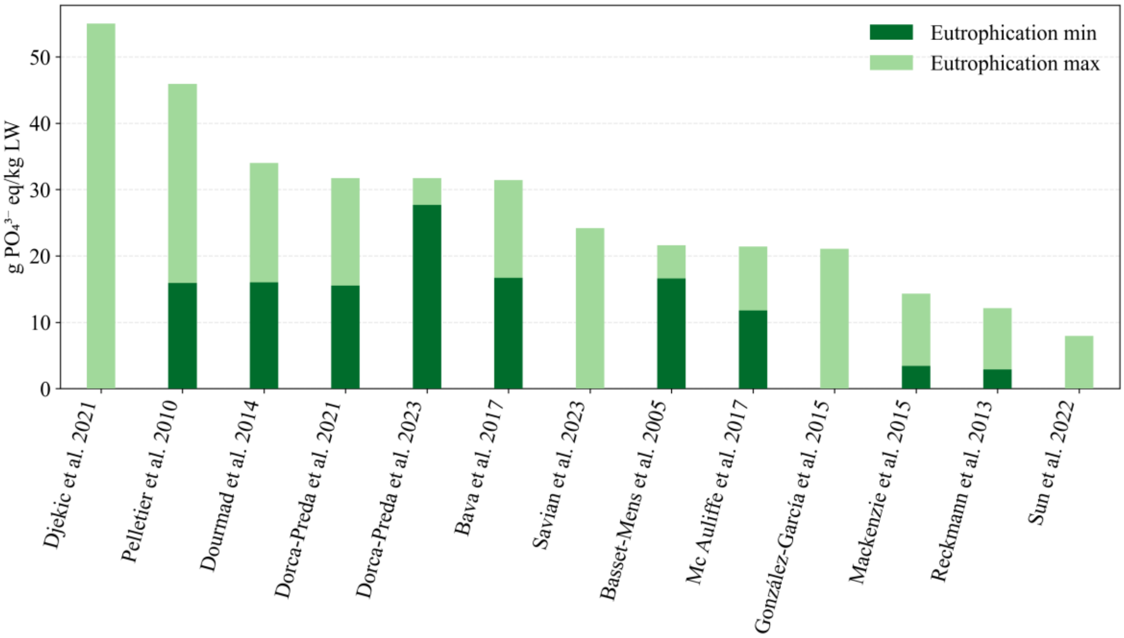


Figure 4. Eutrophication expressed in g PO_4^{3-} eq per kg of live weight for methodologically comparable studies. The visualizations of the 13 studies are retrieved from own calculations based on data from Gislason et al. (2023) and enriched with newer literature sources.

Advancing the value chain, the slaughter process and its environmental impacts move into focus. The density of studies separately assessing the slaughter process of pigs is very low (Valente et al. 2020). The importance of impact categories also changes from agriculture-based to industrially relevant. The level of influence for 1 kg of product drastically decreases as the slaughter process covers a relatively short period of time and less inputs than farming (e.g. McAuliffe *et al.*, 2017; Dorca-Preda *et al.*, 2021). As time consumption for growth and maintenance (feed, manure management) drop out, energy consumption comes to focus in terms of environmental influence.

In addition, there are studies integrating the whole value chain into the assessment, evaluating impacts for the final pork product along the whole value chain (Dorca-Preda et al. 2021; Zira et al. 2021; Hietala et al. 2024). This comprises the processing step to retrieve a final product. In Germany, few large companies dominate the market for meat processing, and they combine slaughter and processing in one facility. Regarding environmental impact, the industrial character of these facilities resembles the slaughter case. Foremost energy related emissions contribute to the results. Studies exclusively evaluating pork meat processing are missing when consulting literature.

In this dissertation, the environmental assessment of facilities covering every value chain step of pork in Germany is performed using the LCA methodology for seven case studies to display the status-quo. The underlying assumptions are harmonized to enable a comparison of systems and studies. Besides, mycoprotein as an optional protein source is assessed through LCA and compared to pork to support finding a substitute that is more environmentally friendly. The protein source represents a bioreactor-based food production that offers many possibilities for improvement of environmental issues in the future. This topic is derived and explained in more detail in Section 2.3.

2.1.4 Life cycle sustainability assessment of pork

LCSA integrates the environmental, economic, and social dimensions of sustainability to enable a holistic evaluation of systems (Kloepffer 2008). In most applications, this integration is achieved by combining the individual results of LCA, life cycle costing (LCC), and social life cycle assessment (SLCA), either through graphical aggregation or numerical synthesis. To allow comparability across dimensions and to ensure consistent interpretation, normalization procedures are commonly applied (Bonneau et al. 2014). These often involve scaling results against defined reference values or benchmarks, or aligning systems to facilitate direct comparison. Such methodological steps support a more coherent interpretation of multidimensional sustainability outcomes within livestock production and other complex systems.

While environmental LCA is well established, additional sustainability dimensions lack similar standardization. Approaches for SLCA are guided by the United Nations framework (Benoit and Mazijn 2009), whereas LCC remains comparatively weakly formalized, with only limited methodological direction available (Swarr et al. 2011). Despite these gaps, an increasing number of studies now assess sustainability across all three pillars within livestock production systems. Integrating social indicators for diverse stakeholder groups alongside economic metrics within consistent system boundaries enables a more comprehensive understanding of potential burden shifting and the interdependence between sustainability dimensions (Aranda et al. 2021; Møller et al. 2024). Such integrated interpretations offer deeper insights into production processes and highlight trade-offs that may remain hidden when dimensions are evaluated in isolation.

For pork production especially regarding the social dimension, stakeholder groups like workers, farmers, local community, consumers and society can be assessed with multiple impact categories (Zira et al. 2020). For choosing economic reference values, there is no guidance like the stakeholder group model and the selection of indicators is rather arbitrary. Every economic benchmark can offer a possible indicator for the system's economic performance. Possible indicators are labor productivity related to social factors and different cost-types (Valente et al. 2020; Zira et al. 2021).

Zira et al. (2021) build a representative sustainability assessment framework for pork that emphasizes data harmonization across predefined production cases, ensuring that environmental, economic, and social indicators are evaluated on a comparable basis. Economic parameters comprise value added over life cycle costs plus labor costs for every value chain link. The social dimension is displayed with social risk time for selected stakeholder groups involving workers, value chain actors, local community and society. Furthermore, their approach incorporates AW by quantifying the *risk pig life days* indicator, thereby extending traditional sustainability assessments beyond conventional impact categories. The study focuses on contrasting average organic and conventional pig production systems in Sweden, using a set of distinct indicators whose results are presented visually through normalized values across cases. While this method provides a coherent comparative overview, a notable limitation is the reliance on average systems rather than empirical case studies, which restricts the ability to capture farm-level heterogeneity and limits the generalizability of conclusions.

Building on these insights, this dissertation aims to integrate economic and social dimensions of pork production into a modeling framework capable of assessing sustainability across alternative network configurations. By combining multidimensional indicators within consistent system boundaries, the work seeks to support more nuanced evaluations of trade-offs and to offer a foundation for decision-making that can reflect stakeholder preferences along the value chain.

2.1.5 Animal welfare as a sustainability dimension

One extra stakeholder group that is assessed in Zira et al. (2020) complementing the SLCA is representing the pigs. The involvement of the animal into the SLCA demonstrates one way to effectively include AW and the animal itself in the sustainability assessment. Though, the integration of AW into LCA or LCSA for livestock production requires measurements that are mostly based on subjective observations. In their review, Lanzoni et al. (2023) identified studies that integrate AW indicators into LCA. These studies consider multiple forms of livestock and follow up products. The approaches to retrieve animal related indicators and the indicators themselves range from direct assessment to querying farm management data. As AW is extremely intangible because the animals cannot be interviewed about their perceptions, quantifiable measurements of welfare are in need. Values like *pig risk life days* or animal losses (mortality rate) can e.g. indicate the herd's health (Dolman et al. 2012; Zira et al. 2020). However, performing a visual on-farm assessment is necessary most of the time, to observe the animals and especially their behavior. Therefore, expert judgement plays an extremely important role when evaluating AW of livestock. Scores like the body condition score and the welfare quality protocol (Welfare Quality® 2009) help to quantify the observed welfare situation. The implementation of a scale or other measurable quantification to map an aggregated result is applied in some studies (Dolman et al. 2012; Zira et al. 2021). The aggregation of the results offers the possibility to integrate the evaluation into an impact category for sustainability assessment or specifically LCA. Conducting a comprehensive sustainability assessment of livestock production necessitates the integration of AW parameters, given that animals constitute a fundamental component of the production system and cannot be disregarded.

For the assessment of AW in this dissertation, the AHP is used to involve expert judgement into building a framework to weight AW indicators. The retrieved weighted set offers the possibility to get a single score for an optional AW impact category. An insight into the implemented methodology and their functionalities and application areas is given in the following Section 2.2. On top of that, a selection of the identified indicators is utilized in a MOO to represent the AW integration into sustainability assessment of the value chain of pork in Paper C of this dissertation.

2.2 Multi-criteria decision making in sustainability assessment

Multi Criteria Decision Analysis (MCDA) is widely applied in scientific research whenever decision support is needed. Especially in sustainability assessment, deciding for the most sustainable option or aggregating results represents a basic application area. MCDA offers a huge toolbox to systematically evaluate options and direct them to the preferred outcome while assessing e.g. defined sets of criteria. The MCDA framework can be separated into two branches—MADM for discrete problems and Multi-Objective Decision Making (MODM) for continuous problems (Gebre et al. 2021; Taherdoost and Madanchian 2023). In this thesis, the focus lies on the pairwise comparison method AHP from the MADM branch and on the mathematical model branch, especially MOO, of MODM (Gebre et al. 2021).

This section commences with an introduction to the AHP, its principles and application. Then MOO characteristics and the applications in livestock production are discussed.

2.2.1 Analytic hierarchy process

The AHP was first introduced by Saaty (1987) and its purpose is providing decision support by performing pairwise comparisons. The AHP is a structured MADM method that organizes complex problems into a hierarchical framework of main criteria and sub-criteria as visualized in Figure 5. The process begins by defining this hierarchy, which allows decision-makers to break down the problem into manageable levels. Weighting is then performed through pairwise comparisons, where criteria and indicators are evaluated against each other to determine their relative importance. These comparisons are expressed using an absolute scale and their reciprocals—traditionally consisting of nine levels ranging from equal to extreme importance—though modified scales can be applied if justified (Dong et al. 2008; Ishizaka et al. 2011). To ensure practicability and knowledge-based decisions, judgments can be collected via expert surveys, where respondents compare elements within each level. When aiming at receiving an overall score, the resulting pairwise comparisons are converted into percentage weights that sum to 100% across the hierarchy. These weights impersonate the importance of the criteria and aim at helping to identify the best option to fit the goal (Figure 5). To ensure reliability, AHP incorporates a consistency check using the critical ratio, with a threshold of 0.1 generally considered acceptable. When multiple experts are involved, individual comparison matrices are aggregated into a single matrix, commonly using the geometric mean, which is well-suited for group decision-making. Overall, AHP provides a systematic, transparent, and hierarchical approach to weighting criteria and is widely recognized as a versatile technique for MCDA. As indicated before, AHP is applied in this dissertation to retrieve a weighted set of indicators representing their relevance in terms of AW. This builds the foundation of an AW impact category development.

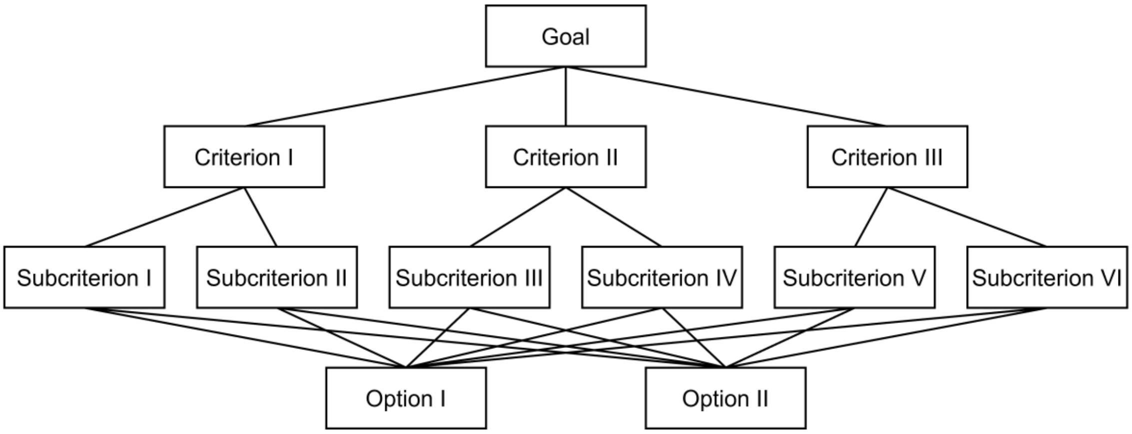


Figure 5. Exemplary structure of a hierarchy with two levels assembled to perform the AHP.

2.2.2 Multi-objective optimization for sustainability assessment

MCDA provides a structured framework for evaluating alternatives against multiple, often conflicting criteria with the aim of supporting rational decision-making (Majumder et al. 2016; De Brouwer 2020). MCDA has been widely applied in environmental decision contexts (Huang et al. 2011), and several systematic reviews of LCSA applications report that MCDA is frequently used to integrate the three pillars of sustainability—environmental, economic, and social—into composite decision metrics (Costa et al. 2019; Visentin et al. 2020; Alejandrino et al. 2021). In typical LCSA practice, MCDA facilitates aggregation and visualization of indicator results and rank-ordering of alternatives for a predefined goal (Kloepffer 2008). However, such aggregation-centric approaches often assess objectives separately and subsequently combine them via scoring, weighting, or value functions, which may obscure trade-offs and impose preference structures a priori.

MOO, as a branch of MODM, directly models simultaneous objectives and identifies Pareto-efficient solutions without requiring full aggregation. In supply-chain contexts, MOO enables the exploration of multiple configurations (e.g., facility siting, capacity decisions, routing, and technology choices) under realistic constraints, revealing trade-offs among environmental, economic, social, and other domain-specific objectives (Marler and Arora 2004). For livestock systems, this is particularly relevant because production outcomes depend on biological, logistical, and behavioral processes that are inherently multivariate and constrained.

Existing optimization studies in meat supply chains predominantly focus on economic costs and GHG emissions to derive location-allocation or transport policies (Mohammed and Wang 2017; Mohebalizadehgashti et al. 2020). While valuable, this scope is environmentally narrow—GHGs alone do not capture other salient impacts such as e.g. eutrophication, acidification (Huijbregts et al. 2017). Moreover, the broader sustainability perspective is often limited to aggregate economic criteria, omitting social dimensions (e.g., labor conditions, impacts on society) and AW indicators—both essential for ethically and socially robust decision support (Welfare Quality® 2009; Benoit-Norris et al. 2012; Mellor 2016).

MOO models consider decision variables (e.g., facility locations, flows) and multiple objective functions subject to constraints. A solution is Pareto-efficient if no other feasible solution can improve one objective without worsening at least one other (Nickel et al. 2022). Among classical approaches, the ε-constraint method is frequently used to produce the Pareto frontier in an a posteriori fashion: one objective is optimized while others are converted to constraints with bounds (ε-values) that are systematically varied to enumerate non-dominated solutions (Eskandarpour et al. 2015). Alternative approaches include e.g. weighted sums and goal programming, each with different requirements for preference articulation (Eskandarpour et al. 2015; Asha et al. 2022). Once the Pareto set is generated, preference information (e.g., stakeholder weights) can be applied to select context-appropriate solutions. In sustainability contexts, it is often desirable to retain non-aggregated transparency alongside any final scoring, enabling stakeholders to observe the trade-offs explicitly.

The dissertation advances an MOO model that explicitly integrates indicators for the three sustainability dimensions alongside AW. The model is configured for a case study-based pork supply chain, with constraints reflecting production yields. The augmented ε-constraint method is used to generate Pareto-optimal solutions, after which stakeholder preferences may be applied to identify a context-specific compromise solution. This approach extends the conventional LCSA framework by replacing simple result aggregation with an optimization-based methodology that generates a diverse set of Pareto-efficient solutions, thereby enabling more informed and preference-sensitive decision-making.

2.3 Comparative life cycle assessment of meat and microbial protein

Although the principles of LCA have been introduced earlier in this chapter, this section focuses on comparative LCAs and their application to meat and microbial protein systems. This discussion complements the foundational knowledge and clarifies the methodological basis for the dissertation’s structure.

Comparative LCA enables the systematic alignment of two or more assessments to ensure methodological consistency and enhance comparability. This alignment typically involves harmonizing system boundaries, FUs, and inventory data—critical steps for robust interpretation. By facilitating the transferability of results across systems, comparative LCA addresses one of the inherent limitations of conventional LCA: its context-specific nature.

The methodological adaptation is particularly relevant for evaluating alternative protein sources—traditional meat as the baseline and microbial protein (MP) as an emerging option. Meat production is associated with substantial environmental burdens, while societal attitudes toward animal-based food systems have shifted significantly over the past decade. Consequently, alternative proteins have gained prominence. Since protein provision remains the primary nutritional and market driver for meat, alternative sources must be assessed for their environmental performance. MP represents a biotechnological substitute produced via controlled fermentation processes, contrasting sharply with the biological variability of livestock systems. Whereas pork production centers on the growth of live animals, MP is derived from fungal biomass cultivated in bioreactors under optimized conditions.

Fermentation-based MP is emerging as a sustainable alternative to conventional protein sources, produced in controlled bioreactors rather than fluctuating agricultural systems (Pereira et al. 2024). Compared to meat or plant-based systems, MP offers superior feedstock efficiency, higher production rates, and reduced ethical concerns (Matassa et al. 2016; Shepon et al. 2016; Choi et al. 2022). Furthermore, MP offers innovation potential for land- and climate-independent production chains, including CO_2 valorization, which could drastically reduce environmental impacts and achieve order-of-magnitude improvements over meat and plant-based proteins (Pikaar et al. 2018; Minden et al. 2024). Currently, agricultural carbon sources dominate as feedstock, though future systems may utilize captured CO_2. Despite these advantages, challenges remain—high production costs, scalability, consumer acceptance, regulatory barriers, and market entry constraints regulation (World Economic Forum 2019; Hartmann et al. 2022; Synonym Biotechnologies 2023; Sturme et al. 2025).

Conducting a comparative LCA fundamentally depends on rigorous system predefinition and methodological alignment. Parallel evaluation of products or processes requires harmonized structural and procedural choices, even when the systems differ substantially in design and function. For comparisons between meat and MP, one of the most critical decisions is the selection of an appropriate FU. This choice should reflect the primary function of the systems under study. Given that both systems provide protein, a nutritional FU such as 1 kg of protein is commonly applied (Upcraft et al. 2021; Herrmann et al. 2024). Mass-based FUs are frequently used in literature (Järviö et al. 2021; Smetana et al. 2021; Kobayashi et al. 2023; Huguet et al. 2023; Tang et al. 2024), while more advanced approaches consider multiple nutritional components or composite profiles (Souza Filho et al. 2019; Mazac et al. 2023; Herrmann et al. 2024). FU selection directly influences system boundary definition, another prerequisite for ensuring comparability. Furthermore, geographical scope, temporal coverage, and underlying assumptions must be harmonized across systems; therefore, comprehensive documentation of all methodological choices and assumptions is essential for transparency and reproducibility. Looking at LCI, data accessibility and quality strongly affect comparability. Inventory data must be consistently mapped to databases such as ecoinvent, requiring alignment of flows and processes alongside the systems.

Comparative LCAs of meat and MP consistently indicate that MP offers a substantially lower environmental impact compared to pork. Its GHG emissions are markedly reduced, often outperforming even plant-based proteins, and remain far below pork across most system boundaries (Derbyshire 2020; Shahid et al. 2024; Lee et al. 2025). While certain scenarios involving high energy inputs or specific formulations can elevate emissions to levels comparable to pork, these cases are exceptions rather than the norm (Lee et al. 2025). In terms of land use, mycoprotein requires dramatically less agricultural area, positioning it among the most space-efficient protein sources (Smetana et al. 2015; Derbyshire 2020; Rubio et al. 2020). Water demand is also significantly lower than pork and generally below plant-based alternatives, though some feedstock choices could increase water use toward levels associated with beef, which remains far higher than pork (Finnigan et al. 2017; Rubio et al. 2020; Lee et al. 2025). The primary trade-off lies in energy demand: fermentation-based production is considerably more energy-intensive than conventional meat systems, partially offsetting other environmental gains (Smetana et al. 2015; Rubio et al. 2020). While the optimization potential of industrial animal meat production in terms of energy demand is mostly expended, anticipatory LCAs of bioreactor-derived protein sources promise order of magnitude ameliorations e.g. by shifting from purified glucose syrup to molasses, which is a by-product from the sugar industry (Smetana et al. 2015).

2.4 Relation of research fields and companion studies

The research fields outlined above are addressed through four studies conducted within the framework of this dissertation, as summarized in Table 1. The overarching focus remains on the sustainability assessment of pork production using the LCA methodology. Studies A and B examine distinct methodological aspects and serve as preparatory stages for Study C. Study C constitutes the central analysis of this dissertation, integrating the methodological components and findings from Studies A and B while extending the scope toward a comprehensive sustainability assessment. Finally, Study D provides a perspective on future developments by presenting a comparative LCA of pork and mycoprotein—a fermentation-derived protein source produced in a bioreactor.

Table 1. Relation of research fields and associated topics in companion studies.

Research field		A	B	C	D
2.1	Sustainability assessment of pork	x	x	x	x
2.1.1	Principles of life cycle assessment	x	x	x	x
2.1.2	Characteristics of the pork value chain	x		x	x
2.1.3	Environmental impacts of pig production	x		x	x
2.1.4	Life cycle sustainability assessment of pork			x	
2.1.5	Animal welfare as a sustainability dimension		x	x	
2.2	Multi-criteria decision making in sustainability assessment		x	x	
2.2.1	Analytic hierarchy process		x		
2.2.2	Multi-objective optimization for sustainability assessment			x	
2.3	Comparative life cycle assessment of meat and microbial protein				x

The literature predominantly referenced in relation to the assessments conducted within this cumulative dissertation is compiled and reviewed in Table 2. While the literature does not provide an entirely holistic representation of all research fields involved, it offers the most closely related approaches to the studies conducted within the scope of this dissertation. Key methodological aspects and their respective outcomes are highlighted, alongside their implementation in the four studies presented subsequently. This table illustrates the significant gaps in existing literature that are addressed by the studies included in this work. Moreover, the novelty of the research approaches becomes evident through the integration of diverse methods, the specific application context, and the comprehensive nature of the assessments.

Table 2. Overview of the contribution of the studies to literature.

Study	Application area	Method	System boundary	Sustainability dimensions	Output	Result presentation
Bonneau et al. (2014)	Pig	LCSA	Farm	LCA, LCC, SLCA, AW	System comparison	seperate
Dolman et al. (2012)	Pig	LCSA	Farm	LCA, LCC, SLCA, AW	System comparison	seperate
Zira et al. (2021)	Pig	LCSA	Supply chain	LCA, LCC, SLCA, AW	System comparison	seperate
Oglethorpe (2010)	Pig	MOO	Supply chain	LCA, LCC, SLCA	System comparison	combined
Mohammed and Wang (2017)	Meat	MOO	Supply chain	LCA, LCC	Supply chain configuration	combined
Mohebalizadehgashti et al. (2020)	Meat	MOO	Supply chain	LCA, LCC	Supply chain configuration	seperate
Paper A	Pig	LCA	Facility	LCA	System comparison	seperate
Paper B	Pig	AHP	n.a.	AW	n.a.	n.a.
Paper C	Pig	LCSA, MOO	Supply chain	LCA, LCC, SLCA, AW	Supply chain configuration	combined
Paper D	Pig, Mycoprotein	LCA	Supply chain	LCA	System comparison	seperate

3 Summaries of papers and results

This chapter summarizes each of the four papers of this cumulative dissertation in a separate section, including the objective and methodology, results and discussion and limitations. More specifically, the study context and the scientific contribution of the articles are presented first, followed by the results and their discussion. The corresponding research papers are included in Part II of the dissertation.

3.1 Paper A: Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany

The following subsections refer to the article "Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany", co-authored with Andreas Rudi and Frank Schultmann. The article is published in the *Journal of Cleaner Production* and is cited in this thesis as Treml et al. (2025b). The graphical abstract is presented in Figure 6.

3.1.1 Objective and methodology

Agriculture is essential for global food supply but is also a major driver of climate change, biodiversity loss, and nutrient pollution (Beylot et al. 2019). Livestock systems, particularly pig production, exert significantly higher environmental pressures than plant-based foods (Xu et al. 2021; Halpern et al. 2022). Pork is among the most consumed and economically important meats in Europe (Notarnicola et al. 2017b), while also being identified as one of the most environmentally burdensome foods in terms of GHG emissions, land use, nutrient discharges, and water demand. To better understand and mitigate these impacts, LCA provides a widely accepted methodological framework (Notarnicola et al. 2017a). This study delivers an up-to-date LCA of the German pork sector using seven case studies based entirely on primary data, collected directly from farms and facilities for the year 2021. Germany, being one of the world's largest pork producers (FAO 2023), offers a representative basis for this analysis. The research addresses three value chain stages: pig farming, slaughtering, and meat processing. Four farms are studied (a breeding farm BRE, a fattening farm FAT, and two integrated systems PIG 1 and PIG 2), along with one slaughterhouse (SLA) and two processing plants (PRO 1, PRO 2). The objective is to quantify environmental burdens, identify hotspots, and assess potential improvements through sensitivity and scenario analyses. The analysis follows ISO 14040/14044 standards (2009; 2018), with the FU defined as one kilogram of product—live pig, carcass, or processed meat depending on the stage. Pig farming includes detailed feed compositions, housing, manure management, and energy supply from biogas, photovoltaics, or fossil fuels. Manure and digestate are credited via avoided fertilizer and energy production. The slaughterhouse case study captures slaughtering, cleaning, waste and wastewater treatment, with impacts largely allocated to carcasses, while the processing plants cover packaging, cooling, smoking, and waste handling, with notable differences in energy sources and scale. Processes involving energy production or yielding co-products that are used beyond the system boundaries are addressed using system expansion to avoid allocation. For digestate and manure, the production of appropriate fertilizers is selected, guided by nutrient composition data provided by the farms. In addition, the electricity generated is credited against the German electricity production mix, following system expansion principles. Primary data is collected directly from managers, supplier invoices, and emission declarations, ensuring higher reliability compared to earlier literature-based studies. Environmental impacts are assessed for three key categories: global warming, acidification, and eutrophication, using the CML-IA baseline method from the openLCA LCIA methods 2.3.2 package (Guinee et al. 2002; GreenDelta GmbH 2023a). The life cycle impact assessment is based on the ecoinvent 3.9.1 dataset (Ecoinvent Association 2023) and performed in OpenLCA (GreenDelta GmbH 2023b). Sensitivity and scenario analyses further explore improvement options, such as reducing feed inputs, minimizing waste, switching to renewable energy, excluding biogas, or applying alternative allocation methods for feed by-products.

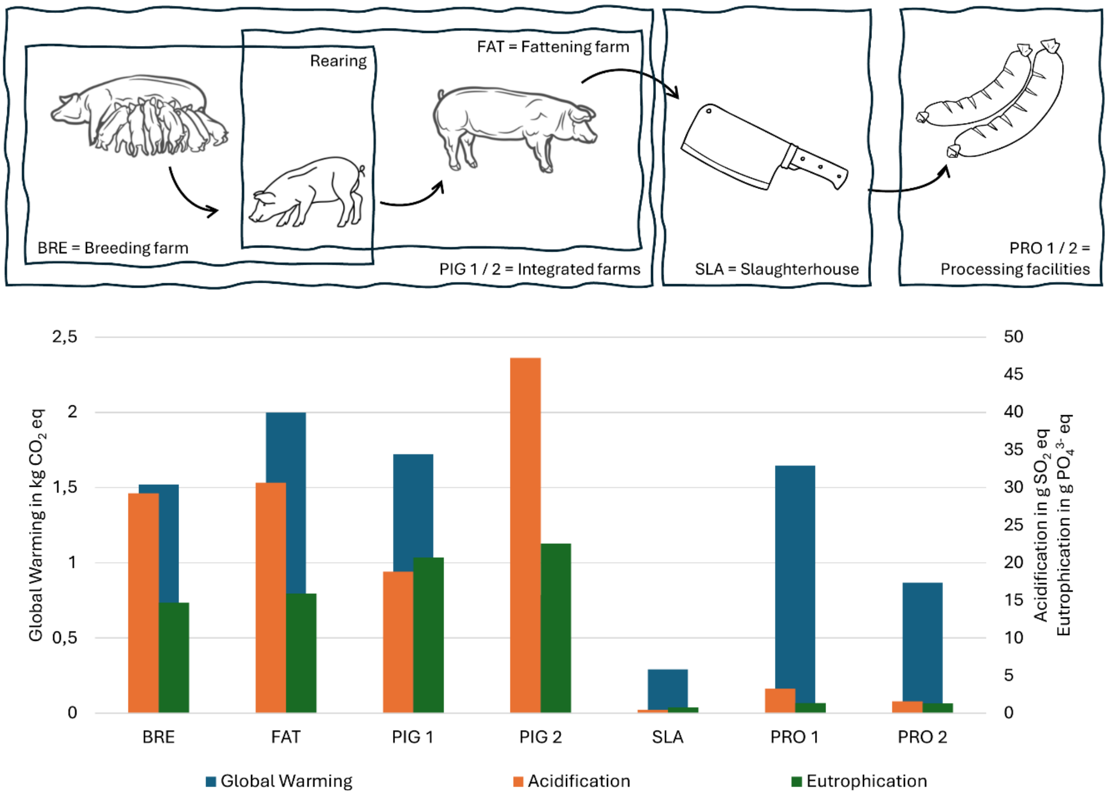


Figure 6. Graphical representation of the pig and pork production value chain and associated environmental impacts across key life cycle stages. The upper panel illustrates the production stages from breeding (BRE) and fattening (FAT) to integrated farms (PIG 1 and PIG 2), slaughterhouse (SLA), and processing facilities (PRO 1 and PRO 2). The lower panel displays the corresponding impact results for global warming (kg CO_2-eq), acidification (kg SO_2-eq), and eutrophication (kg PO_4^{3-}-eq). Own visualization published in Treml et al. (2025b).

This study brings actuality to the field of pig and pork LCAs with its use of comprehensive primary data from seven real-world case studies across the German pork value chain, providing one of the most detailed and up-to-date environmental life cycle assessments of pork production. Unlike previous research that relies largely on secondary or aggregated datasets, this study integrates farm-, slaughterhouse-, and processing-level data, enabling a granular analysis of environmental hotspots and scenario-based improvement potentials within a national context. Its approach delivers both methodological robustness and practical relevance for advancing sustainable livestock production.

3.1.2 Results

Pig farming shows by far the largest environmental burdens compared to the other value chain links. Feed production dominates impacts in all categories, especially through soybean, wheat, and barley components. Global warming (GW) is highest in fattening farms due to soybean use, while acidification and eutrophication are strongly linked to feed and manure management. Biogas use reduces the environmental impacts through credits for electricity and fertilizer. Integrated farms differ: one (PIG 1) benefits from manure credits, while the other (PIG 2) shows very low GW but very high acidification and eutrophication due to intensive biogas and substrate use. Slaughterhouse operations have much lower impacts per kilogram of product than farming. Waste treatment, especially slaughterhouse waste and wastewater, is the main contributor, while energy use (CHP and natural gas) and electricity supply also play a role. Processing facilities show moderate but distinct results. The small-scale, fuel-oil-heated facility (PRO 1) has higher GW and acidification impacts, while the large-scale factory (PRO 2) has lower results but is more dependent on grid electricity. In both cases, electricity, waste treatment, and auxiliary materials are key impact drivers.

Comparison with literature confirms that the examined German case studies mostly fall below international averages, except for PIG 2, which exceeds typical values for acidification and eutrophication. Sensitivity analyses demonstrate that reducing feed inputs by 10% substantially lowers GW impacts in pig farming. At the slaughterhouse, lowering waste volumes strongly reduces the impact for all the categories. In processing, cutting heating demand or electricity use improves performance slightly. Scenario analyses for case study BRE show that including the production of feed by-products with economic allocation raises burdens, while removing biogas increases GW and eutrophication but lowers acidification. For the slaughterhouse, replacing grid electricity with photovoltaic supply reduces overall environmental impacts up to 21%. Overall, results emphasize that feed production is the critical driver of environmental impacts in pig farming, while waste and energy supply dominate at slaughter and processing stages. Biogas and renewable energy integration can reduce climate impacts, but may shift burdens to other categories, underscoring the need for balanced strategies.

3.1.3 Discussion and limitations

The study confirms that pig farming is the dominant contributor to environmental impacts, with feed production consistently identified as the main hotspot across impact categories. While slaughtering and processing play a comparatively smaller role, waste treatment and energy supply at these stages remain important levers for improvement.

Limitations include the consideration of one year, reflecting operational and data collection constraints. The selection of the case studies brings another limitation, as there is no fully connected value chain assessed. The comparability of the capacity of the slaughterhouse is lacking in comparison to the German standard, with a few big players operating extremely large integrated slaughter and processing facilities. The trend develops towards the operation of a smaller number of big farms like bespoken BRE and FAT. Overall, the case studies show a glimpse into the diversity of farming systems in Germany but do not aspire to cover the German pork value chain in its generosity. The scenario and sensitivity analyses are very case-specific, and the economic profitability is not assessed, as the focus lies on the environmental impacts. Benchmarking against other studies is constrained by differences in methods, data quality, and disclosure. Many comparative studies rely on less precise or non-transparent data, limiting the robustness of cross-study comparisons.

From the methodological perspective, the selection of impact categories is restricted by the choice of the LCIA method CML-IA baseline. Other important categories, such as land use are excluded in the study's assessment.

3.2 Paper B: Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming

The following subsections refer to the article "Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming", co-authored with Elias Naber and Frank Schultmann. The article is published in the Journal *MDPI: sustainability* and is cited in this thesis as Treml et al. (2025a).

3.2.1 Objective and methodology

The objective of this study is to advance sustainability assessment by developing a framework that integrates AW as a societal impact category within LCA of pig farming. While conventional LCA focuses on environmental dimensions such as global warming, acidification, and eutrophication, the ethical and societal relevance of farm animal well-being requires a systematic inclusion of welfare considerations. To operationalize this, the study introduces a structured set of welfare indicators and applies the AHP to derive quantitative weights based on expert judgment. The framework is designed to translate diverse AW characteristics into a comparable and implementable score. The assessment builds on four main criteria—husbandry conditions, feed intake, operation-specific parameters, and single animal observation—further broken down into fifteen sub-indicators. These are defined through literature review and validated in expert interviews. To test the feasibility of the weighting approach, a survey was conducted with nine experts from animal husbandry, agricultural sciences, and veterinary medicine. Therefore, the participants rated the intensity of importance of the indicators in relation to each other separated under every main criterion. The importance is provided by a three-level scale of equal importance (1), strong importance (5), and extreme importance (9), as well as their reciprocals. This scale differs from the traditional AHP scale of nine levels. Additional consideration of inconsistencies in judgement is required and performed by assessment of the critical ratio's threshold that should not exceed 0.1. The results of the pairwise comparisons of indicators for each respondent are aggregated using geometric means. The calculated weights then represent the foundation of the characterization model for the impact category.

The novelty of this study lies in the development of a methodological framework for integrating AW into sustainability assessment through the creation of a dedicated impact category. By applying the AHP to weight and aggregate welfare indicators through expert judgement, the study introduces a transparent, quantitative approach that transforms complex welfare attributes into a single comparable score. This represents a significant advancement in bridging environmental and ethical dimensions within sustainability assessment of livestock systems.

3.2.2 Results

The study demonstrates that it is feasible to integrate AW indicators in a characterization model of an impact category into LCA of pig farming. Using the AHP with input from nine experts, a consistent weighting scheme for AW indicators is generated. This approach offers the possibility to involve experts into the assembly of an impact category's characterization model. The selection of indicators to determine the impact category can be performed using the AHP methodology with the pairwise comparison.

Results show that the main criteria feed intake and single animal observation are the most highly rated. This rating highlights the importance of an animal-centered approach, when evaluating AW. On indicator level, animal losses and fitness condition have the highest priority against the other indicators under the assigned main criterion after the survey evaluation. The weight of animal losses as an indicator stands out, taking into account the rating of the associated main criterion of operation-specific parameters, which is significantly lower than that of the highest rated criteria. The interviewed experts have determined that the percentage of animal losses in a husbandry section exceeding a certain number is an essential indicator that animal health is affected, which is in line with the findings of Dolman et al. (2012). The second highest rated indicator is fitness condition, that is received via the body condition score.

3.2.3 Discussion and limitations

The results highlight the benefits of weighting indicators, as housing conditions and animal-based measures emerge as central drivers of welfare outcomes. However, the study also underscores the complexity of indicator selection. AW is a contested concept, and experts differ in their views on which criteria are essential. The hierarchical categorization into four criteria and 15 sub-indicators provides a workable structure, yet consensus-building and refinement remain necessary. Iterative AHP applications and broader expert surveys could help eliminate less relevant indicators and improve robustness. At present, the limited number and profile of experts may bias the weighting toward industry priorities. Methodological refinements are also needed. While AHP provides transparency, uncertainties in expert judgments and subjective perceptions of welfare indicators suggest that fuzzy AHP or alternative MCDA techniques (e.g., TOPSIS, PROMETHEE) could better capture nuances and weak preferences. Moreover, the framework currently prioritizes indicators that are standardized and feasible for on-farm data collection, which supports comparability but risks underrepresenting complex or qualitative aspects such as affective state or enrichment use. This focus may unintentionally bias results toward production-oriented measures. Complementary qualitative assessments or hybrid methods could help address this gap. Finally, the framework requires consistent assignment of indicator characteristics to a nominal scale. The reliability of results depends on ensuring that these characteristics are detectable, distinguishable, and quantifiable, which in turn demands an adequate number of expert judgments. Thus, while the study provides a significant methodological step toward incorporating welfare into LCA, its limitations lie in the scope of indicators, the narrow expert base, and methodological uncertainties. Future refinements should aim to broaden indicator coverage, integrate more diverse expertise, and explore alternative decision-support tools.

3.3 Paper C: Assessing sustainability in the pork value chain: A multi-objective approach

The following subsections refer to the article “Assessing sustainability in the pork value chain: A multi-objective approach”, co-authored with Andreas Rudi and Frank Schultmann. The article is submitted to a scientific journal and is cited in this thesis as Treml et al. (2026b). The graphical abstract of the article is presented in Figure 7.

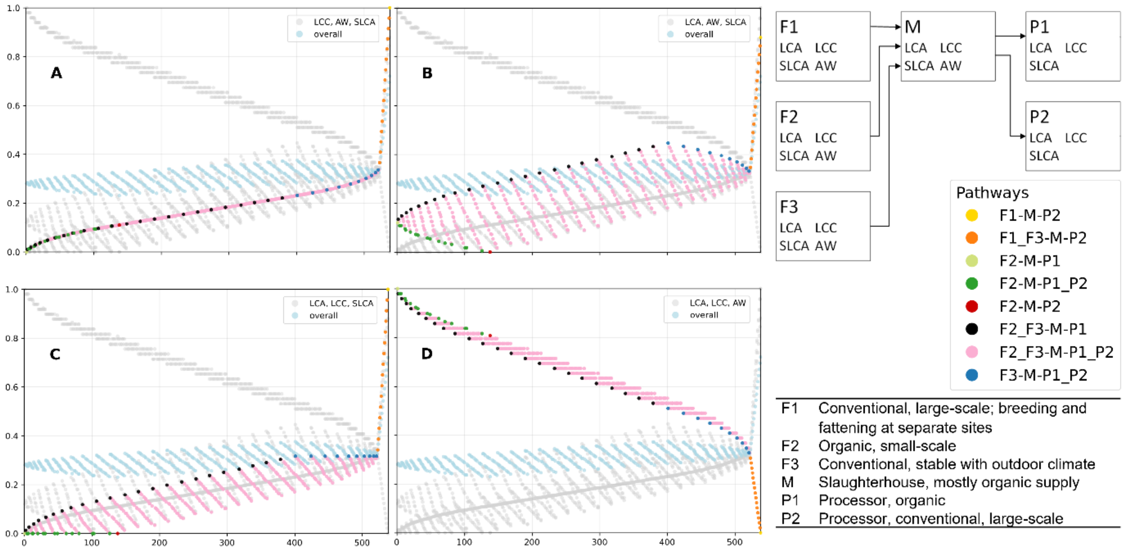


Figure 7. Multi-objective optimization of pork supply chain configurations integrating environmental (LCA), economic (LCC), social (SLCA), and animal welfare (AW) dimensions. Panels A-D illustrate Pareto frontiers for different objective combinations, highlighting trade-offs and synergies across pathways. Colored points represent alternative value chain configurations (F1, F2, F3: farm types; M: slaughterhouse; P1, P2: processors), ranging from conventional large-scale systems to organic and mixed strategies. The diagram on the right shows the hierarchical structure of value chain elements and associated sustainability dimensions. Own visualization.

3.3.1 Objective and methodology

The objective of this study is to develop and apply an integrated modeling framework that optimizes pork production by simultaneously considering environmental, economic, social, and AW dimensions. While previous analyses have primarily assessed these sustainability aspects separately, this study aims to bridge the gap between LCSA and optimization by providing a quantitative decision-support model for pork production systems. The approach builds on the findings from the preceding studies by incorporating empirical data from German case studies and expanding them into a comprehensive multi-objective optimization model. The novelty of this study lies in the integration of LCSA and AW dimensions into a unified MOO framework for livestock value chains. Using primary data from six German case studies, the study applies the augmented ε-constraint method to generate Pareto-efficient solutions, providing one of the first demonstrations of a comprehensive LCSA for livestock embedded within a mathematical optimization model. This approach advances sustainability assessment by quantitatively revealing trade-offs and synergies among competing objectives in real-world pork production systems. Especially the integration of AW indicators represents an extension to existing LCSA and MOO frameworks.

The methodological framework combines LCA, LCC, and SLCA with quantified AW indicators to create a holistic evaluation basis. The model represents a multi-echelon pork value chain, consisting of several farm types, a slaughterhouse, and processing facilities, which are connected through material and energy flows. All environmental and economic parameters are derived from the primary data obtained within the SPECK project, complemented by some picked welfare indicators developed in Treml et al. (2025a). These indicators capture husbandry conditions, mortality rates, and transportation distances, ensuring consistency across the sustainability dimensions.

The optimization is implemented in the GAMS software environment using linear programming and follows a multi-objective approach based on the augmented ε-constraint method. Four objectives are considered simultaneously: minimization of environmental impacts, maximization of economic performance, minimization of social burden, and minimization of AW impacts. Environmental data includes the impact categories GW, acidification, eutrophication, and LU, derived from the ReCiPe 2016 midpoint method and the ecoinvent 3.9.1 database (Huijbregts et al. 2017; Ecoinvent Association 2023). Economic performance is measured by net profit per kilogram of product, while the social dimension is represented through regional employment and consumer affordability. AW is integrated as an additional quantifiable pillar using scores described earlier. The optimization model is designed to identify Pareto-efficient solutions through the network, enabling the analysis of trade-offs and synergies among sustainability goals across the pork value chain.

3.3.2 Results

The optimization results reveal distinct trade-offs among the environmental, economic, social, and AW objectives. The set of Pareto-efficient solutions illustrates that environmental, economic, and animal welfare performance can be improved simultaneously to a certain extent, whereas the social objective often conflicts with the other dimensions. The environmentally optimal configurations favor farms organic and enhanced systems, achieving lower GHG emissions, acidification, and eutrophication potentials. These configurations are also associated with better AW outcomes due to lower stocking densities and improved housing conditions. Economic performance is closely linked to production scale and efficiency. The optimization identifies hybrid production pathways that combine conventional and organic practices as the most balanced solutions, achieving both profitability and acceptable environmental and welfare outcomes. In contrast, socially optimal solutions emphasize consumer affordability and employment in the region but often correspond to less sustainable production structures with higher emissions and lower welfare standards. This divergence underlines the complexity of balancing short-term social benefits with long-term ecological and ethical sustainability.

The trade-off analysis shows that the economic dimension exerts the strongest influence on overall sustainability performance, while AW and environmental objectives tend to align under similar system configurations. The findings demonstrate that structural adjustments, such as integrating renewable energy, optimizing feed efficiency, and promoting higher-welfare production systems, can enhance overall sustainability without necessarily compromising economic viability.

3.3.3 Discussion and limitations

The study demonstrates that multi-objective optimization provides an effective tool for integrating diverse sustainability dimensions within pork production systems. By linking empirical life cycle data with mathematical optimization, the framework enables a more comprehensive understanding of the interactions between environmental, economic, social, and AW performance indicators.

However, several limitations need to be considered when interpreting the findings. The analysis is based on a limited number of case studies from Germany, which, although representative of typical production systems, may not capture the full heterogeneity of the pork sector. Furthermore, while the optimization model incorporates real-world data, the value chain represented is a virtual construct and does not depict a fully connected operational network. The social indicators used, particularly employment and consumer price, provide a simplified representation of social sustainability and omit aspects such as working conditions, equity, or consumer acceptance. Similarly, AW indicators are limited to a quantifiable set. Finally, the system boundaries of this study are limited to production and processing stages, excluding downstream processes such as packaging, distribution, and consumption.

3.4 Paper D: Meat versus microbial protein—a life cycle assessment of present-day value chains

The following subsections refer to the article “Meat versus microbial protein—a life cycle assessment of present-day value chains”, co-authored with Steven Minden, Alexander Grünberger, Rebekka Volk, Andreas Rudi, Frank Schultmann and Anne Kaster. The article is published in the Journal *The International Journal of Life Cycle Assessment* and is cited in this thesis as Treml et al. (2026a). The graphical abstract of the article is presented in Figure 8.

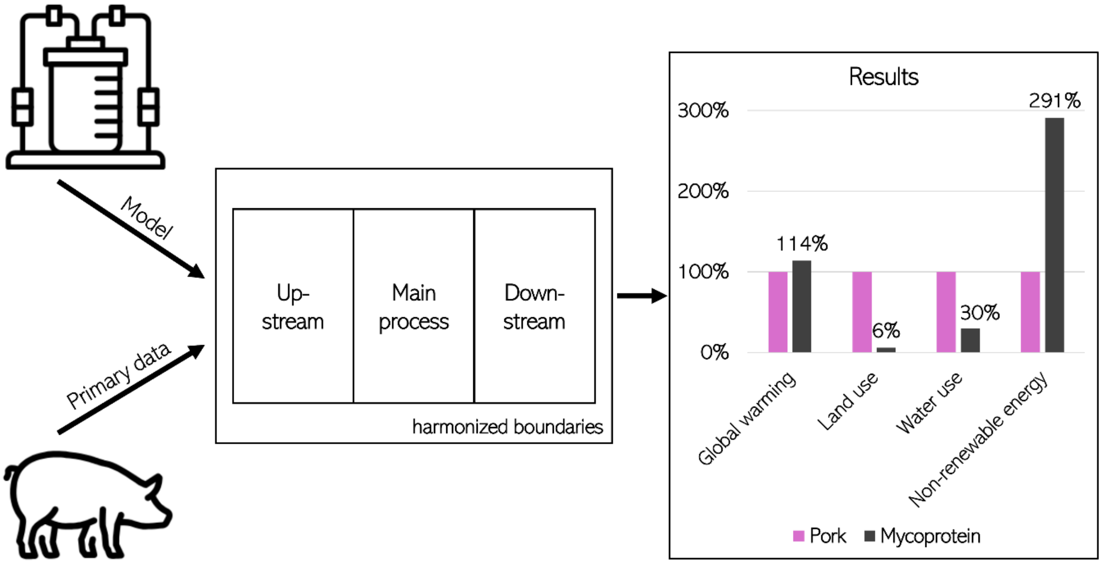


Figure 8. Mycoprotein and pork production processes and their environmental impacts. Primary data for pork and simulation-based data for mycoprotein were used to represent upstream, main process, and downstream stages, resulting in the displayed impact profiles. Pork shows lower impacts in global warming potential and non-renewable energy demand, whereas mycoprotein performs better in land use and water use. Own visualization.

3.4.1 Objective and methodology

The objective of this study is to compare the environmental performance of pork meat and bioreactor-based microbial protein (mycoprotein) as representative protein sources in contemporary food production. Both value chains are analyzed to provide a transparent benchmark for future sustainable protein strategies. A comparative LCA is conducted according to ISO 14040/14044 standards (2009; 2018), following a cradle-to-gate approach. The analysis includes the key life cycle stages of breeding, fattening, and slaughtering for pork, and medium preparation, fermentation, and downstream processing for mycoprotein.

Literature lacks a systematic comparison of meat- and microbial protein value chains representing the status quo as a metric for future decision making. Available studies are either anticipatory of not yet developed technology or value chains are not comparable due to different underlying methodologies (e.g., FUs, or system boundaries), assumptions, and research goals (Roßmann et al. 2021).

The FU is defined as 1 kg of crude protein, enabling a nutritional and not purely mass-based comparison. Primary data for pork originate from German production facilities previously detailed in Treml et al. (2025b), while mycoprotein data are derived from process simulations based on the Quorn™ production model. Both systems are modeled using openLCA with the ecoinvent 3.9.1 and agribalyse 3.1 databases (Ecoinvent Association 2023; ADEME 2023). Environmental impacts are assessed in four categories: global warming (GW), land use (LU), water use (WU), and non-renewable energy demand (NRE), using the ReCiPe (H) midpoint 2016 (Huijbregts et al. 2017), AWARE 1.2 (Boulay et al. 2018), and Cumulative Energy Demand (HHV[1]) (Ecoinvent Association 2023) methods. To ensure robustness, a Monte Carlo simulation with 1,000 iterations is applied to evaluate uncertainty, especially for the literature-based microbial protein data.

3.4.2 Results

The comparative LCA shows distinct environmental trade-offs between the two protein systems. Mycoprotein demonstrates substantial reductions in land and water use—by approximately 94% and 70%, respectively—compared to pork, reflecting its independence from feed crop cultivation and more efficient carbon conversion in fermentation. However, it exhibits a slightly higher GW and nearly threefold higher NRE, primarily due to glucose syrup production and energy-intensive medium sterilization.

For pork, the fattening stage dominates all impact categories, largely driven by feed production. Biogas generation from manure provides significant credits, reducing GW and NRE impacts. In contrast, mycoprotein impacts are concentrated in the medium preparation stage, where glucose and energy requirements account for more than 75% of the emissions throughout.

The Monte Carlo simulation confirms the reliability of these trends, with low variance for mycoprotein results and higher variability for pork due to agricultural uncertainties. When compared to existing literature, the results align well for land and water use but indicate slightly higher GW and NRE for mycoprotein, reflecting methodological differences such as the AWARE water model and specific German energy mixes. The analysis underscores that while microbial protein currently requires more industrial energy, it holds significant potential for impact reduction through the use of low-impact carbon feedstocks (e.g., molasses) and renewable energy inputs. Overall, mycoprotein production presents a promising pathway for decoupling protein supply from land and water constraints, supporting sustainable food transitions.

3.4.3 Discussion and limitations

Several limitations constrain the generalizability of this comparison. The study's cradle-to-gate scope excludes downstream stages such as processing, packaging, and consumption, which may affect total environmental impacts. The data quality differs between systems, with pork modeled from primary German data and mycoprotein relying on literature-based process simulations, introducing asymmetry in representativeness. The glucose feedstock used in the mycoprotein model represents a high-purity industrial source; alternative feedstocks or energy mixes could yield substantially different results. Additionally, while the FU (1 kg protein) ensures nutritional comparability, it may not capture differences in amino acid profile, digestibility, or consumer acceptance.

From a methodological standpoint, uncertainties persist in system boundaries and allocation procedures, particularly for manure and biogas credits in pork production. Furthermore, the assessment focuses exclusively on environmental categories, omitting social, ethical, and economic

---

[1] Higher heating value

dimensions, such as AW, labor conditions, or production costs. Finally, microbial protein production remains an emerging technology, meaning that results represent current industrial performance rather than optimized future processes. Despite these limitations, the study provides a transparent benchmark for assessing protein alternatives and informs future system improvements in sustainable food production.

4 Critical reflection

Evaluation techniques can only approximate reality to a limited extent. It is therefore essential to approach these representations with a clear understanding of their inherent limitations and underlying assumptions. This chapter critically reflects on the constraints, simplifications, and trade-offs embedded in the assessments and models developed in this dissertation. For each aspect discussed, potential directions for future research are outlined. Detailed discussions of specific limitations can be found in the respective paper discussion sections.

Life cycle assessment

LCA constitutes the methodological foundation of this dissertation, and its intrinsic challenges significantly influence the results and interpretations. A major obstacle in conducting LCAs lies in the initial methodological settings and definitions. The typical goal of LCA is to compare outputs from different systems using the same FU. Therefore, methodological consistency—covering data collection approaches, system boundaries, and process implementations—is essential. When comparing LCAs from the scientific literature, alignment of these parameters is critical to ensure robust conclusions. However, such comparability is often difficult to evaluate because published data rarely provides sufficient detail to enable accurate matching of findings. To address this, the LCAs presented in Papers A, C and D are based on a comprehensive and harmonized dataset outlined in detail across similar cases to ensure comparability. Furthermore, Paper A provides an in-depth description of the data foundation to facilitate transparency and reproducibility. Data quality plays a pivotal role in LCA. Primary data represents the gold standard, followed by secondary data supplemented with assumptions. The assessments in this dissertation primarily rely on primary data, complemented by database-matched flows. While many studies employ non-transparent data collection practices, this dissertation consistently builds upon the same case studies and data foundation. Nevertheless, challenges in data curation persist. Assumptions were necessary, and some data had to be matched to imperfect database flows. By nature, LCI compilation depends on the willingness of system managers to share accurate and current process data. This introduces uncertainty, as data precision and timeliness are contingent upon external cooperation. Despite these limitations, the research predominantly relies on primary, up-to-date data aligned with the processes under investigation. In the publications of this cumulative dissertation, all data foundations, sources, and the procedures for matching them to databases are documented in detail, representing a critical prerequisite for delivering a transparent and scientifically robust LCA study. However, the standardization of documentation practices in LCA must be prioritized in future methodological developments to ensure consistency and comparability across studies more profoundly. The focus must be placed on strengthening these foundations rather than introducing additional methodological extensions built upon an unstable basis.

Animal welfare in LCA

Integrating AW into sustainability assessment entails specific prerequisites. Within the LCA framework, implementing AW as an impact category appears conceptually straightforward.

However, the primary challenge lies in identifying quantifiable indicators that can be aggregated into a single category score. Paper B addresses part of this challenge by proposing a normalization scheme for indicator values, yet the initial quantification of welfare indicators remains unresolved. To overcome this, indicators identified through literature review and expert surveys must undergo evaluation by specialists in animal health and welfare, as expertise in animal behavior is indispensable. This dissertation proposes a methodological scheme for merging indicator results using a MADM approach, analogous to the assembly of LCA impact categories by characterization factors. However, indicator assessment depends on data availability and therefore falls outside the scope of a purely LCA-based methodology. The intermediate step—normalizing each indicator on a five-point scale—also lies beyond the scope of this work and requires close coordination with expert-driven quantification. Further limitations arise from the potential need to revise the set of indicators after expert-based quantification has been completed. Consequently, any changes in indicator selection may necessitate repeated adjustments to the weighting scheme to maintain methodological consistency. As indicated, future research should prioritize the expert-driven identification of measurable AW indicators and the development of a standardized scale that translates these measurements into comparable values. While the proposed framework provides a structured basis for this process, its successful implementation largely depends on extensive expert involvement to ensure validity and consistency.

Holistic sustainability assessment

The sustainability assessment presented in this dissertation faces several limitations, primarily related to data availability. Comprehensive optimization requires objectives that fully capture the intended purpose of the assessment. Impact selection can be aligned with regulatory requirements or stakeholder preferences, but this necessitates clear goal definition and access to suitable data. Obtaining authentic and relevant data remains a major challenge, as most assessed studies focus on isolated facilities rather than representing a fully integrated value chain with realistic linkages. Furthermore, quantifying issues across all sustainability dimensions forms the foundation of the optimization process. This quantification restricts interpretability, as certain aspects—particularly social and ethical considerations—are not inherently numerical and require scale transformations. Additionally, the selection of impacts inevitably simplifies complex realities, creating opportunities for omission and bias. Tackling some of the difficulties discussed, a promising direction for future research is the integration of exclusively realistic value chain linkages combined with explicit consideration of stakeholder preferences. This approach would enable the identification of optimal pathways through the value chain while respecting diverse priorities across actors. To achieve this, a comprehensive and high-quality data basis is essential to accurately represent and evaluate each stakeholder’s objectives. Once these prerequisites are met, the proposed framework can evolve into a practical decision-support tool, offering actionable sustainability guidance for real-world livestock production systems.

Comparison to an alternative protein source

The comparative assessment of pork and MP introduces specific limitations. While MP offers a promising perspective for reducing environmental impacts, current production processes rely on glucose-based feedstocks and energy-intensive procedures, limiting differentiation from conventional agricultural systems. The envisioned transition to carbon capture-based feedstock remains a future scenario. Without this implementation, the forward-looking potential of MP is constrained, and assessments can only reflect scenarios where feedstock impacts are assumed to decline significantly. Future evaluations should incorporate carbon capture technologies and their integration into production systems. Moreover, production scale must be aligned with pork to represent a realistic substitution scenario. Identifying transformative processes and modeling plausible pathways is essential to determine the feasibility and extent of substitution.

5 Summary, conclusion and outlook

Global food production fundamentally relies on agricultural processes, which inevitably exert significant impacts on the environment. While the term “environment” primarily denotes ecological and biophysical conditions, it also encompasses social and economic dimensions as integral components. Accordingly, sustainability must be understood as a multidimensional concept that interlinks environmental, social, and economic aspects. As livestock production predominantly relies on animals, this perspective must be explicitly incorporated to achieve a comprehensive sustainability assessment. While it could be partially assigned to the social dimension, it primarily introduces an additional layer of complexity to sustainability evaluations. Emphasizing this inclusion is essential, as the animal represents the core of the production process. Given the enduring necessity of food production, enhancing the sustainability performance of the agricultural sector is imperative. Livestock systems—particularly pork production, which serves as a representative meat product due to its widespread global consumption—require comprehensive evaluation to identify environmental hotspots and critical leverage points for targeted mitigation strategies. Because social, economic, and environmental impacts are deeply interconnected, these dimensions must be assessed simultaneously. Therefore, a comprehensive evaluation of all sustainability dimensions and the identification of their interdependencies constitutes the essential first step toward process improvement. Beyond this, investigating alternative sources of nutritional protein traditionally provided by pork offers an opportunity for innovative, forward-looking strategies that complement conventional mitigation approaches.

This dissertation presents a comprehensive sustainability assessment based on a series of detailed and recurrent case studies from the German pork production sector. The work offers a high degree of methodological customization and extends the evaluation beyond conventional dietary and production standards. The research systematically assesses the pork value chain as an application area for holistic sustainability analysis, integrating dimensions beyond the traditional environmental-economic-social trinity by incorporating AW considerations. Furthermore, it introduces a forward-looking perspective through the comparative evaluation of alternative protein sources.

The preliminary foundation for the ultimate MOO (Paper C) of the pork production system is established through the LCA study (Paper A) and the development of an AW framework (Paper B). Building on these components, the subsequent optimization of sustainability within a supply chain configuration for livestock production unlocks a new level of comprehensiveness. The integration of AW indicators alongside diverse environmental impact categories significantly enriches the assessment compared to previous studies. Concluding the dissertation with a comparative analysis of pork and microbial protein (Paper D) provides a future-oriented outlook, illustrating how sustainability assessments can inform transformative developments and highlight opportunities arising from the evolution of sustainable practices.

Paper A evaluates pig production, slaughtering, and processing facilities along the value chain. For pig production, across four systems, the majority of environmental impacts consistently originate from feed production, while the impact profile shifts along the chain. Slaughterhouse and processing studies reveal the industrial character of these facilities, where energy commodities dominate environmental influence—an effect amplified by the absence of live animals. These findings confirm the overarching relevance of the animal production stage, particularly feed production, for the environmental footprint of meat products. However, conventional environmental assessments fail to fully capture the implications of livestock production, as the evaluation of the animal as the primary product is largely absent. This gap motivated Paper B, which identifies and weights AW indicators to provide an overview of their influence on four main criteria based on expert judgment. Results indicate that animal-centered factors directly affecting health and behavior offer the most critical insights into welfare, though their quantification remains challenging due to reliance on subjective observations. Building on these insights, the MOO approach, designed to generate a Pareto frontier for sustainability assessment, builds upon the findings of the preceding studies and extends them by incorporating economic and social dimensions in Paper C. For pork production, this optimization-based LCSA represents a novel methodological advancement, introducing a preference-oriented framework for sustainability evaluation. Unlike conventional LCSA studies that typically focus on complex but one-dimensional indicators for comparing static systems or hypothetical projections, this approach emphasizes dynamic supply chain configurations and their potential for change. By integrating mathematical modeling with a broad spectrum of environmental impacts, social considerations, and AW dimensions—rather than limiting the analysis to economic viability—the model enables a systemic evaluation of multiple sustainability objectives. On top of this, stakeholder preferences can be applied after generating the Pareto frontier, guiding the selection of optimal solutions and influencing subsequent decisions regarding supply chain configurations and trade-offs across interconnected stages of the livestock value chain.

Departing from the previously emphasized holistic assessment, the focus narrows to environmental impacts, as this targeted approach offers the most reliable basis for projecting future developments and deriving robust conclusions supported by high-quality data in Paper D. Recognizing that feed consumption constitutes the predominant environmental impact across the value chain, targeted strategies must focus on this factor to enhance system performance. However, as the feed conversion rate in pigs is genetically determined and has been optimized over decades of industrial breeding, further improvements in this parameter are limited. Consequently, alternative strategies for reducing environmental impacts become necessary. One potential approach involves producing protein that can substitute for meat-derived protein. Paper D explores areas where the environmental impacts of pork production can be outperformed by mycoprotein production as a replacement. The assessment demonstrates that land and water use categories can be substantially improved through microbial protein systems. While the results serve as reference values, they also reveal that feedstock selection is the primary contributor to negative impacts in mycoprotein production. Currently based on glucose as a carbon source, future developments should aim to replace this feedstock with carbon captured from environmentally harmful sources, such as through direct air capture technologies. This transformation would exemplify how emissions can be converted into valuable resources, aligning protein production with circular and climate-positive principles.

In summary, the methodological robustness of this dissertation fundamentally depends on the accessibility, completeness, and reliability of underlying data. Mindful, knowledge-based data assessment is critical, as data quality can significantly influence results. When data optimization is not feasible, assumptions and adjustments must be documented transparently and comprehensively. By adhering to principles of comparability and methodological consistency, the limitations inherent in sustainability assessments can be mitigated, though not entirely eliminated.

However, while the presented studies already provide important results, there remains considerable potential for structural and methodological enhancements to improve their applicability in real-world contexts. Future work could focus on refining data integration processes, expanding indicator coverage, and examining different stakeholder preferences implemented on the optimization results. Additionally, advancing approaches for AW quantification and exploring emerging protein technologies will further strengthen the practical relevance of sustainability assessments.

6 References

ADEME (2023) Agribalyse Database (Version 3.1). ADEME (Agence de la transition écologique), Angers, France

Alejandrino C, Mercante I, Bovea MD (2021) Life cycle sustainability assessment: Lessons learned from case studies. Environmental Impact Assessment Review 87:106517. https://doi.org/10.1016/j.eiar.2020.106517

Andretta I, Hickmann FMW, Remus A, Franceschi CH, Mariani AB, Orso C, Kipper M, Létourneau-Montminy M-P, Pomar C (2021) Environmental Impacts of Pig and Poultry Production: Insights From a Systematic Review. Front Vet Sci 8. https://doi.org/10.3389/fvets.2021.750733

Aranda J, Zambrana-Vásquez D, Del-Busto F, Círez F (2021) Social Impact Analysis of Products under a Holistic Approach: A Case Study in the Meat Product Supply Chain. Sustainability 13(21):12163. https://doi.org/10.3390/su132112163

Asha LN, Dey A, Yodo N, Aragon LG (2022) Optimization Approaches for Multiple Conflicting Objectives in Sustainable Green Supply Chain Management. Sustainability 14(19):12790. https://doi.org/10.3390/su141912790

Bandekar PA, Leh M, Bautista R, Matlock MD, Thoma G, Ulrich R (2019) Life cycle assessment of alternative swine management practices. Journal of Animal Science 97(1):472–484. https://doi.org/10.1093/jas/sky425

Basset-Mens C, van der Werf HMG (2005) Scenario-based environmental assessment of farming systems: the case of pig production in France. Agriculture, Ecosystems & Environment 105(1–2):127–144. https://doi.org/10.1016/j.agee.2004.05.007

Bava L, Zucali M, Sandrucci A, Tamburini A (2017) Environmental impact of the typical heavy pig production in Italy. Journal of Cleaner Production 140:685–691. https://doi.org/10.1016/j.jclepro.2015.11.029

Benoit C, Mazijn B (2009) Guidelines for social life cycle assessment of products: a social and socio-economic LCA code of practice complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development. United Nations Environmental Programme

Benoit-Norris C, Cavan DA, Norris G (2012) Identifying Social Impacts in Product Supply Chains:Overview and Application of the Social Hotspot Database. Sustainability 4(9):1946–1965. https://doi.org/10.3390/su4091946

Beylot A, Secchi M, Cerutti A, Merciai S, Schmidt J, Sala S (2019) Assessing the environmental impacts of EU consumption at macro-scale. Journal of Cleaner Production 216:382–393. https://doi.org/10.1016/j.jclepro.2019.01.134

Bonneau M, Klauke TN, Gonzàlez J, Rydhmer L, Ilari-Antoine E, Dourmad JY, de Greef K, Houwers HWJ, Cinar MU, Fàbrega E, Zimmer C, Hviid M, van der Oever B, Edwards SA (2014) Evaluation of the sustainability of contrasted pig farming systems: integrated evaluation. Animal 8(12):2058–2068. https://doi.org/10.1017/S1751731114002122

Boulay A-M, Bare J, Benini L, Berger M, Lathuillière MJ, Manzardo A, Margni M, Motoshita M, Núñez M, Pastor AV, Ridoutt B, Oki T, Worbe S, Pfister S (2018) The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int J Life Cycle Assess 23(2):368–378. https://doi.org/10.1007/s11367-017-1333-8

Cederberg C, Wivstad M, Bergkvist P, Mattsson B, Ivarsson K (2005) Environmental Assessment of Plant Protection Strategies Using Scenarios for Pig Feed Production. AMBIO: A Journal of the Human Environment 34(4):408–413. https://doi.org/10.1579/0044-7447-34.4.408

Cherubini E, Zanghelini GM, Alvarenga RAF, Franco D, Soares SR (2015) Life cycle assessment of swine production in Brazil: a comparison of four manure management systems. Journal of Cleaner Production 87:68–77. https://doi.org/10.1016/j.jclepro.2014.10.035

Choi KR, Yu HE, Lee SY (2022) Microbial food: microorganisms repurposed for our food. Microbial Biotechnology 15(1):18–25. https://doi.org/10.1111/1751-7915.13911

CML (2016) CML-IA Characterisation Factors Database. Institute of Environmental Sciences, Leiden University, Leiden

Costa D, Quinteiro P, Dias AC (2019) A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues. Science of The Total Environment 686:774–787. https://doi.org/10.1016/j.scitotenv.2019.05.435

De Brouwer P (2020) The Big R-Book: From Data Science to Learning Machines and Big Data. In: 1st edn. Wiley

Derbyshire EJ (2020) Is There Scope for a Novel Mycelium Category of Proteins alongside Animals and Plants? Foods 9(9):1151. https://doi.org/10.3390/foods9091151

Djekic I, Bozickovic I, Djordjevic V, Smetana S, Terjung N, Ilic J, Doroski A, Tomasevic I (2021) Can we associate environmental footprints with production and consumption using Monte Carlo simulation? Case study with pork meat. J Sci Food Agric 101(3):960–969. https://doi.org/10.1002/jsfa.10704

Dolman MA, Vrolijk HCJ, Boer IJM (2012) Exploring variation in economic, environmental and societal performance among Dutch fattening pig farms. Livestock Science 149(1–2):143–154. https://doi.org/10.1016/j.livsci.2012.07.008

Dong Y, Xu Y, Li H, Dai M (2008) A comparative study of the numerical scales and the prioritization methods in AHP. European Journal of Operational Research 186(1):229–242. https://doi.org/10.1016/j.ejor.2007.01.044

Dorca-Preda T, Kongsted AG, Andersen HM-L, Kristensen T, Theil PK, Knudsen MT, Mogensen L (2023) Refining life cycle nutrient modeling in organic pig production. An analysis focusing on feeding strategies in organic Danish pig farming. Livestock Science 272:105248. https://doi.org/10.1016/j.livsci.2023.105248

Dorca-Preda T, Mogensen L, Kristensen T, Knudsen MT (2021) Environmental impact of Danish pork at slaughterhouse gate – a life cycle assessment following biological and technological changes over a 10-year period. Livestock Science. https://doi.org/10.1016/j.livsci.2021.104622

Dourmad JY, Ryschawy J, Trousson T, Bonneau M, Gonzàlez J, Houwers HWJ, Hviid M, Zimmer C, Nguyen TLT, Morgensen L (2014) Evaluating environmental impacts of contrasting pig farming systems with life cycle assessment. Animal 8(12):2027–2037. https://doi.org/10.1017/S1751731114002134

Ecoinvent Association (2023) Ecoinvent Version 3.9.1 APOS

Eskandarpour M, Dejax P, Miemczyk J, Péton O (2015) Sustainable supply chain network design: An optimization-oriented review. Omega 54:11–32. https://doi.org/10.1016/j.omega.2015.01.006

FAO (2023) Global Statistical Yearbook, FAO Regional Statistical Yearbooks. In: FAOSTAT. https://www.fao.org/faostat/en/#data/QCL/visualize. Accessed 11 Mar 2024

Finnigan T, Needham L, Abbott C (2017) Mycoprotein. In: Sustainable Protein Sources. Elsevier, pp 305–325

Gebre SL, Cattrysse D, Alemayehu E, Van Orshoven J (2021) Multi-criteria decision making methods to address rural land allocation problems: A systematic review. International Soil and Water Conservation Research 9(4):490–501. https://doi.org/10.1016/j.iswcr.2021.04.005

Gislason S, Birkved M, Maresca A (2023) A systematic literature review of life cycle assessments on primary pig production: Impacts, comparisons, and mitigation areas. Sustainable Production and Consumption 42:44–62. https://doi.org/10.1016/j.spc.2023.09.005

González-García S, Belo S, Dias AC, Rodrigues JV, Da Costa RR, Ferreira A, Andrade LP, Arroja L (2015) Life cycle assessment of pigmeat production: Portuguese case study and proposal of improvement options. Journal of Cleaner Production 100:126–139. https://doi.org/10.1016/j.jclepro.2015.03.048

GreenDelta GmbH (2023a) CML-IA baseline Method in openLCA

GreenDelta GmbH (2023b) openLCA

Guinee JB, De Bruijn H, Van Duin R, Huijbregts MAJ, Gorree M, Heijungs R, Huppes G, Kleijn R, De Koning A, Van Oers L, Wegener Sleeswijk A, Suh S, Udo De Haes HA (eds) (2002) Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards. Springer Netherlands, Dordrecht

Halberg N, Hermansen JE, Kristensen IS, Eriksen J, Tvedegaard N, Petersen BM (2010) Impact of organic pig production systems on CO2 emission, C sequestration and nitrate pollution. Agron Sustain Dev 30(4):721–731. https://doi.org/10.1051/agro/2010006

Halpern BS, Frazier M, Verstaen J, Rayner P-E, Clawson G, Blanchard JL, Cottrell RS, Froehlich HE, Gephart JA, Jacobsen NS, Kuempel CD, McIntyre PB, Metian M, Moran D, Nash KL, Többen J, Williams DR (2022) The environmental footprint of global food production. Nat Sustain 5(12):1027–1039. https://doi.org/10.1038/s41893-022-00965-x

Hartmann C, Furtwaengler P, Siegrist M (2022) Consumers' evaluation of the environmental friendliness, healthiness and naturalness of meat, meat substitutes, and other protein-rich foods. Food Quality and Preference 97:104486. https://doi.org/10.1016/j.foodqual.2021.104486

Herrmann M, Mehner E, Egger L, Portmann R, Hammer L, Nemecek T (2024) A comparative nutritional life cycle assessment of processed and unprocessed soy-based meat and milk alternatives including protein quality adjustment. Front Sustain Food Syst 8:1413802. https://doi.org/10.3389/fsufs.2024.1413802

Hietala S, Usva K, Vieraankivi M-L, Vorne V, Nousiainen J, Leinonen I (2024) Environmental sustainability of Finnish pork production: life cycle assessment of climate change and water scarcity impacts. Int J Life Cycle Assess 29(3):483–500. https://doi.org/10.1007/s11367-023-02258-7

Huang IB, Keisler J, Linkov I (2011) Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. Science of The Total Environment 409(19):3578–3594. https://doi.org/10.1016/j.scitotenv.2011.06.022

Huguet J, Chassard C, Lavigne R, Irlinger F, Souchon I, Marette S, Saint-Eve A, Pénicaud C (2023) Environmental performance of mixed animal and plant protein sources for designing new fermented foods. Cleaner Environmental Systems 9:100115. https://doi.org/10.1016/j.cesys.2023.100115

Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22(2):138–147. https://doi.org/10.1007/s11367-016-1246-y

Ishizaka A, Balkenborg D, Kaplan T (2011) Influence of aggregation and measurement scale on ranking a compromise alternative in AHP. Journal of the Operational Research Society 62(4):700–710. https://doi.org/10.1057/jors.2010.23

ISO (2009) ISO 14040 Standard. 13.020.10

ISO (2018) ISO 14044 Standard. 13.020.10

Järviö N, Maljanen N-L, Kobayashi Y, Ryynänen T, Tuomisto HL (2021) An attributional life cycle assessment of microbial protein production: A case study on using hydrogen-oxidizing bacteria. Science of The Total Environment 776:145764. https://doi.org/10.1016/j.scitotenv.2021.145764

Kloepffer W (2008) Life cycle sustainability assessment of products: (with Comments by Helias A. Udo de Haes, p. 95). Int J Life Cycle Assess 13(2):89–95. https://doi.org/10.1065/lca2008.02.376

Kobayashi Y, EL-Wali M, Guðmundsson H, Guðmundsdóttir EE, Friðjónsson ÓH, Karlsson EN, Roitto M, Tuomisto HL (2023) Life-cycle assessment of yeast-based single-cell protein production with oat processing side-stream. Science of The Total Environment 873:162318. https://doi.org/10.1016/j.scitotenv.2023.162318

Lanzoni L, Whatford L, Atzori AS, Chincarini M, Giammarco M, Fusaro I, Vignola G (2023) Review: The challenge to integrate animal welfare indicators into the Life Cycle Assessment. Animal 17(5(100794)). https://doi.org/10.1016/j.animal.2023.100794

Lee DY, Mariano E, Choi Y, Park JM, Han D, Kim JS, Park JW, Namkung S, Li Q, Li X, Venter C, Hur SJ (2025) Environmental Impact of Meat Protein Substitutes: A Mini-Review. Food Science of Animal Resources 45(1):62–80. https://doi.org/10.5851/kosfa.2024.e109

Mackenzie SG, Leinonen I, Ferguson N, Kyriazakis I (2015) Accounting for uncertainty in the quantification of the environmental impacts of Canadian pig farming systems. J Anim Sci 93:3130–3143. https://doi.org/10.2527/jas2014-8403

Majumder M, Saha AK, Majumder M, Saha AK (2016) Multi Criteria Decision Making. Springer Singapore, Singapore, pp 9–12

Makara A, Kowalski Z, Lelek Ł, Kulczycka J (2019) Comparative analyses of pig farming management systems using the Life Cycle Assessment method. Journal of Cleaner Production 241:118305. https://doi.org/10.1016/j.jclepro.2019.118305

Marler RT, Arora JS (2004) Survey of multi-objective optimization methods for engineering. Struct Multidisc Optim 26(6):369–395. https://doi.org/10.1007/s00158-003-0368-6

Matassa S, Boon N, Pikaar I, Verstraete W (2016) Microbial protein: future sustainable food supply route with low environmental footprint. Microbial Biotechnology 9(5):568–575. https://doi.org/10.1111/1751-7915.12369

Mazac R, Järviö N, Tuomisto HL (2023) Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future. Science of The Total Environment 876:162796. https://doi.org/10.1016/j.scitotenv.2023.162796

McAuliffe GA, Takahashi T, Mogensen L, Hermansen JE, Sage CL, Chapman DV, Lee MRF (2017) Environmental trade-offs of pig production systems under varied operational efficiencies. Journal of Cleaner Production 165:1163–1173. https://doi.org/10.1016/j.jclepro.2017.07.191

Mellor DJ (2016) Updating Animal Welfare Thinking: Moving beyond the “Five Freedoms” towards “A Life Worth Living.” Animals (Basel) 6(3). https://doi.org/10.3390/ani6030021

Minden S, Grünberger A, Van Der Schaaf U, Neumann A, Rösch C, Sauer J, Kaster A-K (2024) Producing food from CO2 using microorganisms: Lots to do, little to lose! Trends in Food Science & Technology 154:104778. https://doi.org/10.1016/j.tifs.2024.104778

Mohammed A, Wang Q (2017) The fuzzy multi-objective distribution planner for a green meat supply chain. International Journal of Production Economics 184:47–58. https://doi.org/10.1016/j.ijpe.2016.11.016

Mohebalizadehgashti F, Zolfagharinia H, Amin SH (2020) Designing a green meat supply chain network: A multi-objective approach. International Journal of Production Economics 219:312–327. https://doi.org/10.1016/j.ijpe.2019.07.007

Møller H, Rydhmer L, Christensen T, Poulsen LK, Olsen HF (2024) Social life cycle assessment in current and future Norwegian livestock production. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-024-02345-3

Nguyen TLT, Hermansen JE, Mogensen L (2011) Environmental Assessment of danish pork

Nickel S, Rebennack S, Stein O, Waldmann K-H (2022) Operations Research. Springer Berlin Heidelberg, Berlin, Heidelberg

Notarnicola B, Sala S, Anton A, McLaren SJ, Saouter E, Sonesson U (2017a) The role of life cycle assessment in supporting sustainable agri-food systems: A review of the challenges. Journal of Cleaner Production 140:399–409. https://doi.org/10.1016/j.jclepro.2016.06.071

Notarnicola B, Tassielli G, Renzulli PA, Castellani V, Sala S (2017b) Environmental impacts of food consumption in Europe. Journal of Cleaner Production 140:753–765. https://doi.org/10.1016/j.jclepro.2016.06.080

Noya I, Villanueva-Rey P, González-García S, Fernandez MD, Rodriguez MR, Moreira MT (2017) Life Cycle Assessment of pig production: A case study in Galicia. Journal of Cleaner Production 142:4327–4338. https://doi.org/10.1016/j.jclepro.2016.11.160

Oglethorpe D (2010) Optimising Economic, Environmental, and Social Objectives: A Goal-Programming Approach in the Food Sector. Environ Plan A 42(5):1239–1254. https://doi.org/10.1068/a42292

Pazmiño ML, Ramirez AD (2021) Life Cycle Assessment as a Methodological Framework for the Evaluation of the Environmental Sustainability of Pig and Pork Production in Ecuador. Sustainability 13(21):11693. https://doi.org/10.3390/su132111693

Pelletier N, Lammers P, Stender D, Pirog R (2010) Life cycle assessment of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper

Midwestern United States. Agricultural Systems 103(9):599–608. https://doi.org/10.1016/j.agsy.2010.07.001

Pereira A, Delmoitié B, Sakarika M (2024) Understanding the Potential of Microbial Protein as a more Sustainable Food Source. Food Science and Nutrition Cases 2024:fsncases20240008. https://doi.org/10.1079/fsncases.2024.0008

Pikaar I, Matassa S, Bodirsky BL, Weindl I, Humpenöder F, Rabaey K, Boon N, Bruschi M, Yuan Z, van Zanten H, Herrero M, Verstraete W, Popp A (2018) Decoupling Livestock from Land Use through Industrial Feed Production Pathways. Environ Sci Technol 52(13):7351–7359. https://doi.org/10.1021/acs.est.8b00216

Reckmann K, Traulsen I, Krieter J (2013) Life Cycle Assessment of pork production: A data inventory for the case of Germany. Livestock Science 157(2–3):586–596. https://doi.org/10.1016/j.livsci.2013.09.001

Roßmann M, Stratmann M, Rötzer N, Schäfer P, Schmidt M (2021) Comparability of LCAs — Review and Discussion of the Application Purpose. In: Albrecht S, Fischer M, Leistner P, Schebek L (eds) Progress in Life Cycle Assessment 2019. Springer International Publishing, Cham, pp 213–225

Rubio NR, Xiang N, Kaplan DL (2020) Plant-based and cell-based approaches to meat production. Nat Commun 11(1):6276. https://doi.org/10.1038/s41467-020-20061-y

Saaty RW (1987) The analytic hierarchy process—what it is and how it is used. Mathematical Modelling 9(3–5):161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Savian M, Da Penha Simon C, Holden NM (2023) Evaluating environmental, economic, and social aspects of an intensive pig production farm in the south of Brazil: a case study. Int J Life Cycle Assessment 28(11):1544–1560. https://doi.org/10.1007/s11367-023-02223-4

Shahid M, Shah P, Mach K, Rodgers-Hunt B, Finnigan T, Frost G, Neal B, Hadjikakou M (2024) The environmental impact of mycoprotein-based meat alternatives compared to plant-based meat alternatives: A systematic review. Future Foods 10:100410. https://doi.org/10.1016/j.fufo.2024.100410

Shepon A, Eshel G, Noor E, Milo R (2016) Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. Environ Res Lett 11(10):105002. https://doi.org/10.1088/1748-9326/11/10/105002

Smetana S, Mathys A, Knoch A, Heinz V (2015) Meat alternatives: life cycle assessment of most known meat substitutes. Int J Life Cycle Assess 20(9):1254–1267. https://doi.org/10.1007/s11367-015-0931-6

Smetana S, Profeta A, Voigt R, Kircher C, Heinz V (2021) Meat substitution in burgers: nutritional scoring, sensorial testing, and Life Cycle Assessment. Future Foods 4:100042. https://doi.org/10.1016/j.fufo.2021.100042

Souza Filho PF, Andersson D, Ferreira JA, Taherzadeh MJ (2019) Mycoprotein: environmental impact and health aspects. World J Microbiol Biotechnol 35(10):147. https://doi.org/10.1007/s11274-019-2723-9

Sturme M, Berg JP van der, Kleter G (2025) Precision fermentation. FAO, Rome, Italy

Sun R, Liu X, Li D, Zhuang J, Qi S, Meng B, Liu M (2022) Optimization of China's pig production system to reduce environmental impacts based on a data envelopment and life cycle analysis model. Resources, Conservation and Recycling 185:106483. https://doi.org/10.1016/j.resconrec.2022.106483

Swarr TE, Hunkeler D, Klöpffer W, Pesonen H-L, Ciroth A, Brent AC, Pagan R (2011) Environmental life-cycle costing: a code of practice. Int J Life Cycle Assess 16(5):389–391. https://doi.org/10.1007/s11367-011-0287-5

Synonym Biotechnologies (2023) State of Global Fermentation Capacity. Industrial Biotechnology 19(2):62–68. https://doi.org/10.1089/ind.2023.29304.syn

Taherdoost H, Madanchian M (2023) Multi-Criteria Decision Making (MCDM) Methods and Concepts. Encyclopedia 3(1):77–87. https://doi.org/10.3390/encyclopedia3010006

Tang M, Miri T, Soltani F, Onyeaka H, Al-Sharify ZT (2024) Life Cycle Assessment of Plant-Based vs. Beef Burgers: A Case Study in the UK. Sustainability 16(11):4417. https://doi.org/10.3390/su16114417

Treml N, Naber E, Schultmann F (2025a) Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming. Sustainability 17(10):4677. https://doi.org/10.3390/su17104677

Treml N, Rudi A, Schultmann F (2025b) Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany. Journal of Cleaner Production 503(145408). https://doi.org/10.1016/j.jclepro.2025.145408

Treml N, Minden S, Grünberger A, Volk R, Rudi A, Schultmann F, Kaster A (2026a) Meat versus microbial protein—a life cycle assessment of present-day value chains. The International Journal of Life Cycle Assessment 31(5):65. https://doi.org/10.1007/s11367-026-02637-w

Treml N, Rudi A, Schultmann F (2026b) Assessing sustainability in the pork value chain: A multi-objective approach. *Submitted to a Scientific Journal.*

Umweltbundesamt (2024) Berichterstattung unter der Klimarahmenkonvention der Vereinten Nationen und dem Übereinkommen von Paris 2024. Umweltbundesamt

Upcraft T, Tu W-C, Johnson R, Finnigan T, Hung NV, Hallett J, Guo M (2021) Protein from renewable resources: mycoprotein production from agricultural residues. Green Chem 23(14):5150–5165. https://doi.org/10.1039/D1GC01021B

Valente C, Møller H, Johnsen FM, Saxegård S, Brunsdon ER, Alvseike OA (2020) Life cycle sustainability assessment of a novel slaughter concept. Journal of Cleaner Production 272:122651. https://doi.org/10.1016/j.jclepro.2020.122651

Visentin C, Trentin AWDS, Braun AB, Thomé A (2020) Life cycle sustainability assessment: A systematic literature review through the application perspective, indicators, and methodologies. Journal of Cleaner Production 270:122509. https://doi.org/10.1016/j.jclepro.2020.122509

Welfare Quality® (2009) Welfare Quality® assessment protocol for pigs (sows and piglets, growing and finishing pigs). Welfare Quality® Consortium, Lelystad, Netherlands

Williams A, Audsley E, Jones R, Weller R, Bryson R, Philipps L, Whitmore A, Glendining M, Dailey G (2006) Determining the environmental burdens and resource use in the production of agricultural and horticultural commodities. Cranfield University and Defra, Bedford

Winkler T, Schopf K, Aschemann R, Winiwarter W (2016) From farm to fork – A life cycle assessment of fresh Austrian pork. Journal of Cleaner Production 116:80–89. https://doi.org/10.1016/j.jclepro.2016.01.005

World Economic Forum (2019) Alternative Proteins. WEForum

Xu X, Sharma P, Shu S, Lin T-S, Ciais P, Tubiello FN, Smith P, Campbell N, Jain AK (2021) Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nat Food 2(9):724–732. https://doi.org/10.1038/s43016-021-00358-x

Zira S, Röös E, Ivarsson E, Hoffmann R, Rydhmer L (2020) Social life cycle assessment of Swedish organic and conventional pork production. Int J Life Cycle Assess 25(10):1957–1975. https://doi.org/10.1007/s11367-020-01811-y

Zira S, Rydhmer L, Ivarsson E, Hoffmann R, Röös E (2021) A life cycle sustainability assessment of organic and conventional pork supply chains in Sweden. Sustainable Production and Consumption 28:21–38. https://doi.org/10.1016/j.spc.2021.03.028

Part II
Research Papers

Paper A

Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany

Reference

Treml N, Rudi A, Schultmann F (2025b) Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany. Journal of Cleaner Production 503(145408). https://doi.org/10.1016/j.jclepro.2025.145408.

Journal of Cleaner Production 503 (2025) 145408

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Evaluating environmental impacts of pork production: A life cycle assessment of seven case studies in Germany

Nina Treml [*], Andreas Rudi, Frank Schultmann

Institute for Industrial Production (IIP), Karlsruhe Institute of Technology (KIT), Hertzstr. 16, 76187, Karlsruhe, Germany

ARTICLE INFO

Handling Editor: Yutao Wang

Keywords:
Pig farming
Biogas production
Slaughter
Processing
Sustainable agriculture
Meat sector
Livestock production

ABSTRACT

This study presents a cradle-to-gate life cycle assessment (LCA) of pork production in Germany, focusing on pig farming, slaughtering, and processing. The objective is to identify key stages in the production process that contribute most to environmental burdens and explore strategies for mitigation. Seven case studies are analysed, with primary data collected, and evaluated using the functional unit of 1 kg of product. The case studies include four pig farms: one breeding and rearing farm (BRE), one rearing and fattening farm (FAT), and two integrated farms (PIG 1, PIG 2). These farms cover feed production, manure management, and energy generation via biogas, where applicable. One slaughterhouse (SLA) and two processing facilities (PRO 1, PRO 2) complete the analysis. Environmental impacts are evaluated in three categories: global warming, acidification, and eutrophication. Compared to existing studies, global warming impacts are lower, while acidification and eutrophication impacts vary, with PIG 2 showing higher levels. The impacts of SLA are comparable or lower than those in the literature. Across all farming stages, feed production is the dominant contributor to environmental impacts, while energy consumption and waste treatment are key factors in slaughtering and processing. Sensitivity analyses examine variations in feed and energy inputs, and scenario analyses explore alternative feed composition, biogas use, and renewable energy integration. Results suggest biogas production reduces global warming and eutrophication impacts but increases acidification. Introducing economic allocation for feed by-products slightly raises overall burdens, and transitioning energy supply to renewable sources at the slaughterhouse improves environmental performance.

1. Introduction

The agricultural sector feeds the world, but it is also a substantial contributor to climate change and biodiversity loss. Although consumers do not yet believe that their food choices are influenced by sustainability concerns, the need for involvement of this topic is evident in the future (van Bussel et al., 2022). Dietary decisions are not only crucial for human health but also relevant when talking about pollution and emissions (Tilman and Clark, 2014). Food systems with their diverse structured supply chains offer a huge potential for improvement whilst being responsible for a remarkable part of anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021). Since not only GHG emissions are a menace for the environment, but the combination of emissions from the food sector influences many parts of the environment (Beylot et al., 2019), it becomes essential to broaden the assessment towards the inclusion of several effects besides those of GHG. Especially livestock production is contributing in several ways to threatening the environment exceeding those of plant-based foods by far (Halpern et al., 2022; Xu et al., 2021). Regarding the environmental pressure of food types considering their global production volume broken down by classes of pressure, Halpern et al. (2022) identify pig meat as the most burdening influence compared to other livestock, crops and fish. Moreover pig meat is not only one of the most consumed products but also has one of the highest economic values in Europe (Notarnicola et al., 2017a). The mentioned classes of pressure considered, are disturbed land area, greenhouse gas emissions, nutrient exposure, and water use (Halpern et al., 2022). To evaluate these classes, the methodology of live cycle assessment offers a broadly accepted toolbox (Notarnicola et al., 2017b). This paper provides a comprehensive, up-to-date environmental impact assessment of the pig and pork production sector in Germany, based on seven case studies in Germany. As Germany is one of the largest pork producers globally, these case studies offer detailed representative insights into the sector's value chain (FAO, 2023). Following the Paris agreement for climate protection from 2015 (UNFCCC, 2015), the

---

* Corresponding author.
E-mail address: nina.treml@kit.edu (N. Treml).

https://doi.org/10.1016/j.jclepro.2025.145408
Received 1 October 2024; Received in revised form 29 January 2025; Accepted 29 March 2025

German government takes action for the achievement of sustainability goals by supporting research in the agri-food sector enabling the presented study (BMEL, 2024). The study's primary objective is to compare environmental impacts across different production systems, emphasising the importance of careful interpretation when comparing case studies under varying conditions. Four case studies represent the pig farming stage, each reflecting distinct farming systems with different operational structures. Comparability between these systems must be approached cautiously, taking into account the specific features of each farm and acknowledging differences (Notarnicola et al., 2017b). Accordingly, van der Werf et al. (2020) highlight the necessity of considering system variations, such as organic farming, which can affect environmental performance due to functional unit choices. For slaughtering and processing, three more case studies are analysed. In addition, sensitivity analyses are conducted to explore the key drivers for each case study. It is noteworthy that previous studies have already documented the considerable influence of feed on the LCA results of pig farms (Gislason et al., 2023). Therefore, in addition to the reference scenario for the case study with the most reliable data sample, a scenario analysis focusing on the allocation of feed components is carried out. To assess the potential benefits of biogas production and renewable energy utilization, another scenario is calculated for the same case study. All assessments are standardised using the functional unit of 1 kg of product, acknowledging that the product evolves from live pigs to processed pork and various pork products throughout the value chain. The data used for this LCA was collected directly from farm and facility managers, ensuring robust and reliable input for the analysis. This data collection procedure elevates our approach in comparison to the lastly performed study on the German pork value chain from Reckmann et al. (2013). They obtained their data, as many studies do, from reports and literature sources, but not from an actual case study (González-García et al., 2015; McAuliffe et al., 2017; Pelletier et al., 2010; Reyes et al., 2019; Savian et al., 2023; Sun et al., 2022).

2. Materials and methods

The conducted LCA follows the guidelines of ISO standards 14040 and 14044 (ISO, 2018, 2009) as the structure builds up on the four phases.

2.1. *Definition of goal and scope*

As mentioned above, the most recent environmental assessment of pig and pork production in Germany was conducted by Reckmann et al. (2013). While their study integrated data from various sources, the present study is based entirely on primary data collected from on-farm assessments. This data is integrated into life cycle inventories and mapped to appropriate flows within the utilised databases. The study extends the scope by modelling three key stages of the pork value chain - pig farming, slaughtering, and processing - across seven case studies. This broader approach provides a more detailed and system-specific analysis of environmental impacts. All farms and facilities evaluated in this study are located in central Germany. The goal of this research is to quantify the environmental burdens associated with each production process and highlight the system-specific differences that influence the results. The functional unit is defined as 1 kg of product, aligned with the operational scope of each facility. Most of the case studies focus on pig production, covering a range of farming systems from a cradle-to-farm gate perspective (BRE, FAT, PIG 1, PIG 2). While BRE represents a breeding farm and FAT a fattening farm, PIG 1 and 2 cover integrated pig breeding and fattening. These systems exhibit a diversity of husbandry practices, encompassing both conventional and organic approaches. Additionally, they demonstrate a spectrum of integration across the three principal stages of pig farming: breeding, rearing, and fattening (see Fig. 1 and Table 1). However, they are unified by a common functional unit, defined as 1 kg of live weight for the pig. Following animal production, the value chain progresses through slaughterhouse operations captured by a case study of a slaughterhouse (SLA) with the functional unit of 1 kg carcass weight to the final processing of pork products (PRO 1, PRO 2). The case studies PRO 1 and 2 present two processing facilities that are assessed and share the functional unit of 1 kg processed meat. Transport between facilities is excluded from the assessment, and each case study employs a gate-to-gate approach. Importantly, the case studies do not represent a continuous, integrated supply chain. For instance, in Fig. 1 the connection between fattening and slaughtering is presented to demonstrate the general structure of the value chain, but these links are not exclusive and based on real world supply chains. Two partial exceptions exist: BRE supplies weaners and fattening pigs to FAT, and SLA delivers pork halves to PRO 1. The farms BRE and FAT are operated by the same entity, making them comparable in terms of operational structures, but BRE is not the sole supplier to FAT, and PRO 1 sources from multiple

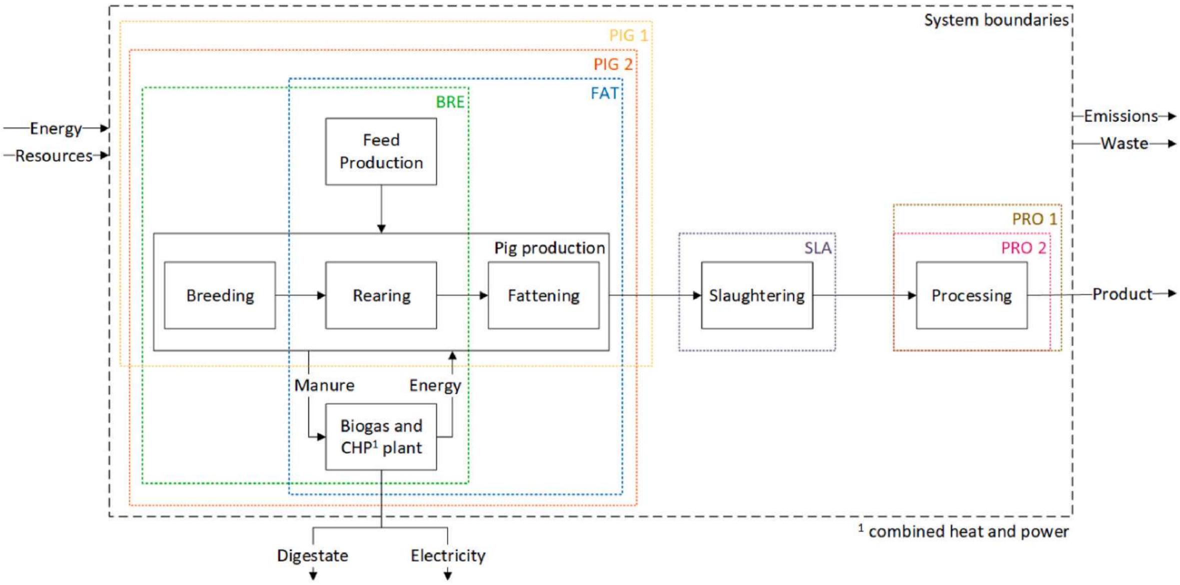


Fig. 1. System boundaries for the considered case studies aligned with the supply chain.

Table 1
Main farm characteristics of the pig production case studies.

Characteristics		BRE	FAT	PIG 1	PIG 2
System		conv[a]	conv	org[b]	conv, oc[c]
Number of sold pigs in 2021 (average weight of pigs when sold in kg)	*Sows*	1054 (240)		47 (245)	46 (232)
	Suckling piglets		1736 (26)		
	Piglets	158898 (28)	8934 (28)	700 (33)	30 (30)
	Finisher		57040 (125)	579 (136)	5134 (141)
Biogas plant installed		yes	yes	no	yes
Heating source		biogas	biogas, natural gas, light fuel oil	natural gas	biogas
Energy exported to grid		CHP[d]	CHP	PV[e]	PV, CHP
Water source		well	well	tap	tap
Emissions declaration required		yes	yes	no	no

[a] Conventional.
[b] Organic.
[c] Stable with outdoor climate.
[d] Combined heat and power plant.
[e] Photovoltaic.

slaughterhouses, not just SLA. Thus, the study does not depict a complete linear value chain. Despite the gate-to-gate approach, waste treatment is considered in all processes. A total of seven case studies are analysed, with sensitivity and scenario analyses performed to examine their specific characteristics (see Sections 3.5 and 3.6).

2.1.1. *Pig farming*

The diversity of the four pig production case studies, as shown in Fig. 1, provides insight into the wide range of possible pig farming systems. Pig production is divided into three primary horizontally integrated sub-systems, alongside vertically integrated feed production and an optional manure treatment process including a biogas plant (see Fig. 1). The feed production process for all farms includes the most detailed breakdown of feed compositions, with components and their respective mass proportions representing primary data from the farm management assigned to data from Ecoinvent and Agribalyse (ADEME, 2023; Ecoinvent Association, 2023). All feed mixtures are derived from commercial labels or the record of on-farm based processing and not from predefined mixtures from the databases. Fig. 2 exemplifies the detailed information on ingredients and compositions for one feed mixture of case study BRE. This level of detail is achieved for every feed component of the case studies BRE and FAT. Regarding supplement mixtures like the Gestation mix of Fig. 2, a descending list by bulk quantity is given. Therefore, we assumed a descending percentage according to the other mixtures (see Fig. 2: downstream branches of Gestation Mix). For PIG 1 and 2, the feed mixes are essentially fewer and less cross-linked, in line with the size of the farms (see Fig. 3), which makes it easier to implement in the inventory. All ingredients, to the level of detail shown in Fig. 2, are derived from primary sources from farm management and are only mapped to the most accurate lowest level flow from Ecoinvent and Agribalyse as for example wheat grain production or salmon oil (see Fig. 2). To comprehensively gather the impact of the feed sources of purchased feed components the market

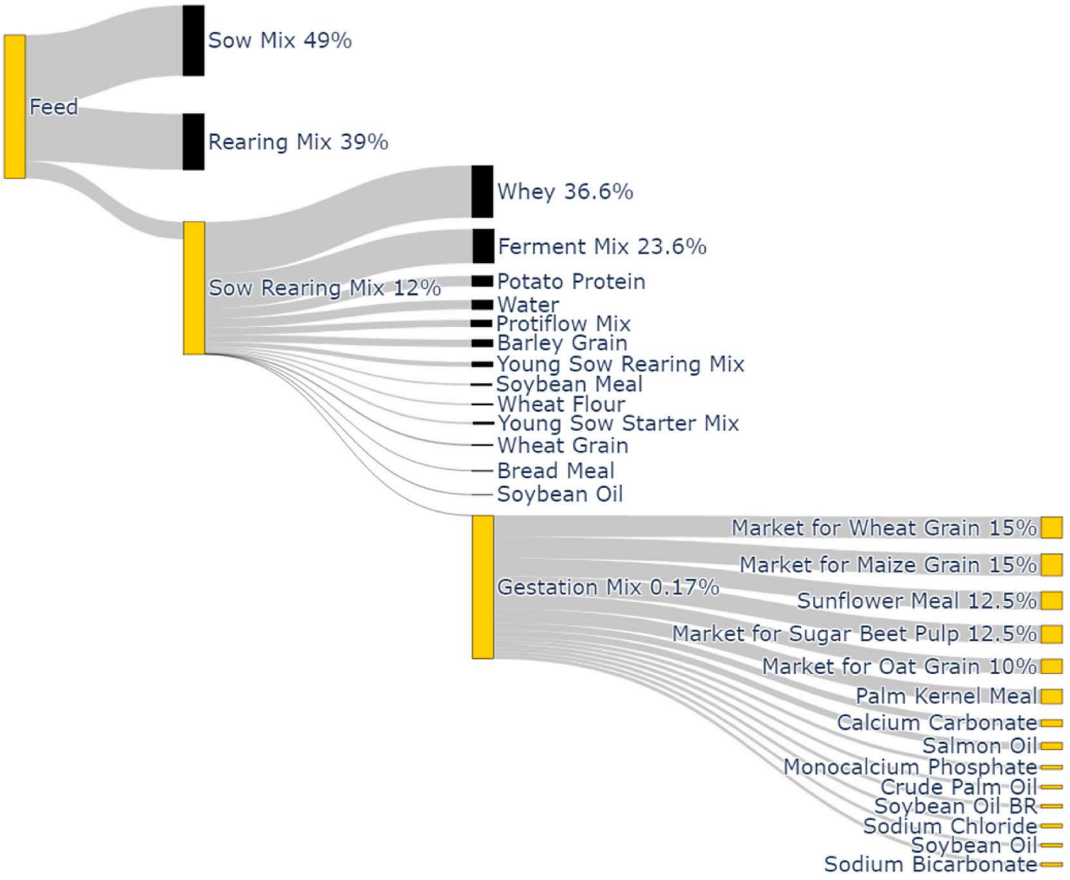


Fig. 2. The Sankey diagram quantitatively visualises the disaggregation of the feed composition of the BRE case study, broken down from mixtures and components to ingredients for the specific feed mix *Gestation Mix*.

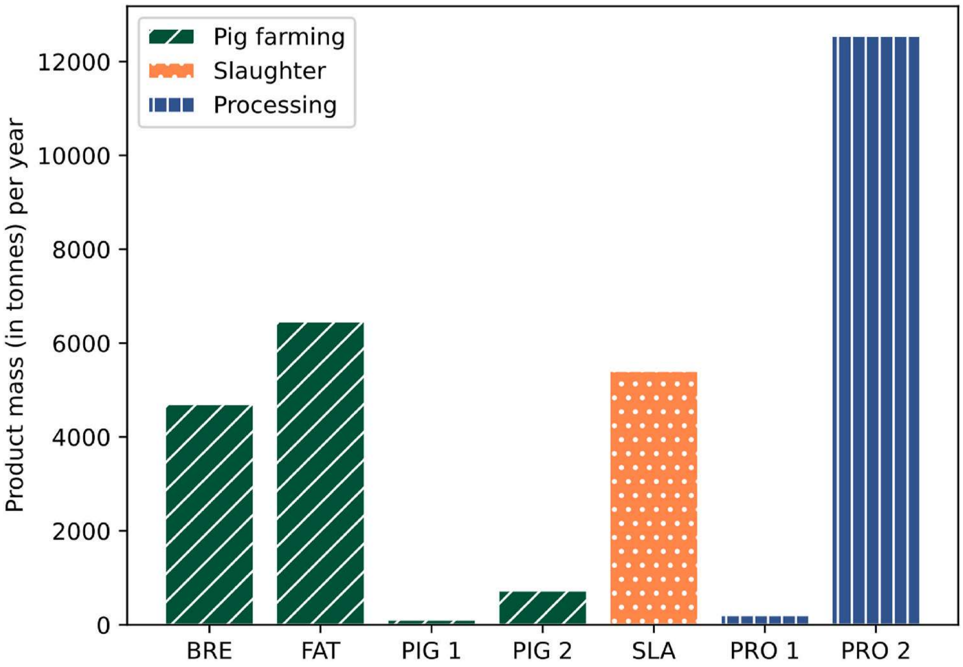


Fig. 3. Product masses in tonnes per year and case study.

activity providers are chosen for Ecoinvent data especially covering transportation processes (Ecoinvent Association, 2023). For the case studies BRE and FAT feed is completely sourced outside the farm, while PIG 1 and 2 also partly produce their own feed components. These components are wheat and barley in the case of PIG 2, and clover grass and straw, which represent the largest mass fraction for PIG 1's own production. For feed produced on the farm, the Ecoinvent production processes are mapped without additional transport (Ecoinvent Association, 2023). Most Agribalyse processes do not offer more than one possible provider, so the feed components mapped to this database are assigned to the only or most suitable provider based on the above approach (ADEME, 2023). Water is sourced from wells for both BRE and FAT, but while water use is recorded for BRE, no such data is available for FAT. The case study BRE covers the entire cycle, beginning with insemination (7 days), followed by gestation (115 days), farrowing, and a 25-day lactation period. Weaning occurs at 8 kg, and rearing continues for 49 days until the piglets reach 30 kg. For products BRE distinguishes between piglets destined for breeding and those for fattening, with the latter being sent off-farm for fattening, while breeding piglets remain for 207 days of gilt rearing before the cycle repeats. On FAT, the fattening process begins with 30 kg piglets and continues for 130 days until a live weight of around 125 kg. Additionally, the farm covered by case study FAT, like BRE, maintains a rearing unit where weaners are raised to fattening piglets. In contrast, the case studies PIG 1 and PIG 2 integrate breeding, rearing, and fattening on a single farm. The main characteristics of these farms considering the farm management, such as energy consumption, production, and housing systems, are detailed in Table 1. Across all systems, the primary product is the pig, though manure can also be considered a valuable co-product. In accordance with ISO standards, allocation is avoided, and system expansion is applied for manure treatment via biogas plants or avoided fertilizer production (ISO, 2018). The considered farms produce energy in form of electricity or/and heat that is either used on farm or transferred to the grid (for further detail see the specific inventories in Appendix A). This energy is provided by either the biogas plant, which is connected to a combined heat and power (CHP) plant, or photovoltaic panels installed on the stables or both. The data for mapping these production processes, such as the specific power of the CHP, to the Ecoinvent data is obtained from the relevant manuals provided by the farm management. In addition, the energy consumption of the case studies is determined by reviewing energy supplier invoices. This data is collated and then matched to the processes offered by Ecoinvent, trying to stay as close as possible to the original data. See Appendix D for the task.

One notable observation is the substantial variation in production volumes between farms, even within the same value chain stages as shown in Fig. 3. Both case studies, BRE and FAT, stand out compared to the other two pig farms in terms of the mass of pigs sold. Their larger production scales, encompassing all on-farm processes, exceed regulatory thresholds, requiring them to submit emissions declarations. In Germany, companies and plant operators that exceed certain threshold values for emissions must submit an emissions declaration every four years. An emissions declaration is an official statement of the amount and type of pollutants a company or facility releases into the environment. It is regularly required as part of the legal monitoring of environmental pollution (LUBW, 2024). The emissions declaration is based on calculation factors assigned to emissions for e.g. specific agricultural systems, machines and power production procedures based on the research of IPCC (2014). Therefore, the implementation of the emissions declarations results into the inventory offers a convenient way to assess the emerging emissions of these processes. For the BRE and FAT study, emissions for pig housing are included in these emissions declarations, which include not only enteric fermentation emissions but also manure-related emissions. As enteric fermentation does not play a relevant role for pigs compared to ruminants (FAO, 2018; Zervas and Tsiplakou, 2012), the associated emissions are not included for PIG 1 and 2 due to their low production volumes. Manure management is included as described above and in Section 2.2. Furthermore, these cut-off decisions are based on the production output of BRE and FAT compared to PIG 1 and 2. The size of BRE and FAT provides much more scope for mitigation strategies in these sectors, making a specific assessment much more relevant.

2.1.2. Slaughtering and processing

The slaughterhouse (SLA) produces pork carcasses as the main product, with blood being a by-product. To exlusively assess the pork as product the application of an allocation becomes inevitable. The LCA results are allocated based on mass, with over 99.7 % of the impacts assigned to the main product, which is in line with the findings of Vergé et al. (2016) for allocation in the case of environmental assessment of swine. The facility primarily serves smaller producers with low animal numbers, often from organic farming systems. The animals are delivered by trucks, then have time to relax before the slaughter process starts. The pig are stunned with an electro stunning device before they are slaughtered by a stab in the carotid artery in consequence of which they bleed out. The bristles are then removed in a special hot water process and the carcass is eviscerated and cleaned. Heat for these processes is supplied by an on-site combined heat and power (CHP) plant and gas boilers fueled by natural gas. Electricity is generated by the CHP and supplemented by the power grid. The product system also includes water use and treatment, the consumption and disposal of auxiliary and operating materials, and the treatment of slaughterhouse waste. Slaughterhouse waste comprises non useable parts for further processing for example the intestines and most of the blood.

PRO 2 stands out as a large-scale meat processing factory in terms of product volume, while PRO 1 is a smaller facility producing approximately 200 tonnes of pork products annually (see Fig. 3). Additionally, PRO 1 primarily handles small quantities of organic meat. Both processing factories produce various pork products, utilising a range of materials beyond just packaging and cleaning supplies. The facilities are characterised by the presence of installed cooling and smoking chambers, in addition to packaging lines. The product systems include energy consumption and waste treatment for the materials used. While PRO 2 focuses exclusively on pork products, around 20 % of PRO 1's output is beef. Consequently, environmental impacts are allocated by mass to the pork products.

2.2. Life cycle inventory

Primary data for the seven case studies was collected from 2022 to 2024 as a part of the SPECK research project (SPECK, 2021). Three case studies (BRE, FAT, SLA) were conducted with directly involved project participants and therefore hold the most reliable and comprehensive data sets in comparison to the obtained data for the other considered studies. Four additional case studies, not directly connected to the project, were acquired through comprehensive data collection. The data is obtained by interviewing the managers of the facilities and farms. The retrieved data sets are aligned with Ecoinvent datasets of version 3.9.1 and the French agriculture database Agribalyse of version 3.1 (ADEME, 2023; Ecoinvent Association, 2023). For inventory data for all seven case studies, we refer to Appendix A, while the inventory of case study BRE and the affiliated biogas production and conversion process are displayed in this section.

The farm of case study BRE includes the breeding and rearing of both fattening pigs and breeding sows, as described in Section 2.1.1. The inventory for this breeding farm, along with its associated manure treatment processes, is presented in Table 2 and Table 3. The pig farming process inventory is normalised based on the total mass of pigs sold annually (see Fig. 3), resulting in a functional unit of 1 kg live weight pig. This process covers the overall farm performance, including the biogas production and conversion system. As in all pig production case studies, feed production is incorporated into the LCA. Fig. 2 details the composition of a specific feed component for BRE, and such breakdowns are performed for every case study. For BRE, 13.15 kg of feed is consumed per kilogram of sold pig. This contrasts with FAT, where the feed consumption is approximately 4 kg (see Appendix A). The difference can be attributed to the varying nutritional requirements and metabolic efficiencies between breeding and fattening farms.

The energy requirements are met through heat generated by the on-site CHP plant, which uses biogas produced on the farm (see Fig. 1), and electricity sourced from the grid. Per kilogram of sold pig, approximately 50 g of carcasses and other animal-related waste must be treated. This waste stream originates from various sources, such as pigs that die from illness, remnants from castration, or birth-related materials like afterbirths. The emissions listed on the output side are derived from the farm's emissions declaration, which is based on specific multipliers tailored to the farm's operational characteristics.

Table 2
Inventory data per functional unit (1 kg of live weight pig at farm gate) corresponding to the breeding farm (BRE).

Inputs/Outputs	Amount	Unit	Data source	Comment
Inputs				
Feed	13.15	kg	Primary data	
Electricity: grid	0.56	kWh	Primary data	Average 2018–2020
Heat: CHP	0.91	kWh	Primary data	Output from biogas process
Water	7.06	dm^3	Primary data	
Outputs				
Sows and piglets	*1*	*kg*	Primary data	Functional unit
Manure	8.93	dm^3	Primary data	Input for biogas process
Waste: household waste	55.29	g	Primary data	
Waste: carcasses	50.54	g	Primary data	
Ammonia	10.33	g	Primary data	Based on emissions declaration
Nitrous oxide	0.29	g·a	Primary data	Based on emissions declaration
Methane	3.16	g	Primary data	Based on emissions declaration
Particulate Matter, <2.5 um	0.16	g	Primary data	Based on emissions declaration
Particulates	0.90	g	Primary data	Based on emissions declaration
Particulates, <10 um	0.57	g	Primary data	Based on emissions declaration

Table 3
Inventory data per cubic meter added manure corresponding to the biogas plant and CHP of the breeding farm (BRE).

Inputs/Outputs	Amount	Unit	Data source	Comment
Inputs				
Maize silage	142.86	kg	Primary data	
Manure	*1*	m^3	Primary data	Functional unit; Output from main process
Outputs				
Heat: CHP	101.58	kWh	Primary data	Input to main process
Electricity: CHP	148.81	kWh	Primary data	Fed to grid; credit
Inorganic nitrogen fertilizer, as N	4.25	kg	Primary data	Credit for digestate
Inorganic phosphorus fertilizer, as P_2O_5	0.83	kg	Primary data	Credit for digestate
Inorganic potassium fertilizer, as K_2O	4.54	kg	Primary data	Credit for digestate

The inventory for the manure treatment process in the biogas plant, along with its subsequent use in the CHP plant to produce electricity and heat, is detailed in Table 3. In this case study, the pigs produced a total of 42,000 m^3 of manure in 2021. This manure then is co-fermented with maize silage to produce biogas. The substrate ratio calculated from the values in Table 3 reveals a relatively low input of the energy crop maize silage with 12.5 %. This co-substrate must be sourced and purchased from outside the farm, and its cultivation generates additional emissions. The resulting biogas is converted into heat, which is used directly on the farm, and electricity, which is fed into the grid, providing a credit in the LCA.

Table 4
Environmental impact of the four pig production case studies for 1 kg live weight at farm gate for the considered impact categories global warming, acidification and eutrophication. Some insights into the contribution of feed, manure management and the resulting credits are added in italics. The produced heat from the CHP is used directly on-farm for every case study and therefore is not influencing the results.

Impact category		BRE	FAT	PIG 1	PIG 2
Global Warming		**1.52**	**2.00**	**1.72**	**0.79**
kg CO_2 eq	*contribution of feed*	*1.82*	*1.95*	*1.86*	*2.35*
	w/o credits from biogas/manure	*2.43*	*2.78*	*1.89*	*5.04*
	credit for fertilizer	*−0.27*	*−0.26*	*−0.16*	*−1.03*
	credit for electricity (CHP)	*−0.63*	*−0.53*	-	*−3.22*
Acidification		**29.25**	**30.65**	**18.83**	**48.10**
g SO_2 eq	*contribution of feed*	*11.98*	*11.54*	*19.89*	*18.47*
	w/o credits from biogas/manure	*31.85*	*32.99*	*19.84*	*61.94*
	credit for fertilizer	*−1.49*	*−1.42*	*−1.01*	*−6.02*
	credit for electricity (CHP)	*−1.10*	*−0.92*	-	*−7.83*
Eutrophication		**14.71**	**15.90**	**20.71**	**22.46**
g PO_4^{3-} eq	*contribution of feed*	*11.83*	*11.68*	*21.25*	*16.74*
	w/o credits from biogas/manure	*18.38*	*19.00*	*21.04*	*40.13*
	credit for fertilizer	*−0.51*	*−0.48*	*−0.32*	*−1.94*
	credit for electricity (CHP)	*−3.15*	*−2.62*	-	*−15.74*

Additionally, the digestate from the biogas process replaces synthetic fertilizers, generating another credit by offsetting the production of synthetic fertilizers. The basis for calculating the credit is the nutrient analysis of the digestate in tanks, scaled up to the masses stored. The system expansion is based on the resulting nutrient masses that are mapped 1:1 to the fertilizer processes, e.g. 1 kg of nitrogen in the digestate to 1 kg of inorganic nitrogen fertilizer as nitrogen, listed in Table 3 (Hollas et al., 2022). The substituted fertilizer process is from Ecoinvent (2023) (see also Appendix D). Manure and digestate are stored in covered tanks for every assessed case study and therefore do not cause considerable additional emissions. The leakages of methane are negligible and not included in this study (Adams and McManus, 2019; Lijó et al., 2014; Riaño and García-González, 2015). For the remaining two case studies FAT and PIG 2 with a biogas plant the co-substrate situation is as follows. For FAT, the co-substrates maize silage and wheat grain are purchased. Case study PIG 2 produces some co-substrates such as maize and ryegrass silage and grains on the farm but expands its portfolio with supplied cattle and poultry manure (see Appendix A.5).

2.3. Life cycle impact assessment

Following the LCA framework, the impact assessment forms a crucial phase as it includes the selection of impact categories and the relevant factors influencing the results. The impact categories in the case studies are chosen based on a comprehensive literature review of LCAs in pig farming and pork production (see Appendix C) and the findings of Gislason et al. (2023). These categories align with the findings of McAuliffe et al. (2016) and McClelland et al. (2018) regarding LCAs for pork production and livestock systems in general. The chosen categories are global warming, acidification and eutrophication, representing by far the most applied categories as Gislason et al. (2023) detected. Assessing these categories therefore forms the basis for the comparability and tangibility of our study, in line with the majority of research on livestock value chains. We applied the widely recognised CML-IA baseline method from the openLCA LCIA Methods 2.3.2 package, as it is compatible with the versions of the databases used as introduced in Section 2.2 (GreenDelta GmbH, 2023). The CML method is a midpoint-oriented approach, covering the relevant categories of global warming measuring the global warming potential (GWP) over a 100-year time horizon without land use change consideration, acidification, and eutrophication (European Commission, 2011). It should be noted that land use or occupation, another important impact category in this context (Gislason et al., 2023), is not addressed in this study. This is because the impact assessment method presented here does not encompass this category, and the combination of different impact assessment methods may obscure the clarity of the results.

Processes involving energy production or yielding co-products that are used beyond the system boundaries are addressed using system expansion to avoid allocation. For digestate and manure, the production of appropriate fertilizers is selected, guided by nutrient composition data provided by the farms. In addition, the electricity generated is credited against the German electricity production mix, following system expansion principles.

2.4. Sensitivity and scenario analyses

To facilitate interpretation, sensitivity analysis is used to assess the robustness of the results and to determine the sensitivity of the model to uncertainties in the LCI. The analysis focused on input parameters related to realistic improvement possibilities based on variation in sourcing inputs like energy sources and further use cases of by-products reported in secondary data sources. With the reduction of inputs of 10 %, 25 % and 50 % for the biggest environmental impact the three categories are assessed for every case study. The reduction range is adapted for every case based on literature review and the facility's specifications.

Scenario analyses are performed for the case studies BRE and SLA representing two stages of the value chain. Three major impacts on the environmental performance of the case studies are assessed in scenarios that are based on realistic adjustments and regulatory guidelines. Two scenarios are conducted for the case study BRE. Based on the comprehensive data sample, the two scenarios focus on feed allocation and the exclusion of the biogas plant, examining the methodology of LCA and regulatory changes emerging from expiring subsidies (NDR, 2024). The treatment and use of manure in a biogas plant for energy production has already been evaluated in many studies (Freitas et al., 2022; Hollas et al., 2022; Prapaspongsa et al., 2010). Prapaspongsa et al. (2010) focus on the calculation of multiple scenarios based on European database data comparable to the scenarios of this study, which distinguishes our approach in evaluating a realistic farm covered by primary data. The assessed scenario for SLA highlights the influence of a change in electricity consumption, from grid-based to self-produced renewable electricity. Switching electricity supply to renewables is a well-established scenario in LCA (Klöpffer, 2014).

3. Results and discussion

3.1. Pig farming

Table 4 presents the LCA results for the four pig farms under analysis, covering the impact categories of global warming, acidification, and eutrophication for the functional unit of 1 kg live weight. In addition, the manure management practices for each farm are broken down into the resulting credits compared to the overall result without them. These values should be interpreted within the specific context of each farm's operation and particularities.

Fig. 4 presents a comparative overview of the environmental impacts per process for the four pig production case studies. As demonstrated in previous studies (Gislason et al., 2023), feed production remains the dominant contributor to all impact categories, except for the direct emissions of BRE and FAT in the acidification category. Global warming from feed is significantly lower for BRE than for FAT, due to the higher soybean consumption at the fattening farm, which contributes significantly to emissions with more than 44 % of the impact for feed alone. This highlights the disparity in feed consumption masses between the varying pig types having differing needs, previously outlined in Section 2.2 with reference to Appendix A. Taking a deeper look into the results, the predominant impacts of the feed mixes for every impact category foremost trace back to wheat, barley and soybean components. In the organic system of PIG 2 considerable impacts also originate from fava bean with around 20 %. Soybean components foremost drive global warming while wheat and barley upfront affect acidification and eutrophication. For the study PIG 1, the influence of feed represents almost the end results in all categories. Referring to the inventory of PIG 1, the impact of electricity use is overruled by the exported electricity produced on farm by photovoltaic. Overall, the positive impact of biogas production is evident. For the case study FAT, the credit of the biogas production is reduced in comparison to BRE because wheat grain is used as another co-substrate causing additional environmental impacts with its cultivation. Meanwhile, the biogas and CHP processes, as well as manure management, offer credits in the global warming category due to system expansion, discussed in Section 2.3. For PIG 2, biogas and CHP have a meaningful positive influence owing to its substantial energy production, which is over ten times greater than in case study BRE. This can be attributed to the disparate substrate inputs; PIG 2 uses additional pig and poultry manure, maize silage, wheat grain, and ryegrass silage, which results in much higher biogas output and associated credits for fertilizer replacement. However, the increased substrate input leads to higher emissions in the acidification and eutrophication categories, primarily due to fertilizer production and application for crop cultivation. With regard to the location of emissions, the cultivation and production of substrates is located close to PIG 2, and the assessed impacts are mainly local impacts of acidification and eutrophication that directly affect the region of PIG 2.However, the credits for avoided electricity production are based on the German electricity mix and therefore do not improve the environmental balance locally, nor does the avoided fertiliser production. In contrast, BRE and FAT benefit from avoided electricity production, which mitigates the eutrophication (Felix and Gheewala, 2012), whereas PIG 2's electricity production does not compensate for the impacts of substrate cultivation. The farm covered by case study PIG 1, lacking a biogas plant, credits its manure directly as a fertilizer replacement. While this yields positive impacts in all categories, the absence of energy production credits from a biogas-powered CHP means the benefits are more modest. Additionally, the use of natural gas for heat production at PIG 1 contributes to global warming, whereas the other farms rely on heat from the integrated CHP systems. In summary, the results demonstrate the critical role of feed and biogas production in determining environmental impacts across the three categories. The relative contributions of water and waste, as shown in Fig. 4, are minimal and do not essentially influence the overall results.

3.2. Slaughtering

When comparing the results presented in Section 3.1 with those from case study SLA, the pronounced impact of waste flows becomes immediately apparent. The environmental impacts of the slaughterhouse are distributed among waste treatment, energy-related flows, water use, and other auxiliary and operational materials, as listed in Table 5.

For every impact category, the results for 1 kg of product from the SLA case study are largely lower than those from the pig farming case studies. However, the impact of waste treatment, particularly slaughterhouse waste, is notably crucial. The small fraction of slaughterhouse waste, which amounts to only one-tenth of the product mass, exerts a disproportionate environmental influence. Wastewater treatment, included within the waste flow, contributes approximately 6 % to eutrophication, adding a noteworthy impact to this category. Electricity from the grid also has a clear effect across all impact categories. Finally, the production of heat and electricity by the CHP plant, powered by natural gas, represents another important, though expected, contribution to the overall environmental footprint. This case highlights the role of waste management and energy sourcing in shaping the environmental impacts of slaughterhouse operations.

3.3. Processing

The LCA results for the two pork processing facilities, PRO 1 and PRO 2, are presented in Table 6. While both facilities fall within a similar environmental impact range, there are notable distinctions. Fig. 5 provides a detailed breakdown of the contributions from different processes for each impact category.

PRO 1 has a distinct higher impact in the global warming and acidification categories due to its reliance on heating generated by burning light fuel oil in a boiler. This contrasts with PRO 2, which has a lower impact in these categories. Another important factor is that PRO 1's electricity comes entirely from renewable sources on the grid, which has a positive impact on global warming and eutrophication compared to PRO 2. As seen in the figure, electricity, waste, and auxiliary materials are major contributors to the environmental impact of both facilities. Waste treatment has a particularly strong effect on PRO 1 compared to PRO 2. This could be due to the higher data availability for this facility, as the waste flows were not as clearly traceable for PRO 2 as for PRO 1.

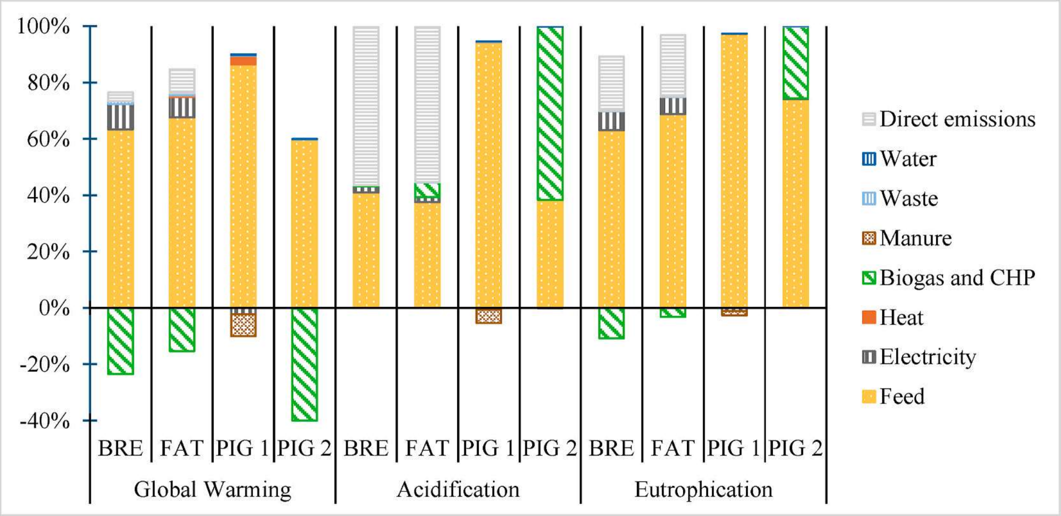


Fig. 4. Environmental impacts per process for the four pig production case studies expressed as relative percentages per impact category.

Table 5
Environmental impacts of case study SLA showing relative contributions of each process for the functional unit of 1 kg of carcass weight at slaughterhouse gate.

Impact category	Waste		Heat		Electricity		Water		Other materials		Result
Global Warming *kg CO_2 eq*	0.183	*63 %*	0.064	*22 %*	0.044	*15 %*	9.48E-04	*0.3 %*	6.84E-04	*0.2 %*	**0.293**
Acidification *g SO_2 eq*	0.360	*75 %*	0.035	*7 %*	0.078	*16 %*	4.30E-03	*0.9 %*	3.40E-03	*0.7 %*	**0.480**
Eutrophication *g PO_4^{3-} eq*	0.643	*82 %*	9.80E-03	*1.3 %*	0.13	*16 %*	2.37E-03	*0.3 %*	1.63E-03	*0.2 %*	**0.783**

Table 6
Environmental impacts of processing facilities PRO 1 and PRO 2 for the functional unit of 1 kg processed pork.

Impact category		PRO 1	PRO 2
Global Warming	*kg CO_2 eq*	1.65	0.87
Acidification	*g SO_2 eq*	3.25	1.60
Eutrophication	*g PO_4^{3-} eq*	1.36	1.31

The use of auxiliary and operational materials also contributes decisively to the impacts in all three categories for both facilities. The analysis highlights the substantial differences between the two facilities, driven by their heating methods, electricity sources, and data quality. These differences emphasise the role of energy sources and waste management in shaping the environmental profile of pork processing operations.

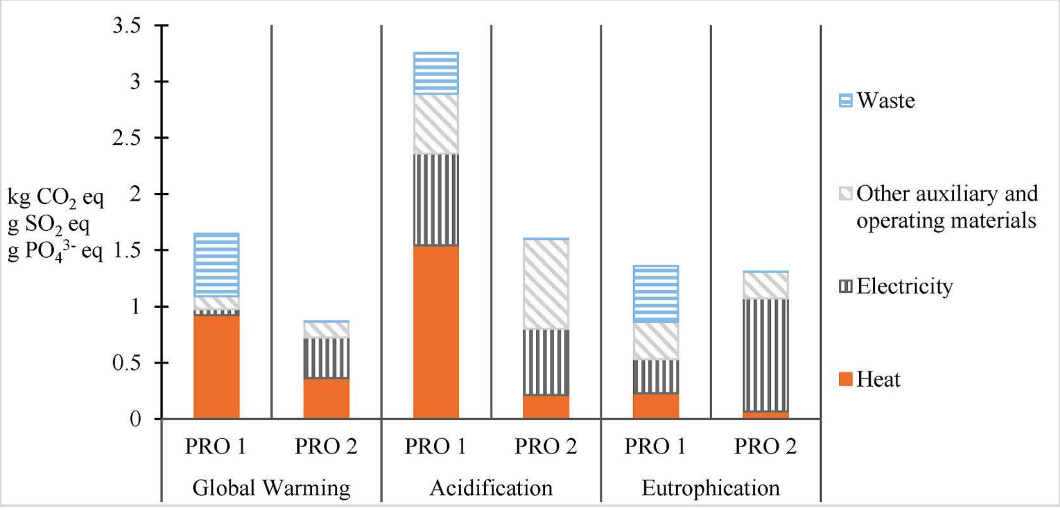


Fig. 5. Environmental impacts per processing case study parted by impact categories and processes.

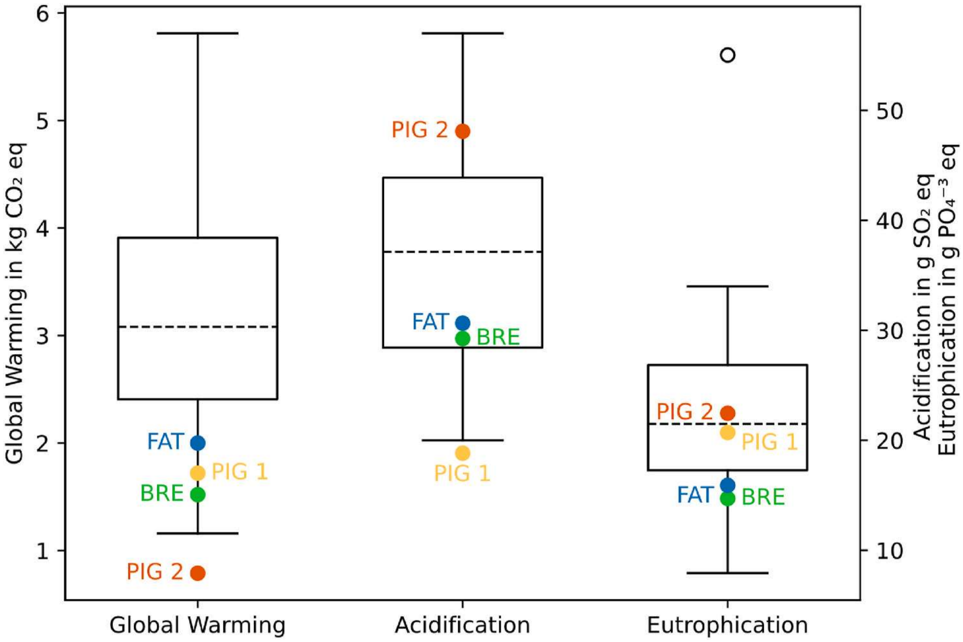


Fig. 6. Results of the presented case studies (coloured dots) in comparison with those of 22 scenarios from nine comparable studies, displayed in a boxplot with dotted lines indicating the medians for each category.

3.4. Comparison with related studies

Fig. 6 illustrates the results of nine comparable studies that calculated 22 systems and scenarios, with specifications detailed in Appendix B. These studies cover systems analysed in previous studies in different countries. On the one hand, the comparability is ensured with the selection of studies that calculate the impact assessment using CML and the associated impact categories. On the other hand, we only examined studies that use the same functional unit of 1 kg live weight and of course matching system boundaries. Another rather limiting factor for the visualization is determined by the requirement that all three values for each study must be present in order to build a comprehensive comparison. The median for each impact category is indicated by a dotted line. Additionally, the four case studies from this paper are plotted on the same diagram, without influencing the boxplot results.

The results from the presented case studies generally fall below the median across all categories. However, the impacts calculated for PIG 2 stand out with values above the median for both acidification and eutrophication. The high acidification value for PIG 2 may be explained by the considerable contribution of multiple substrates used in its biogas plant. Despite the elevated acidification impact, PIG 2 achieves low global warming impacts due to the credits from biogas production and its conversion into electricity. This case highlights the importance of expanding beyond a carbon footprint analysis to include other relevant impact categories, thereby achieving a more comprehensive assessment of environmental effects. Another notable result is the low acidification impact for PIG 1, which is considerably below the median. For the BRE and FAT case studies, excluding direct emissions would lower their acidification values even further, bringing them closer to the lower range of the compared scenarios. In the case of PIG 1, the feed is a major contributor to the acidification burden, while a reduction in the acidification impact is observed due to the credit from manure management. Overall, the values of the case studies align reasonably well with the comparative data. However, it is important to note that the comparative scenarios often rely on data that is not as precise or fully disclosed, limiting the feasibility and usefulness of a more detailed comparison.

Accordingly, the environmental impacts of the slaughterhouse case study SLA are analysed and compared with the results of other studies to provide a comprehensive evaluation of environmental performance, as presented in Table 7. The analysis reveals that SLA shows comparable or, in some cases, lower values in the categories of global warming, acidification, and eutrophication than other studies in the literature. Specifically, SLA shows a moderate value of 0.293 kg CO_2 equivalent in the global warming category, which is slightly lower than the studies by McAuliffe et al. (2017) and Reckmann et al. (2013). Similar observations can be made for the categories of acidification and eutrophication, where SLA's results fall within the middle range of the studies considered.

Table 7
Comparable LCA results for slaughterhouses that produce pork for the functional unit of 1 kg carcass weight.

Study	Global Warming *kg CO_2 eq*	Acidification *g SO_2 eq*	Eutrophication *g PO_4^{3-} eq*	System expansion
SLA	*0.293*	*0.480*	*0.783*	*yes*
Cherubini et al. (2015)	0.049	0.08		yes
Dorca-Preda et al. (2021)	0.2	0.2		yes
McAuliffe et al. (2017)	0.31	1.1	4.1	yes
Nguyen et al. (2011)	0.179	0.185		yes
Reckmann et al. (2013)	0.21	0.3	1.9	yes
Winkler et al. (2016)	0.142	0.61		no

3.5. Sensitivity analysis: adjusting key influences to assess their impact on results

In the baseline scenario, feed production is identified as the most critical factor influencing the environmental profile of all farms in pig production. This finding aligns with comparable studies, which also highlight feed production as a notable hotspot (Gislason et al., 2023). Because of this notable influence, feed production is the case of many studies that evaluate the environmental impact of different diets and feed mixes for pigs (e.g. Eriksson et al., 2005; Mackenzie et al., 2016). Soleimani and Gilbert (2021) assess the environmental impact of different diets and find reductions of up to 15 % in the three impact categories assessed in this study. Reckmann et al. (2016) replace soybean products with various feed sources and dietary changes and evaluate the environmental impact changes. van Zanten et al. (2018) accordingly replace soybean meal with rapeseed meal and waste fed-larvae meal and receive reductions up to 10 % for global warming.

To assess the influence of feed consumption on environmental outcomes, a sensitivity analysis is conducted. Ongoingly, breeding programs aim to improve feed conversion ratios; however, this improvement has natural limits imposed by the metabolism of the animals. Though, not exclusively the feed conversion ratio but the feed production and its transportation are crucial factors. In contrast to the conversion ratio, those factors are adjustable in many ways and therefore a sensitivity analysis of reducing the feed's impact drastically up to 50 % can highlight opportunities. For instance, using food waste or by-products from food industry (Alba-Reyes et al., 2023; Mackenzie et al., 2016) as a source for animal feed can tackle these issues. Another possibility, as shown by the above-mentioned studies, is the replacement of feed ingredients with ones that are less harmful to the environment (de Quelen et al., 2021; Eriksson et al., 2005; Reckmann et al., 2016; Soleimani and Gilbert, 2021; Stødkilde et al., 2023; van Zanten et al., 2018). Based on these findings, the impact of a 10 % reduction in feed consumption was evaluated and the results are shown in Fig. 7. In particular, PIG 2 shows substantial reductions in the global warming category due to the impact of feed in the LCA of this study, as already examined. The 10 % reduction in feed consumption leads to a dramatic decrease of 32 %. The results for case study PIG 1 also exhibit reductions across all environmental categories, with the percentage decreases being consistent across all categories and scenarios.

While optimising feed production proves crucial in reducing environmental impacts during the animal rearing phase, addressing waste treatment in slaughterhouse operations is equally important. As shown in Table 5, the largest share of the environmental burden is attributed to waste treatment, especially slaughterhouse waste. To complement the findings on feed production, a further sensitivity analysis was conducted to assess the potential for reducing waste amounts at SLA, highlighting the considerable impact of improved waste management on the overall environmental performance. The plant manager was not surprised by these results and identified this process as an area for improvement. Due to the size of the company and the resulting production volumes, which are much lower than in large slaughter and processing plants, only part of the by-products, such as blood, are processed. The rest of the by-products are used, for example, in waste incineration. Obviously, this is intensified by the lack of an attached processing unit. Possible options for further use of the by-products can be in medicine production industry, animals and pet feed production industry, in biodiesel production plants and in biogas plants as LCA's of slaughterhouse operations indicate (e.g. Dorca-Preda et al., 2021; Pazmiño and Ramirez, 2021). As mentioned in Section 3.2 and shown in the inventory (Appendix A), 1 kg of product contains 110 g of slaughterhouse waste, providing a basis for radical improvement. The sensitivity analysis results indicate that even a 10 % reduction in waste leads to notable improvements in environmental impacts, as summarised in Fig. 8. For instance, in the global

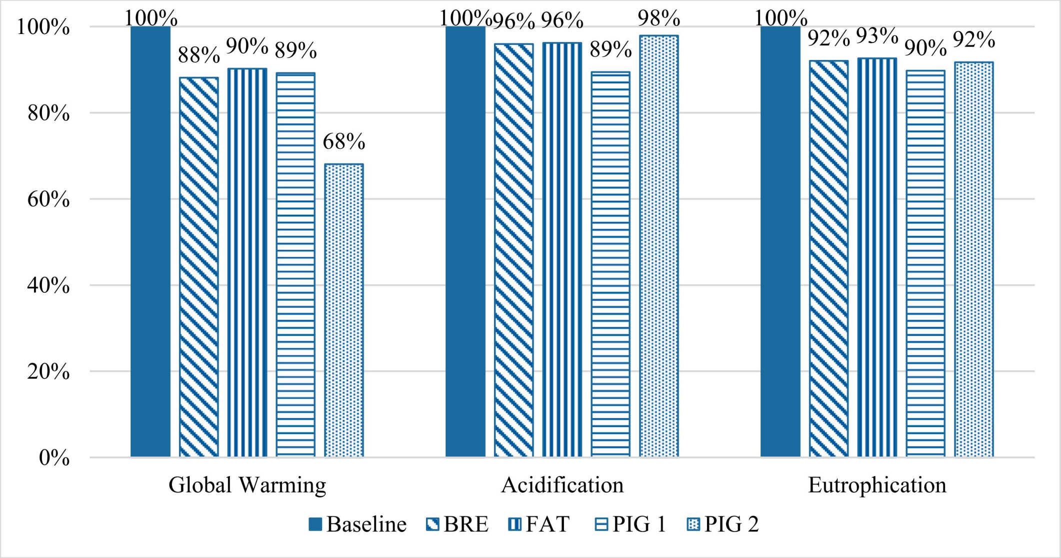


Fig. 7. Comparative environmental results considering −10 % less feed consumption for every case study.

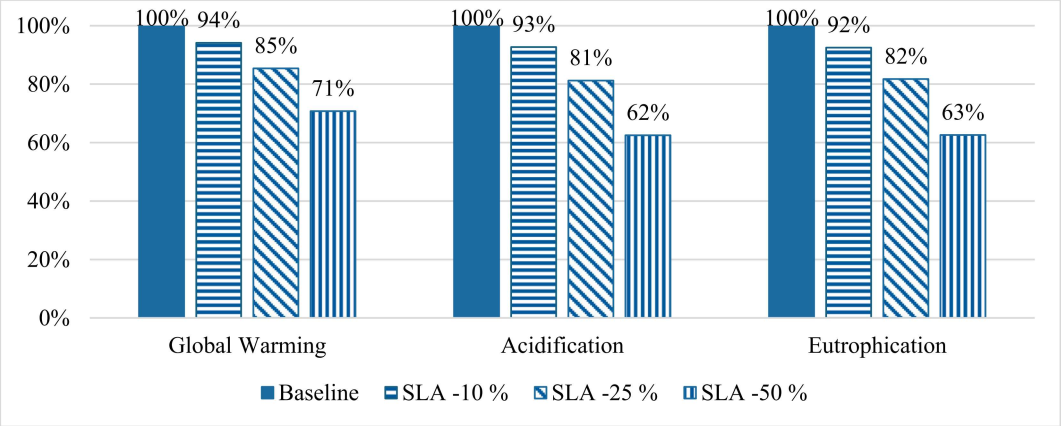


Fig. 8. Comparative environmental results considering −10 % to −50 % less slaughterhouse waste for SLA.

warming category, emissions decrease by 6 % with a 10 % reduction in waste amounts, while a 50 % reduction results in a 29 % decrease. The most substantial improvements are observed in the acidification and eutrophication categories, where a 50 % reduction in waste amounts leads to a 38 % and 37 % reduction in environmental burdens, respectively. These findings underscore the high sensitivity of SLA's environmental performance to waste treatment practices. Reducing slaughterhouse waste presents a substantial opportunity for minimising environmental impacts and should be prioritised as a key mitigation strategy.

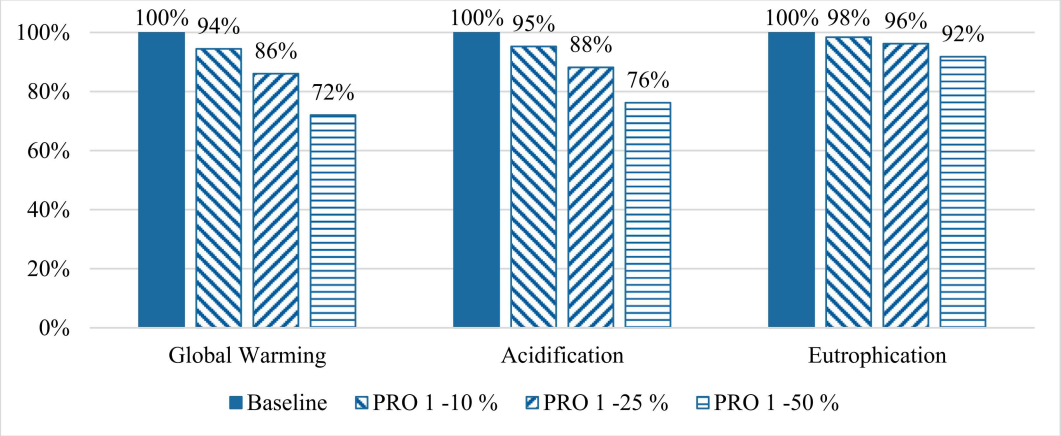


Fig. 9. Comparative environmental results considering −10 % to −50 % less heat heating for PRO 1.

In line with the conducted analyses, a sensitivity analysis was performed for PRO 1, focusing on reducing heating demand by 10 %, 25 %, and 50 %, as pictured in Fig. 9. Heating is targeted due to its distinct contribution to environmental impacts, particularly in the categories of global warming and acidification, as shown in Fig. 5. PRO 1 is heated with light fuel oil, which is the main source of these impacts. A switch to a renewable heating source is already planned for this plant and will dramatically improve the environmental impacts. Therefore, the calculated reductions represent possible scenarios. It is important to note that, in contrast, eutrophication is predominantly influenced by electricity consumption. The results indicate that reducing heating demand leads to a more substantial decrease in global warming and acidification impacts, with reductions ranging from 5 % to 28 %, whereas eutrophication is only marginally affected, with a maximum reduction of 8 %. This suggests that transitioning to a more sustainable heating technology could explicitly enhance the environmental profile of PRO 1.

Similarly, for PRO 2, a sensitivity analysis was conducted to assess the influence of electricity consumption, identified as the major environmental hotspot. Although auxiliary and operating materials are the largest contributors to acidification, reducing electricity consumption predominantly affects the eutrophication category, as presented in Fig. 10. A 10 % reduction in electricity consumption leads to an 8 % decrease in eutrophication, with smaller reductions seen in global warming and acidification. Approximately two-thirds of the electricity for PRO 2 is supplied by the grid's electricity mix, while the remaining one-third comes from an integrated CHP plant powered by natural gas. This analysis suggests that shifting towards a more sustainable electricity supply, either by optimising the purchase to renewable electricity or improving CHP efficiency, could boldly improve PRO 2's environmental profile.

3.6. Scenario analysis: exploring a broader range of operational configurations

The identification of environmental hotspots and the variation of input quantities, as discussed in Section 3.5, provides a robust framework for assessing the potential impacts of reductions in production processes. For two case studies, we extend this approach by examining modified inputs in the LCA calculations, rather than simply adjusting percentages of energy consumption or other resource inputs. This expanded analysis enables a more comprehensive exploration of alternative production systems that could be relevant to the case studies, especially in light of potential legal and regulatory developments.

For the BRE case study, scenario analysis focuses on two key aspects: altering feed composition and leaving out biogas production, specifically by excluding manure processing. These scenarios are structured in comparison to the baseline, with specific parameters that substantially affect the LCA outcomes. In the SLA case study, scenario analysis explores the impact of integrating photovoltaic systems as an alternative electricity source. The sensitivity analysis in Section 3.5 has already emphasised the considerable role of these parameters in shaping the overall environmental performance of both case studies.

3.6.1. Alternative allocation of feed production by-products as feed components

The modelling of feed production for the case study BRE includes specific characteristics that motivate a scenario analysis. In the baseline scenario, a portion of the feed is derived from food industry by-products, whose environmental burdens are allocated 100 % to the main product, which lies outside the scope of this study. For example, in cheese production, whey is considered a by-product and used in the feed mix of BRE and FAT, and following the allocation its environmental burden is excluded from the baseline scenario. The rationale for this causal approach is based on regulatory requirements in Europe, based on the Corporate Sustainability Reporting Directive (CSRD), which includes Scope 1 to 3 emissions (European Union, 2024). The baseline scenario includes Scope 1 emissions and does not include upstream emissions from feed production in the case of by-products.

In the feed composition scenario, we introduce an economic allocation of the by-products based on their market value, which is a standard practice for feed inputs in LCA (FAO, 2018). This scenario should assess the original approach supported by the LCA practitioners and foremost highlight the influences of this methodological change. Economic allocation is the most appropriate method for these by-products, as their mass fraction is dramatically larger than that of the main product, making physical allocation impractical. For instance, in this scenario, whey's environmental impact is allocated according to its economic value, in contrast to the baseline scenario where whey was treated as having no impact to the assessed process. This approach is consistently applied to all by-products used in feed, as defined by the farm's managing operator.

The results presented in Fig. 11 illustrate the relative deviations of two scenarios - feed composition and no biogas - compared to the baseline scenario. The feed composition scenario leads to an increase in environmental impacts across all categories. This effect is primarily due to the inclusion of environmental burdens from feed component production that were previously excluded. However, the deviations from the baseline are not substantial, indicating that while the allocation of the feed composition does influence the environmental profile, the magnitude of its impact remains relatively limited. In this case, the adaptation of the regulatory requirements does not drastically affect the results of the LCA, but the focus on the Scope 1 emissions assessment

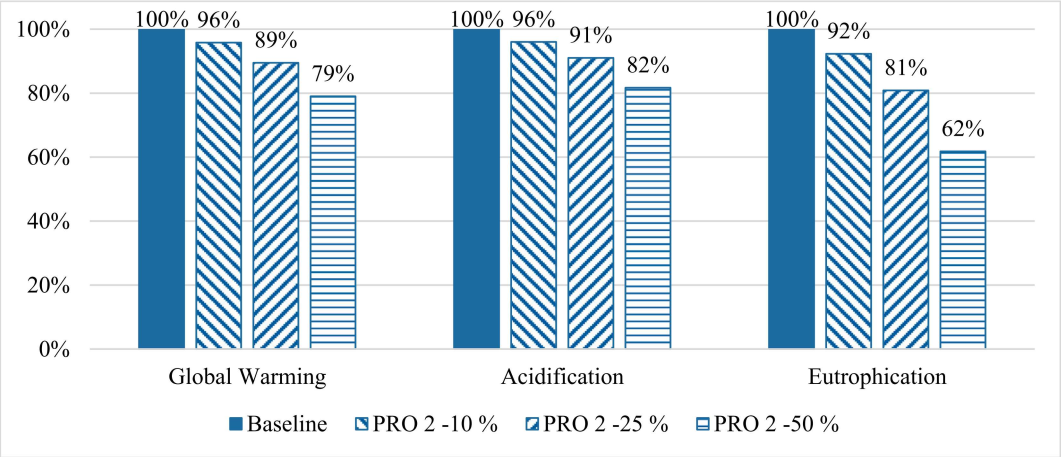


Fig. 10. Comparative environmental results considering −10 % to −50 % less electricity consumption for PRO 2.

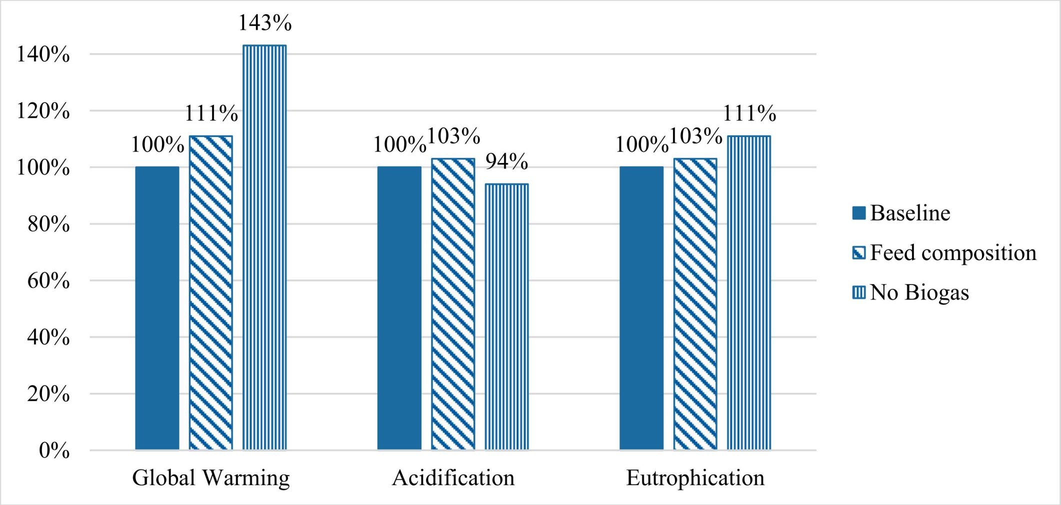


Fig. 11. Relative deviations in environmental impacts for the feed composition and no biogas scenarios compared to the baseline scenario for case study BRE.

illustrates the impact of shifting impacts within scopes.

3.6.2. *Environmental burdens of direct manure use without biogas conversion*

In the case study BRE, pig manure is combined with energy crops, such as maize silage and grain, to produce biogas. This biogas is subsequently converted into heat and electricity through a CHP plant. The generated heat is used on-site, while the electricity is fed into the grid, generating a credit in the LCA due to the avoidance of conventional electricity production. Additionally, the digestate produced during this process is credited for replacing conventional fertilizer production, as it is applied as fertilizer. This process presents an opportunity for scenario analysis because it hinges on the integration of a biogas plant. Not all pig farms have access to such facilities, and government subsidies for biogas production in Germany, which are time-limited, are soon expiring for many existing plants (NDR, 2024). This scenario explores the environmental impact of manure use without biogas conversion.

Unlike the feed composition scenario, the No biogas scenario leads to a notable increase in the global warming category and a reduction in acidification (see Fig. 11). The increase in global warming stems from the absence of credits for electricity production and heat supply, which must be compensated for by alternative energy sources. In this analysis, heat production using natural gas is assumed as the alternative, representing the typical European market for heat in centralised or small-scale facilities. While the credits for avoided fertilizer production from the use of manure are beneficial, they are insufficient to offset the environmental advantages of biogas production. A key observation is that the maize silage used for biogas production generates a similar amount of CO_2-equivalent emissions as the natural gas-based heat production in the no biogas scenario. Similarly, the credit for avoided fertilizer production is comparable between the two scenarios, but the substantial difference in global warming arises from the credit for avoided electricity production in the baseline scenario. The CHP plant feeding electricity to the grid avoids emissions related to average grid electricity production, which is absent in the no biogas scenario. For acidification, the maize silage production in the baseline scenario plays a dominant role. The avoided emissions from electricity and fertilizer production are insufficient to fully compensate for the acidification of maize silage cultivation. In contrast, the no biogas scenario benefits from reduced maize silage-related emissions, leading to a lower overall acidification. In terms of eutrophication, the credits for avoided fertilizer production are again similar between the two scenarios. However, the contribution of electricity production in the baseline scenario improves the result substantially, though maize silage cultivation offsets a large portion of these benefits. In the no biogas scenario, the primary contributor to eutrophication is heat production, but its contribution is minimal, representing less than 1 % of the impact category. Overall, the no biogas scenario performs worse due to the lack of substantial credits, particularly from electricity production, which play a distinct role in the baseline scenario's better environmental performance.

3.6.3. *Using an alternative renewable energy source to replace grid electricity supply*

The SLA facility draws energy from several sources, including a gas-powered boiler, a CHP unit, and electricity from the grid. For the scenario analysis of this case study, the focus is on replacing the electricity supplied from the grid with an alternative renewable energy source.

The research project already included a comprehensive energy assessment of the feasibility of installing on-site solar photovoltaic (PV) panels on the slaughterhouse's roof. This evaluation confirmed that PV systems can efficiently supply the facility with electricity, with any surplus fed back into the grid, generating environmental credits in the LCA. Therefore, this scenario presents a realistic and actionable option for reducing the facility's environmental footprint. The transition to PV has a noticeable impact on the facility's environmental profile, as illustrated in Fig. 12. The overall environmental burden is reduced across several categories, with the most obvious improvements observed in the eutrophication category. This reduction is mainly due to the avoided impacts associated with grid electricity, which in the baseline scenario is supplied through processes like lignite conversion. These conventional electricity production methods are known to have substantial negative effects on freshwater environments, contributing to eutrophication. By replacing grid electricity with solar power and feeding surplus energy into the grid, SLA benefits from both the reduction in direct environmental impacts and the added credits for contributing renewable energy to the grid. This demonstrates the potential of integrating renewable energy sources as a practical strategy for reducing environmental impacts in industrial facilities.

4. Conclusion

Pork is the most widely consumed meat globally, underscoring the importance of assessing the environmental impacts across the entire value chain and providing strategies for mitigation. This study examines seven case studies spanning three key stages of the pork production value chain: pig farming, slaughtering, and meat processing. The focus is placed primarily on production processes, as distribution and retail tend to be consistent across various food products. While numerous LCA

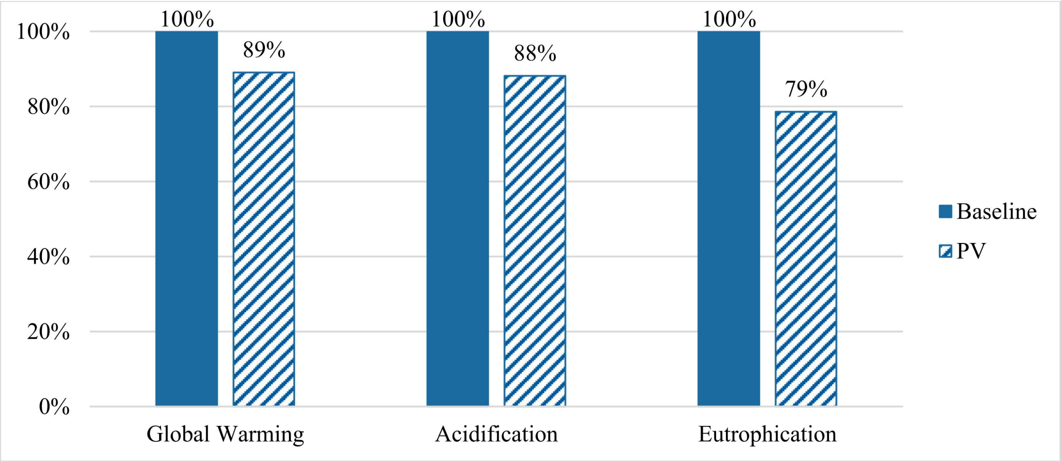


Fig. 12. Comparative environmental results considering the baseline scenario and PV scenario that covers electricity production by photovoltaic and crediting the overlap fed to grid for case study SLA.

studies on pig and pork production exist, few are based on primary data from currently operating facilities. Our case studies provide access to this type of valuable, real-world data, though it is limited to a single year, reflecting operational and data collection constraints. Future studies could benefit from focusing on individual housing units to explore opportunities for improvement within different systems on the same farm.

The results confirm that feed production is the primary driver of environmental impacts in pig farming, with considerable variability across farming systems and operational structures. Scenario analysis provided further insights, highlighting potential improvements through changes in production practices, such as adjusting feed composition or adopting renewable energy sources. Among the value chain stages assessed, pig farming consistently demonstrates the highest environmental burden, far surpassing the impacts of slaughtering and processing. This highlights the urgent need for targeted interventions in feed production and farm-level practices to reduce the overall environmental footprint of pork production, for instance by improving environmental impacts of feed production by using by-products of food industry to replace other protein sources or using the manure to produce biogas and eventually energy.

CRediT authorship contribution statement

Nina Treml: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Andreas Rudi:** Writing – review & editing. **Frank Schultmann:** Writing – review & editing, Funding acquisition.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to mitigate grammatical errors and improve language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The project was supported by the German Federal Ministry of Food and Agriculture (BMEL), with the project SPECK (Systemic optimization of the meat value chain using pig farming as an example through the development and embedding of digital tools), grant number 281A502B19.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2025.145408.

Data availability

Data will be made available on request.

References

Adams, P.W.R., McManus, M.C., 2019. Characterisation and variability of greenhouse gas emissions from biomethane production via anaerobic digestion of maize. J. Clean. Prod. 218, 529–542. https://doi.org/10.1016/j.jclepro.2018.12.232.

ADEME, 2023. Agribalyse Database (Version 3.1) (Datenbank). ADEME (Agence de la transition écologique), Angers, France.

Alba-Reyes, Y., Barrera, E.L., Brito-Ibarra, Y., Hermida-García, F.O., 2023. Life cycle environmental impacts of using food waste liquid fodder as an alternative for pig feeding in a conventional Cuban farm. Sci. Total Environ. 858, 159915. https://doi.org/10.1016/j.scitotenv.2022.159915.

Beylot, A., Secchi, M., Cerutti, A., Merciai, S., Schmidt, J., Sala, S., 2019. Assessing the environmental impacts of EU consumption at macro-scale. J. Clean. Prod. 216, 382–393. https://doi.org/10.1016/j.jclepro.2019.01.134.

BMEL, 2024. Landwirtschaft, Klimaschutz und Klimaresilienz [WWW Document]. URL. https://www.bmel.de/DE/themen/landwirtschaft/klimaschutz/landwirtschaft-und-klimaschutz.html.

Cherubini, E., Zanghelini, G.M., Alvarenga, R.A.F., Franco, D., Soares, S.R., 2015. Life cycle assessment of swine production in Brazil: a comparison of four manure management systems. J. Clean. Prod. 87, 68–77. https://doi.org/10.1016/j.jclepro.2014.10.035.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nat Food 2, 198–209. https://doi.org/10.1038/s43016-021-00225-9.

de Quelen, F., Brossard, L., Wilfart, A., Dourmad, J.-Y., Garcia-Launay, F., 2021. Eco-friendly feed formulation and on-farm feed production as ways to reduce the environmental impacts of pig production without consequences on animal performance. Front. Vet. Sci. 8. https://doi.org/10.3389/fvets.2021.689012.

Dorca-Preda, T., Mogensen, L., Kristensen, T., Knudsen, M.T., 2021. Environmental impact of Danish pork at slaughterhouse gate – a life cycle assessment following biological and technological changes over a 10-year period. Livest. Sci. https://doi.org/10.1016/j.livsci.2021.104622.

Ecoinvent Association, 2023. Ecoinvent Database. Ecoinvent Association, Zurich, Switzerland (Datenbank), Version 3.9.1.

Eriksson, I.S., Elmquist, H., Stern, S., Nybrant, T., 2005. Environmental systems analysis of pig production: the impact of feed choice. Int. J. Life Cycle Assess. 10, 143–154. https://doi.org/10.1065/lca2004.06.160.

European Commission, 2011. In: International Reference Life Cycle Data System (ILCD) Handbook: General Guide for Life Cycle Assessment: Provisions and Action Steps, first ed. Publications Office, Luxembourg. https://doi.org/10.2788/33030.

European Union, 2024. Directive (EU) 2022/2464 of the European Parliament and of the Council.

FAO, 2023. Global statistical yearbook, FAO regional statistical yearbooks [WWW Document]. FAOSTAT. URL. https://www.fao.org/faostat/en/#data/QCL/visualize.

FAO, 2018. Environmental Performance of Pig Supply Chains: Guidelines for Assessment (Version 1), Livestock Environmental Assessment and Performance Partnership. FAO, Rome.

Felix, M., Gheewala, S.H., 2012. Environmental assessment of electricity production in Tanzania. Energy for Sustainable Development 16, 439–447. https://doi.org/10.1016/j.esd.2012.07.006.

Freitas, F.F., Furtado, A.C., Piñas, J.A.V., Venturini, O.J., Barros, R.M., Lora, E.E.S., 2022. Holistic Life Cycle Assessment of a biogas-based electricity generation plant in a pig farm considering co-digestion and an additive. Energy 261, 125340. https://doi.org/10.1016/j.energy.2022.125340.

Gislason, S., Birkved, M., Maresca, A., 2023. A systematic literature review of life cycle assessments on primary pig production: impacts, comparisons, and mitigation areas. Sustain. Prod. Consum. 42, 44–62. https://doi.org/10.1016/j.spc.2023.09.005.

González-García, S., Belo, S., Dias, A.C., Rodrigues, J.V., Da Costa, R.R., Ferreira, A., Andrade, L.P., Arroja, L., 2015. Life cycle assessment of pigmeat production: Portuguese case study and proposal of improvement options. J. Clean. Prod. 100, 126–139. https://doi.org/10.1016/j.jclepro.2015.03.048.

GreenDelta GmbH, 2023. CML-IA baseline Method in openLCA. openLCA LCIA method package 2.3.2.

Halpern, B.S., Frazier, M., Verstaen, J., Rayner, P.-E., Clawson, G., Blanchard, J.L., Cottrell, R.S., Froehlich, H.E., Gephart, J.A., Jacobsen, N.S., Kuempel, C.D., McIntyre, P.B., Metian, M., Moran, D., Nash, K.L., Többen, J., Williams, D.R., 2022. The environmental footprint of global food production. Nat. Sustain. 5, 1027–1039. https://doi.org/10.1038/s41893-022-00965-x.

Hollas, C.E., do Amaral, K.G.C., Lange, M.V., Higarashi, M.M., Radis Steinmetz, R.L., Barros, E.C., Mariani, L.F., Nakano, V., Kunz, A., Sanches-Pereira, A., Martino Jannuzzi, G., 2022. Life cycle assessment of waste management from the Brazilian pig chain residues in two perspectives: electricity and biomethane production. J. Clean. Prod. 354, 131654. https://doi.org/10.1016/j.jclepro.2022.131654.

IPCC, 2014. Climate Change 2013 – the Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

ISO, 2018. ISO 14044 Standard.

ISO, 2009. ISO 14040 Standard.

Klöpffer, W., 2014. Background and Future Prospects in Life Cycle Assessment. Springer, Netherlands, Dordrecht. https://doi.org/10.1007/978-94-017-8697-3.

Lijó, L., González-García, S., Bacenetti, J., Fiala, M., Feijoo, G., Lema, J.M., Moreira, M. T., 2014. Life Cycle Assessment of electricity production in Italy from anaerobic co-digestion of pig slurry and energy crops. Renew. Energy 68, 625–635. https://doi.org/10.1016/j.renene.2014.03.005.

LUBW, 2024. Emissionserklärung nach 11. BImSchV [WWW Document]. LUBW. URL. https://www.lubw.baden-wuerttemberg.de.

Mackenzie, S.G., Leinonen, I., Ferguson, N., Kyriazakis, I., 2016. Can the environmental impact of pig systems be reduced by utilising co-products as feed? J. Clean. Prod. 115, 172–181. https://doi.org/10.1016/j.jclepro.2015.12.074.

McAuliffe, G.A., Chapman, D.V., Sage, C.L., 2016. A thematic review of life cycle assessment (LCA) applied to pig production. Environ. Impact Assess. Rev. 56, 12–22. https://doi.org/10.1016/j.eiar.2015.08.008.

McAuliffe, G.A., Takahashi, T., Mogensen, L., Hermansen, J.E., Sage, C.L., Chapman, D. V., Lee, M.R.F., 2017. Environmental trade-offs of pig production systems under varied operational efficiencies. J. Clean. Prod. 165, 1163–1173. https://doi.org/10.1016/j.jclepro.2017.07.191.

McClelland, S.C., Arndt, C., Gordon, D.R., Thoma, G., 2018. Type and number of environmental impact categories used in livestock life cycle assessment: a systematic review. Livest. Sci. 209, 39–45. https://doi.org/10.1016/j.livsci.2018.01.008.

NDR, 2024. Biogasanlagen ohne Förderung des Bundes unrentabel? Landwirte aus Niedersachsen stehen vor dem Aus [WWW Document]. NDR. URL. https://www.ndr.de/nachrichten/niedersachsen/oldenburg_ostfriesland/Foerderung-endet-2025-Landwirte-erwaegen-Aus-fuer-Biogasanlagen,biogasanlage254.html.

Nguyen, T.L.T., Hermansen, J.E., Mogensen, L., 2011. Environmental Assessment of Danish Pork.

Notarnicola, B., Tassielli, G., Renzulli, P.A., Castellani, V., Sala, S., 2017a. Environmental impacts of food consumption in Europe. J. Clean. Prod. 140, 753–765. https://doi.org/10.1016/j.jclepro.2016.06.080.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017b. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/10.1016/j.jclepro.2016.06.071.

Pazmiño, M.L., Ramirez, A.D., 2021. Life cycle assessment as a methodological framework for the evaluation of the environmental sustainability of pig and pork production in Ecuador. Sustainability 13, 11693. https://doi.org/10.3390/su132111693.

Pelletier, N., Lammers, P., Stender, D., Pirog, R., 2010. Life cycle assessment of high- and low-profitability commodity and deep-bedded niche swine production systems in the Upper Midwestern United States. Agric. Syst. 103, 599–608. https://doi.org/10.1016/j.agsy.2010.07.001.

Prapaspongsa, T., Christensen, P., Schmidt, J.H., Thrane, M., 2010. LCA of comprehensive pig manure management incorporating integrated technology systems. J. Clean. Prod. 18, 1413–1422. https://doi.org/10.1016/j.jclepro.2010.05.015.

Reckmann, K., Blank, R., Traulsen, I., Krieter, J., 2016. Comparative life cycle assessment (LCA) of pork using different protein sources in pig feed. Arch. Anim. Breed. 59, 27–36. https://doi.org/10.5194/aab-59-27-2016.

Reckmann, K., Traulsen, I., Krieter, J., 2013. Life Cycle Assessment of pork production: a data inventory for the case of Germany. Livest. Sci. 157, 586–596. https://doi.org/10.1016/j.livsci.2013.09.001.

Reyes, Y.A., Barrera, E.L., Valle, A.S., Gil, M.P., García, O.H., Dewulf, J., 2019. Life cycle assessment for the Cuban pig production: case study in sancti spiritus. J. Clean. Prod. 219, 99–109. https://doi.org/10.1016/j.jclepro.2019.02.047.

Riaño, B., García-González, M.C., 2015. Greenhouse gas emissions of an on-farm swine manure treatment plant – comparison with conventional storage in anaerobic tanks. Journal of Cleaner Production, Carbon Emissions Reduction: Policies, Technologies, Monitoring, Assessment and Modeling 103, 542–548. https://doi.org/10.1016/j.jclepro.2014.07.007.

Savian, M., Da Penha Simon, C., Holden, N.M., 2023. Evaluating environmental, economic, and social aspects of an intensive pig production farm in the south of Brazil: a case study. Int. J. Life Cycle Assess. 28, 1544–1560. https://doi.org/10.1007/s11367-023-02223-4.

Soleimani, T., Gilbert, H., 2021. An approach to achieve overall farm feed efficiency in pig production: environmental evaluation through individual life cycle assessment. Int. J. Life Cycle Assess. 26, 455–469. https://doi.org/10.1007/s11367-020-01860-3.

SPECK - Systemische Optimierung der Wertschöpfungskette Fleisch am Beispiel der Schweinehaltung durch Entwicklung und Einbettung digitaler Werkzeuge (Research Project No. 281A502B19), 2021. Bundesanstalt für Landwirtschaft und Ernährung.

Stødkilde, L., Mogensen, L., Bache, J.K., Ambye-Jensen, M., Vinther, J., Jensen, S.K., 2023. Local protein sources for growing-finishing pigs and their effects on pig performance, sensory quality and climate impact of the produced pork. Livest. Sci. 267, 105128. https://doi.org/10.1016/j.livsci.2022.105128.

Sun, R., Liu, X., Li, D., Zhuang, J., Qi, S., Meng, B., Liu, M., 2022. Optimization of China's pig production system to reduce environmental impacts based on a data envelopment and life cycle analysis model. Resour. Conserv. Recycl. 185, 106483. https://doi.org/10.1016/j.resconrec.2022.106483.

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522. https://doi.org/10.1038/nature13959.

UNFCCC, 2015. Paris Agreement. United Nations Framework Convention on Climate Change, Paris, France.

van Bussel, L.M., Kuijsten, A., Mars, M., vant Veer, P., 2022. Consumers' perceptions on food-related sustainability: a systematic review. J. Clean. Prod. 341, 130904. https://doi.org/10.1016/j.jclepro.2022.130904.

van der Werf, H.M.G., Knudsen, M.T., Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nat. Sustain. 3, 419–425. https://doi.org/10.1038/s41893-020-0489-6.

van Zanten, H.H.E., Bikker, P., Meerburg, B.G., de Boer, I.J.M., 2018. Attributional versus consequential life cycle assessment and feed optimization: alternative protein sources in pig diets. Int. J. Life Cycle Assess. 23, 1–11. https://doi.org/10.1007/s11367-017-1299-6.

Vergé, X., Maxime, D., Desjardins, R.L., VanderZaag, A.C., 2016. Allocation factors and issues in agricultural carbon footprint: a case study of the Canadian pork industry. J. Clean. Prod. 113, 587–595. https://doi.org/10.1016/j.jclepro.2015.11.046.

Winkler, T., Schopf, K., Aschemann, R., Winiwarter, W., 2016. From farm to fork – a life cycle assessment of fresh Austrian pork. J. Clean. Prod. 116, 80–89. https://doi.org/10.1016/j.jclepro.2016.01.005.

Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciais, P., Tubiello, F.N., Smith, P., Campbell, N., Jain, A.K., 2021. Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. Nat Food 2, 724–732. https://doi.org/10.1038/s43016-021-00358-x.

Zervas, G., Tsiplakou, E., 2012. An assessment of GHG emissions from small ruminants in comparison with GHG emissions from large ruminants and monogastric livestock. Atmos. Environ. 49, 13–23. https://doi.org/10.1016/j.atmosenv.2011.11.039.

Paper B

Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming

Reference

Treml N, Naber E, Schultmann F (2025a) Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming. Sustainability 17(10):4677. https://doi.org/10.3390/su17104677.

sustainability

MDPI

Article

Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming

Nina Treml *, Elias Naber and Frank Schultmann

Institute for Industrial Production (IIP), Karlsruhe Institute of Technology (KIT), Hertzstr. 16,
76187 Karlsruhe, Germany; elias.naber@kit.edu (E.N.); frank.schultmann@kit.edu (F.S.)
* Correspondence: nina.treml@kit.edu; Tel.: +49-721-608-44670

Simple Summary: Farm animals such as pigs are often evaluated based on how efficiently they produce food, but their well-being is just as important. Until now, there has been no clear way to include animal welfare—how healthy and comfortable the animals are and how their surroundings impact them—in environmental assessments that help measure the impact of farming. This study presents a framework as a starting point to add animal welfare into what is known as a life cycle assessment, a tool that helps measure the environmental effects of products like meat throughout the entire production chain. By consulting livestock managing experts, the researchers created a scoring system that fairly compares how different parts of pig farming affect animal welfare. This new approach allows decision-makers, farmers, and consumers to see not only the environmental cost of meat production but also the importance of distinct parts of animal welfare consideration based on expert opinion. In the future, this method could be used to design farming systems that are both environmentally friendly and better for animals, thereby helping society make more informed and ethical choices about food.

Abstract: The understanding of sustainability is shifting from that of a purely environmental dimension to one that includes social concerns. Combined with the growing customer interest in livestock husbandry practices, this study investigates the assessment of animal welfare as a socially influenced impact category for the life cycle assessment (LCA) of pig farming. The weighting of animal welfare impacts is based on a quantitative approach using a set of indicators derived from an expert survey using the Analytic Hierarchy Process (AHP). The aim is to develop an easy-to-implement score that translates the characteristics of several animal welfare indicators into a comparable value. To demonstrate the feasibility of the weighting part of the framework, a case study is conducted with nine experts in the fields of animal husbandry, agricultural sciences, and veterinary medicine. The case study results show that the main criteria of single animal observation and feed intake are the most relevant factors, at 30.6%, followed by operation-specific parameters at 23.9% and husbandry conditions at 14.9%. This case study highlights that animal losses (13.9%) significantly influence the impact category, while access to outdoor areas (1.4%) is less important. The overall conclusion is that an animal health-centered approach is preferable when assessing animal welfare.

Keywords: livestock; sustainability; multi-criteria decision analysis; LCA; AHP; sustainable agriculture; impact category; One Health

check for updates

Academic Editor: Rodrigo Morales

Received: 10 April 2025
Revised: 6 May 2025
Accepted: 17 May 2025
Published: 20 May 2025

Citation: Treml, N.; Naber, E.; Schultmann, F. Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming. *Sustainability* **2025**, *17*, 4677. https://doi.org/10.3390/su17104677

1. Introduction

1.1. Background

A significant proportion of greenhouse gas (GHG) emissions in agriculture are caused by livestock in the form of methane and nitrous oxide resulting from enteric fermentation and feed production [1,2], exceeding those of plant-based counterparts [3–5]. Given the urgency of addressing this environmental concern, a life cycle assessment (LCA) is the main tool used to assess the environmental footprint of livestock production [6]. Studies on the LCA of organic agriculture suggest that the environmental impact in terms of common impact categories such as global warming, acidification, and eutrophication [7] often exceeds that of conventional agriculture [8–12]. This lack of understanding is due to lower animal performance in organic livestock systems [10].

However, sustainability goes beyond environmental considerations. It includes social and ethical dimensions, in particular the welfare of animals in the production process, as pointed out by Florindo et al. [13]. The importance of animal welfare has gained attention, reflecting society's growing awareness of the ethical treatment and living conditions of farm animals [14]. Accordingly, the existing LCA framework needs to be extended and adapted to integrate animal welfare to develop a holistic sustainability assessment [11,15]. This aligns with the One Health approach, which emphasizes the interdependence of human, animal, and environmental health [16]. In line with this, in our approach, animal welfare is included as an impact category to represent the social dimension within an LCA framework. Scherer et al. [17] approve of this integration as an external impact. This paper aims to provide a framework for quantifying the social dimension as an impact category for animal welfare, which could extend LCA as a well-defined methodology for the assessment of environmental sustainability. This methodological extension will aid researchers, policymakers, and practitioners in the fields of sustainability, agriculture, and food production.

1.2. Animal Welfare in LCA

This section highlights several areas for further development and the exploration of animal welfare in LCA as they relate to the characteristics of our framework.

The integration of animal welfare into LCA highlights the inclusion of new indicators in the environmental dimension. Consequently, the inclusion of animal welfare as a social dimension in the LCA framework aligns with the goal of achieving a comprehensive sustainability assessment while maintaining internal consistency. With regard to the existing animal welfare assessment, the observed indicators are embedded in different dimensions or reported as individual categories (see Supplementary Material: Table S1 for details) [18]. These indicators are used to examine husbandry conditions and animal health or a combination of both. Lanzoni et al. [18] noted that the determination of the indicators is based on either a quantitative assessment obtained from an on-farm measurement [19] or an estimation made through literature sources or opinions [20]. To ensure the tangibility of the animal welfare assessment, most indicators are normalized and aggregated into a final single score [12,21,22]. This score can be related to a scale or stand alone. For example, Zira et al. [12] developed a score defining *risk pig life days,* while Ziegler et al. [22] used a traffic light system to make animal welfare visually tangible on a scale. Head et al. [23] used survey methods to obtain a score from 1 to 10 for animal welfare, which is displayed via an app, along with other indicators representing, for example, climate or biodiversity concerns. The scores for each impact category are normalized to produce a single overall score. Ruckli et al. [24] considered four sustainability concerns with environmental, economic, social, and animal welfare indicators, and for animal welfare only, 76 indicators are aggregated into six generic animal welfare issues, scored between 0 and 100. In contrast, Castellini et al. [25]

and Rocchi et al. [20] ranked alternative labels with weights calculated using multi-criteria decision analysis (MCDA) methods, including stakeholder opinions, by comparing the calculated indicator values as results without normalization. Bartlett et al. [19] and Zira et al. [12] focused on pigs, with pork being the most consumed meat product globally, followed by chicken and beef [26]. Pork is also the leading meat in terms of environmental impact [27]. Similarly, the framework we have developed is based on the assessment of pigs and pig farming to provide a representative approach to a broader understanding of animal welfare in the context of industrial animal farming alongside environmental assessment. This paper focuses on the pig value chain in Germany, one of the largest pork producers in the world [28].

According to the results of the reviewed studies (see Supplementary Table S1), these studies essentially aim to compare alternatives to the main farming systems, taking into account sustainability concerns. These assessments are based on a specific set of data, which may vary considerably from case to case. Therefore, the applicability of the presented welfare indicators to other cases seems limited. There is a need for a framework to assess animal welfare for each animal species, type of farming, and individual farm structure.

2. Materials and Methods

The following definition is proposed for the terms under discussion: The evaluation of animal welfare is predicated on a structured set of indicators. A superior structure is characterized by a set of four main criteria that systematically encompass three to five indicators (bundles of indicators). In accordance with the AHP methodology, the indicators are designated as sub-criteria.

The flowchart in Figure 1 summarizes the main steps in the methodology and application of the framework. The following sections describe the steps shown and their interrelationships in detail while highlighting a structured approach.

2.1. Indicator Assembling

Defining animal welfare remains a considerable challenge due to the inherent complexity of interpreting animal experiences in ways that are accessible to human understanding. Recent advancements in animal welfare science, such as the 2020 update of the Five Domains Model by Mellor et al. [29], emphasize the importance of evaluating both negative and positive affective experiences in animals, including those arising from human–animal interactions. The model broadens welfare assessment beyond biological functioning by systematically considering domains such as nutrition, physical environment, health, behavioral interactions, and mental state. This multidimensional approach underscores that welfare is not merely the absence of suffering but also the presence of opportunities for agency and positive experiences. Effective assessment must therefore rely on observable factors such as behavior, health status, and environmental conditions interpreted through the lens of expert judgment. Notably, welfare can vary significantly between individual animals within a group, making individual-level observation a critical component [30]. This study adopts a pragmatic approach, operationalizing animal welfare through measurable indicators related to health, access to resources, behavior, and the microclimate. The assessment focuses on the on-farm life phase, which constitutes the majority of the animal's lifespan and excludes the slaughter process.

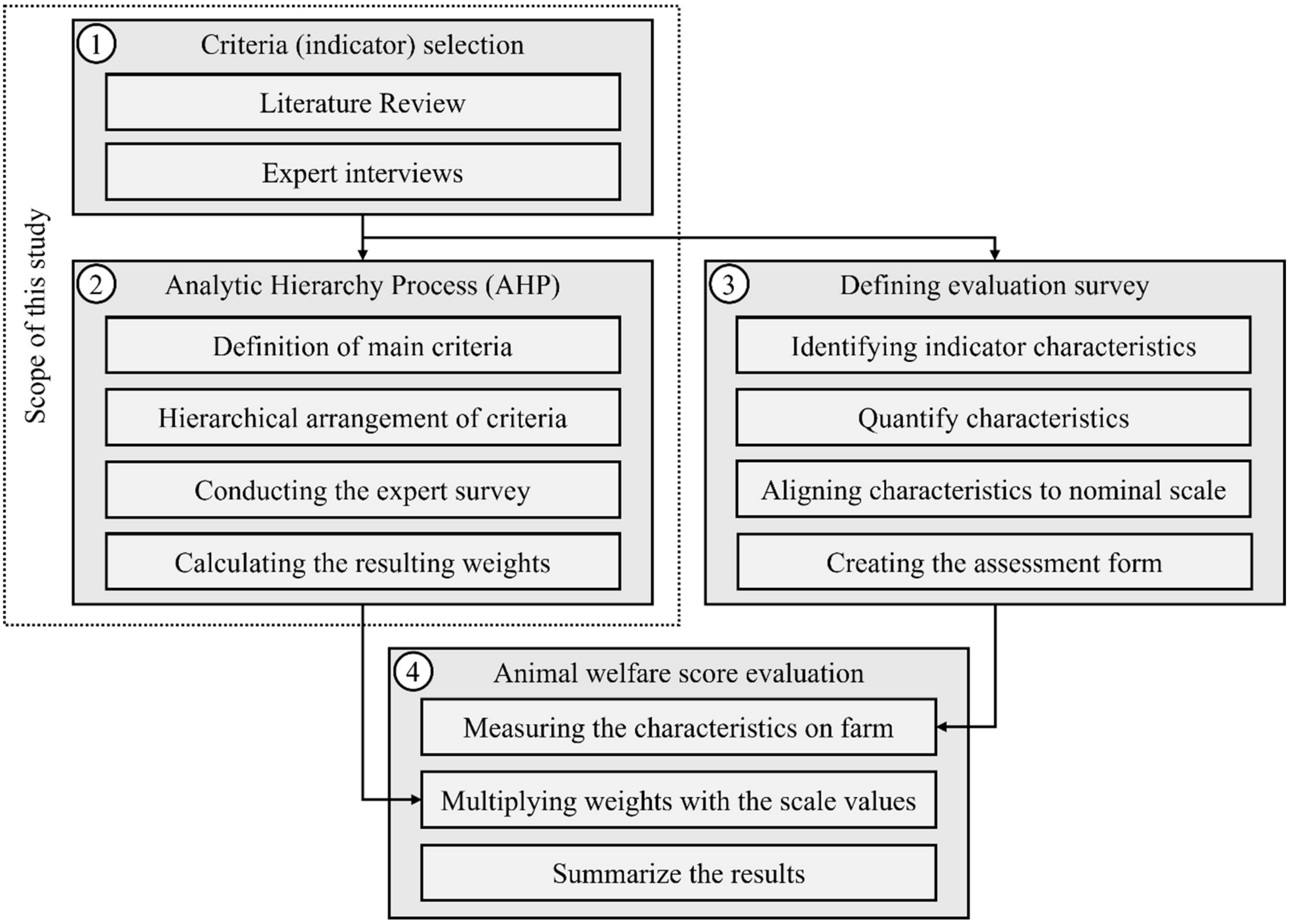


Figure 1. Structure and process of the framework used to retrieve the animal welfare score, with an emphasis on the scope of this study.

The set of assessment indicators, as hierarchically arranged in Figure 2, is defined and verified through qualitative expert interviews based on a literature review, which represents Step 1 in Figure 1. The following section contains detailed information regarding the experts' academic backgrounds, additional knowledge, and professional experience. Further explanation of the characteristics of the indicators and their possible measurability can be found in Table A1. There is an overlap with the indicators identified in other studies that consider the welfare of pigs in the context of LCA, as shown in the literature review in the Supplementary Materials (Table S1). With regard to the main criterion of husbandry conditions, most of the assigned indicator characteristics are objectively measurable, and the lower limits are regulation-specific and defined by German law. Regarding the indicator floor, there are not many possible floor types for pig houses, such as concrete or rubber slatted floors, and their advantages and disadvantages are clear. In addition, the characteristics of these indicators differ among farming systems and provide an opportunity to differentiate on a factual level. The main criterion of feed intake includes indicators that contribute to the welfare of the animal by meeting basic needs such as drinking and eating [31]. Failure to meet these needs can lead to stress and increased incidence of disease [32]. The main criterion of operation-specific parameters supports the rating of the health of the animal group by providing indicators that act as a warning signal when deviations occur. These indicators, such as the percentage of animal losses, are recorded by default and represent quantifiable parameters derived by farm management. Finally, the completely animal-centered indicators of the main criterion of single animal observation should be evaluated by examining and observing the animals as individuals, increasing the difficulty of measurement by introducing mainly subjective measurement. However, while increasing the difficulty, these indicators help to include concrete animal-related factors, such as external integrity, to assess the state of stress in groups of animals [33]. Almost all the indicators presented in Table A2 are in line with the literature, with the exception of daily weight gain and lactation period. Daily weight gain was emphasized by the experts interviewed in order to obtain an overview of the group of animals, especially in case of deviations, from which differences can be deducted. The lactation period is an important indicator of piglet health in terms of future weight gain and lifespan [34]. In Europe, the lower limit of the lactation period is defined by law depending on the farming system [35].

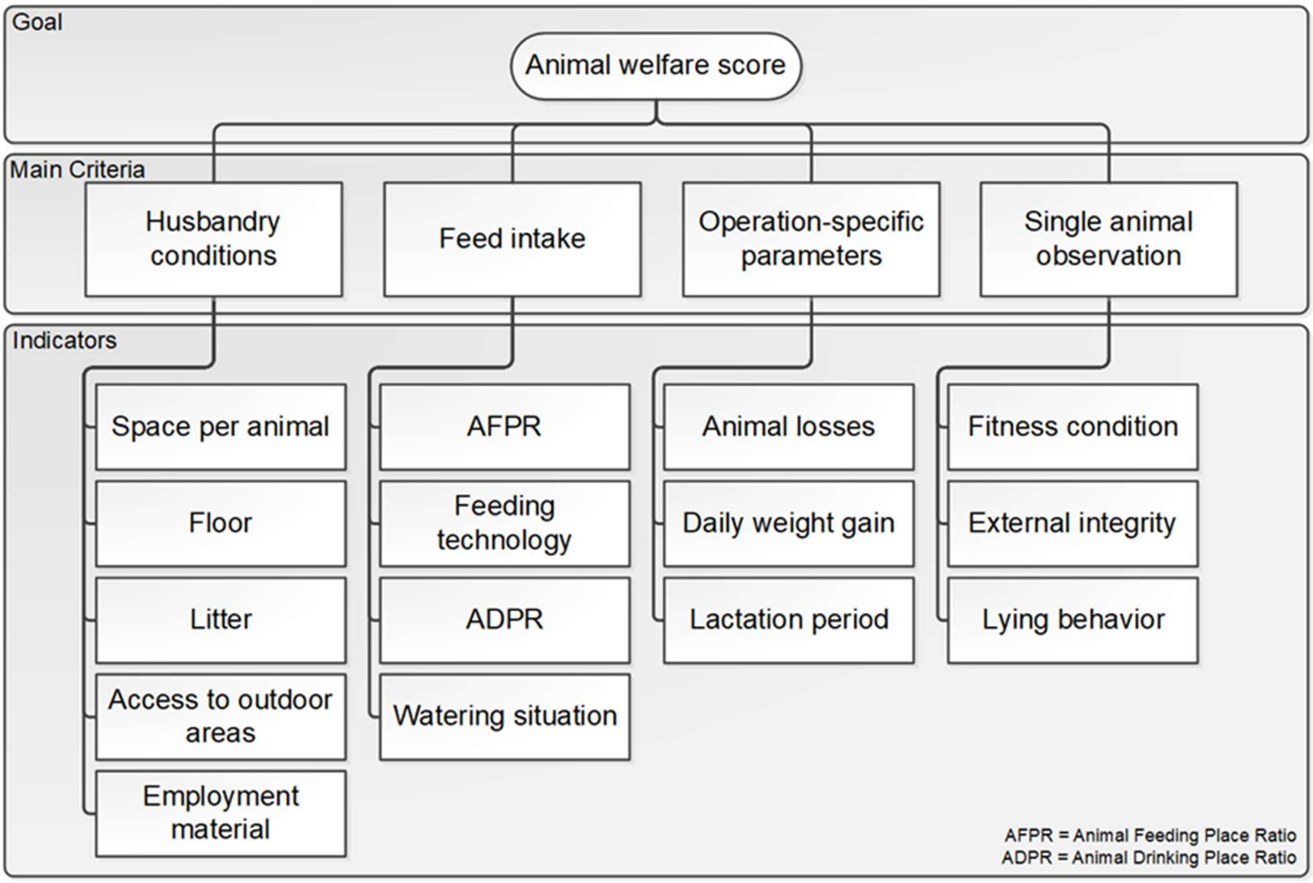


Figure 2. Hierarchical criteria-based structure for the goal of animal welfare assessment in pigs, based on Saaty [36].

2.2. Framework Description

Drawing on the methodology for calculating environmental impacts in a Life Cycle Impact Assessment (LCIA), we develop a synthetic model for an impact assessment that includes animal welfare as an impact category. The framework described in this paper, shown as a flowchart in Figure 1, uses MCDA methods to address the underlying aggregation and weighting process, which represents Step 2 in Figure 1. Ultimately, the developed framework proposes a metric for conducting impact assessments that results in a numerical value, which is standardized with the unit Animal Welfare Equivalent and quantifies the impact category of animal welfare as a result of Step 4 in Figure 1. The main advantage of the presented approach is the tangibility of the scale on which the animal welfare score can be classified. The involvement of pig husbandry and animal health experts in the decision-making process forms the basis of the assessment framework presented. In order to develop an impact category, indicators are needed to define the animal welfare characteristics, as identified in Section 2.1 and shown in Step 1 of Figure 1. The relationships and dependencies between the characteristics of these indicators and their impact categories in the context of LCIA in relation to the presented animal welfare impact category are structured in Figure 3.

For an animal welfare assessment, the individual indicators that make up the Life Cycle Inventory (LCI) need to be measured, weighted, and aggregated to obtain the final score. In the framework presented, the starting point for the required aggregation methodology, namely, the Analytic Hierarchy Process (AHP), is a hierarchically structured set of criteria, which is assembled in Section 2.1 and shown in Figure 2. The corresponding step in the framework is Step 2 (Figure 1). Four main criteria and 15 sub-criteria (indicators) have been identified for the assessment of animal welfare. The hierarchical structure provides criteria-related bundles of indicators arranged as sub-criteria. Each main criterion groups together the corresponding sub-criteria. The application of the AHP methodology starts with the weighting of the sets of indicators against each other. For these pairwise comparisons, the criteria levels and corresponding indicators can be arranged in the structure of matrices. By conducting a survey, the pairwise comparisons are transformed using the AHP, resulting in a percentage weight for each indicator. This widely used method helps to reveal the relative importance, measured as the weight of the hierarchical elements. AHP is a versatile MCDA technique for weighting summable attributes and evaluating alternatives systematically and in a hierarchical structure, as introduced by Saaty [36]. Saaty [36] recommends that the separation shown in Figure 2 creates four relatively homogeneous sets of elements with respect to the common attribute in order to avoid significant errors. Furthermore, grouping is performed because it is hardly possible for respondents to weight all 15 indicators against each other and to consider all further weightings in each decision in order to achieve consistency. Saaty [36] sets the dimensional limit for a bundle of indicators at nine. The main criterion of husbandry conditions combines five indicators, feed intake combines four, and the two persistent main criteria combine three-dimensional indicator matrices. When answering the questionnaire, each respondent successively compares the indicators of the sub-criteria in pairs separated by the main criteria, and then the main criteria are compared in pairs. The weighting of the compared indicators follows the specific scheme of an absolute scale—originally nine importance values and their reciprocals. These values reflect the intensity of the importance of the indicators in relation to each other, as chosen by the respondents editing the survey. In this study, the AHP is applied by consulting nine field experts to complete an online survey that provides a three-level scale of equal importance (1), strong importance (5), and extreme importance (9), as well as their reciprocals. This scale differs from the traditional AHP scale of nine levels. This practical procedural choice is necessary in order to disaggregate the comparisons and thus encourage evaluators to provide more discrete responses. This and other deviations from the traditional AHP scale have been proposed and extensively discussed in the literature [37–42]. In summary, deviating from the well-researched and proven, although sometimes criticized, fundamental scale requires additional consideration and analysis. Consequently, a critical ratio (CR) threshold of 0.1 may indicate, but not reflect, inconsistencies in judgement. For further information on the execution, we refer to the Supplementary Materials (S2).

To demonstrate the feasibility of the approach outlined in the last two stages of Step 2 (Figure 1), a validation run is carried out with nine field experts. Therefore, the application of the AHP methodology described above is carried out by means of a questionnaire. By answering this questionnaire, experts rate the different indicators against each other on the given scale. This requires a basic common understanding of the characteristics of the indicators and their measurability. Prior to the start of the questionnaire, these basic explanations were given to prepare the editors, as shown in Table A1, along with possible characteristics. An online survey was carried out to obtain the experts' assessments. Therefore, experts in pig production and animal health were contacted in August and September 2023. A total of nine completed surveys were collected. The group of respondents consisted of three pig farmers, three agricultural scientists, two agricultural consultants specializing in pig production, and one large animal veterinarian. Finally, an individually weighted set of criteria is obtained for each expert. However, a single set of criteria weightings must be determined for the concept presented. This is achieved by aggregating the individual comparison matrices into a single comparison matrix. The aggregation is performed using the geometric mean. The geometric mean is chosen because it has a proven track record in group judgments [43,44]. After aggregation, the weights obtained add up to one across all indicators, providing the basis for score aggregation as the characterization model of the impact category, as shown in Figure 3.

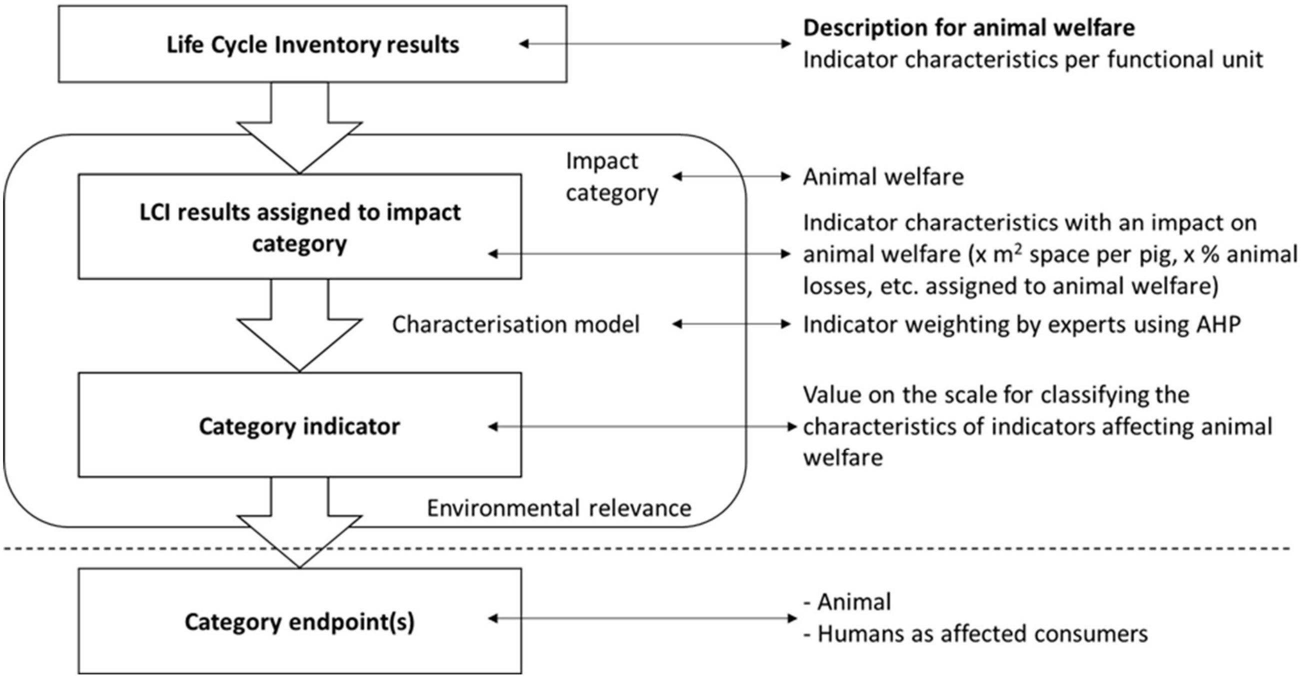


Figure 3. Concept for the implementation of animal welfare as an impact category based on ISO 14044 [45].

In order to calculate the animal welfare score in Step 4 (see Figure 1), Step 3, which is outside the scope of our framework, must be carried out. In Step 3, a five-point nominal scale, representing the category indicator in Figure 3, is introduced to rate the characteristics of the indicators. The five levels range from poor (1) to good (5) for each indicator, thus defining the scale that the evaluator can use for assessment on the farm under consideration. This scale has to be assigned to the characteristics by indicator according to expert interviews and based on a literature review. An example of the application of Step 3 is shown in Table 1 for the indicator space per animal, based on a classification developed by major German food retailers [46]. Based on a classification that refers to the same nominal scale for each indicator, a survey for the on-farm assessment has to be formulated. When the LCI is carried out on the farm in Step 4, a scale value is assigned to each indicator. These indicator-specific values for the farm under consideration are multiplied by the indicator weights (from the AHP in Step 2) using the weighted sum method and result in the animal welfare equivalent. Following the assessment, in relation to a functional unit within the boundaries of the considered systems, the unit for the impact category animal welfare has to be the animal welfare equivalent per kilogram live weight pig of the specific farm or housing section. In order to interpret this impact category indicator value, the nominal scale or category indicator of the characteristic evaluation and its definition must be taken into account. This scale determines the result, as the weighting from the AHP adds up to one when the indicators are combined. Thus, in relation to the definition of the nominal scale, the lower the score, the lower the welfare of the animal examined, and vice versa. Finally, the animal welfare score is an integer value between one and five, related to the functional unit of the study, which constitutes the animal welfare impact category.

Table 1. Exemplary scale to evaluate characteristics of the indicator space per animal for pigs weighing 50–110 kg [46].

Indicator: Space per Animal (50–110 kg)	Measurement by Characteristic (Minimum Indoor Area)
1	0.75 m^2
2	0.825 m^2
3	1.05 m^2
4	1.5 m^2
5	<110 kg: 1.3 m^2; 1 m^2 (outside) >110 kg: 1.5 m^2; 1.2 m^2 (outside)

3. Results

The development of the framework carried out in this paper focuses on the validation of its applicability in weighting the evaluated indicators with AHP, which represents Step 2 (Figure 1), leading to the following results: The starting point is an AHP-based survey with a pre-selected set of indicators in the example of pig farming. Then, following the AHP method described in Section 2.2, the priorities within the hierarchy are derived. The indicator percentages are obtained by multiplying the raw AHP priorities of each indicator by the share of the top-level main criterion, shown in brackets. The extent of the influences is visualized using a Sankey diagram in Figure 4, which is intended to make the weighting more tangible. For the numeric display of the results, we refer to Figure A1. The expert judgement with AHP shows that the overarching criteria of feed intake and single animal observation are the most highly rated. The priority of husbandry conditions is the least derived at 14.9%. This difference may be due to the fact that the high-priority criteria include indicators that directly influence the welfare of the animal in the context of feed intake and observation of the animal itself. The higher priority given to these criteria therefore highlights the importance of an animal-centered approach.

The Sankey diagram in Figure 4 emphasizes that the indicators with the highest priority are animal losses and fitness condition. The weight of animal losses as an indicator stands out, taking into account the rating of the associated main criterion of operation-specific parameters, which is significantly lower than that of the highest rated criteria. When validating the selection of indicators from the reviewed literature with expert interviews, the selection of animal losses as an indicator for the set under consideration was particularly supported. The interviewed experts have determined that the percentage of animal losses in a husbandry section exceeding a certain number is an essential indicator that animal health is affected, which is in line with the findings of Dolman et al. [47]. After animal losses, another highly weighted indicator is fitness condition, which is hierarchically related to single animal observation. Considering all indicators in its branch, fitness condition attracts attention with its individual weight. According to the explanation accompanying the survey (see Table A1), the fitness condition indicator is intended to record the observed fitness level of the animals captured via the established body condition score [48]. By providing data for an animal health-centered view, these two indicators define the focus of an animal welfare assessment using the framework.

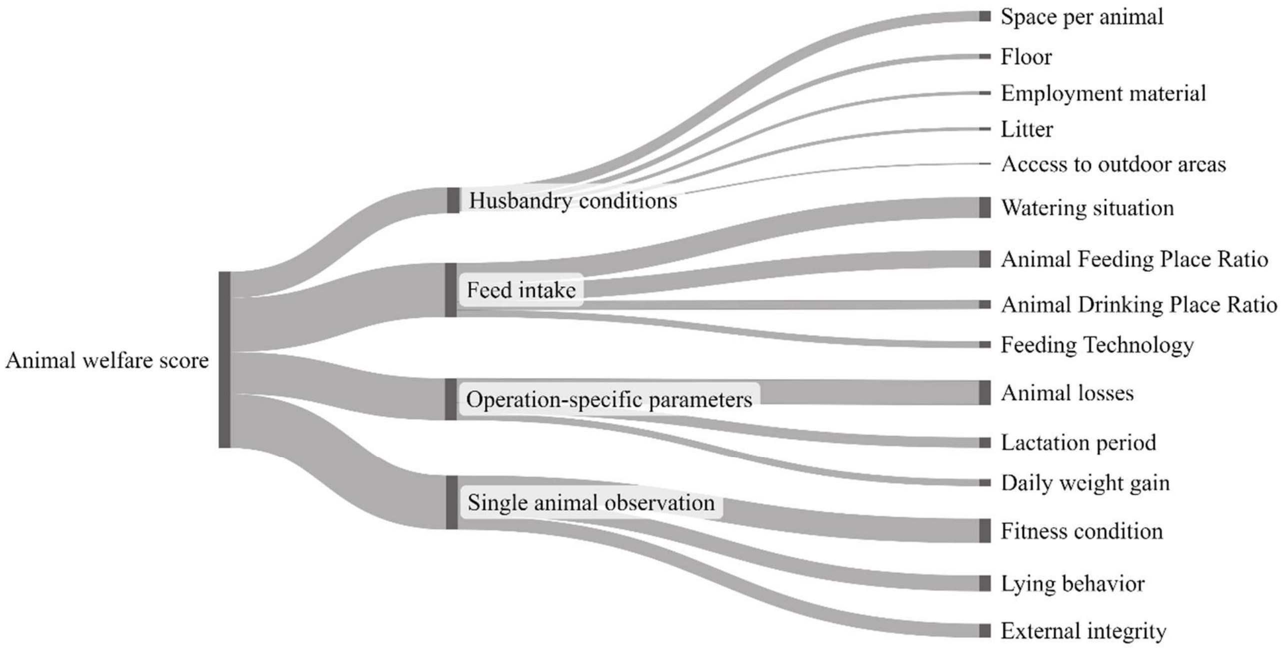


Figure 4. Visualization of the influence of the weights in a Sankey diagram based on the results of the AHP application.

Looking more closely at the high weighting of the fitness condition indicator, the associated main criterion, single animal observation, must be considered as the highest rated criterion. Obviously, it transmits its highest overall influence to its indicators when the weights are transferred. Because of this decisive influence, further analysis of the weights is carried out within the hierarchical branches. The second most important criterion is feed intake, which includes the watering situation and the animal–feeding place ratio (AFPR) as indicators with much higher weights than the other two indicators. Following the expert interviews to compile the set of indicators, high priority was given to health concerns. The watering situation is critical to maintaining animal health due to the susceptibility to contamination, particularly in terms of access to water. For example, different drinking troughs provide different levels of access to water. The watering situation and the animal–feeding place ratio contribute to the accessibility of basic needs. The interruption or disruption of access causes stress for the animals and can lead to health problems.

In terms of husbandry conditions, the space per animal indicator stands out by being somewhat distant from the other indicators with a high share. Furthermore, access to outdoor areas is the least preferred indicator for animal welfare in general. The observed difference is indeed surprising, as it does not correspond to the socially accepted view of animal welfare, which typically envisages animals living on green pastures and in more natural, spacious conditions [49].

To emphasize the importance of the parameter that reflects the quality of the calculations, the CR is visualized in Figure A1. The CR of almost all matrices is below the 10% limit, indicating good consistency across the paired comparisons made by respondents [36]. The CR of the single animal observation bundle exceeds this limit but is only slightly above the limit. This bundle of indicators exhibits some interdependencies in the experts' perceptions that can cause this effect. Furthermore, the small number of indicators increases the influence of an inconsistent response.

In conclusion, the framework gives priority to an animal health perspective. In addition, significant differences in the weighting of indicators within the main criteria branches emphasize the importance of certain indicators over others.

4. Discussion

4.1. Main Results

The framework presented provides an approach to integrating animal welfare into LCA. The development of an animal welfare impact category is part of this approach. What distinguishes our approach is the use of AHP to individually assess and weight the indicators and to guide them toward the improvement of key aspects of animal welfare. In contrast to the literature review (see Appendix A), which mainly compares the welfare characteristics of different labeled farming systems, we propose a different focus when comparing developments on a farm. The inclusion of animal welfare as an impact category within LCA is consistent with this farm-centered approach, which supports more in-depth assessments. The derived animal welfare equivalent is a valuable representation that reflects the actual state of the farm in terms of animal welfare. As with environmental LCA results, the assessment does not end with the score but can be used as a basis for improvement. The quantifiability of the animal welfare assessment, expressed as a score from bad to good, enables both farm managers and consumers to recognize and adjust their practices accordingly. In addition, this approach can be applied to specific areas within livestock production. For example, it is possible to focus on specific parts of the farm, such as the insemination unit or the weaning area. In such cases, if the database is large enough, the results can be aligned with a more specific functional unit of the LCA study, providing more insights than can be obtained when considering the whole farm.

With regard to the evaluation of animal welfare, the individual weighting of the indicators brings a new approach to the consideration of animal welfare in the context of LCA. Most of the approaches found in the literature do not consider weighting. Nevertheless, similar to the presented approach, Zira et al. [50] applied AHP with an expert survey. Thus, the AHP application differs from our approach, as it is applied to weight the subcategories in a social LCA framework, while the assigned indicators are equally weighted [50]. Furthermore, Bartlett et al. [19] used the Welfare Quality® score for pigs as the technical basis and integrated the four Welfare Quality® principles of good feeding, good housing, good health, and appropriate behavior with randomly selected weights. Both studies focused on the inclusion of different scores in animal welfare assessment. While Zira et al. [50] focused on the social LCA inclusion of animal welfare and animals as stakeholders by calculating several social indices, Bartlett et al. [19] introduced a welfare cost approach to include animal welfare. Both processed the original animal-related measurements and parameters with multiple other influencing values to develop the resulting indicator values. Compared to these approaches, the present approach does not transform the welfare assessment results based on indicators and multiple calculation steps into higher scores. Instead, it focuses on a relatively straightforward synthesis of the different welfare indicators into a final score. This synthesis does not take into account any further evaluation of the range of indicators beyond transferring the characteristics of the indicators to a scale. The aim is to produce an easily implemented assessment that translates the characteristics of the indicator into a comparable value while maintaining a direct link to the original indicators.

4.2. Methodology

Beyond the main findings, a closer look at the underlying methodology reveals some notable challenges and shortcomings in the practical application of this approach. One of the main challenges, but also one of the main strengths, is the selection of indicators that comprehensively capture the different facets of animal welfare. Experts disagree on which aspects should be considered, and the definition of animal welfare itself is a subject of ongoing debate. A hierarchical categorization based on key criteria has been used to address these disagreements. The key criteria are intended to explain the general areas in which animal welfare can be assessed. This approach is beneficial, but it is clear that a more comprehensive and rigorous methodology can be developed. Further refinement can be achieved by conducting multiple iterations of the AHP surveys to identify the most critical top-level criteria and their underlying indicators. This process may result in the elimination of certain indicators that prove to have insignificant impacts or importance. The challenge of this refinement is to establish a cut-off criterion. Once indicators have been selected through these iterative processes, the next step is to assign appropriate weights. In summary, the framework presented offers an innovative perspective on animal welfare in the context of LCA but also highlights its complexity. Reaching a consensus on the essential indicators and their relative importance remains a key challenge in this evolving field of research.

The indicator weightings were derived via the Analytic Hierarchy Process (AHP) using a structured survey of nine domain experts. While this offers a transparent and repeatable mechanism, it is subject to the composition of the expert group, which, in this study, leaned toward practical pig production expertise. As such, the results may reflect implicit industry priorities. We recommend that future applications broaden the expert base to include more ethologists and animal welfare scientists to balance the perspectives.

Given the additional challenges of the proposed framework, particularly the adaptation of the importance scale proposed by Saaty [36] for the survey, the implementation of a fuzzy approach can be suggested. The fuzzy AHP method allows for paired comparisons based on vague, fuzzy ratings [51]. Furthermore, the method allows for the quantification of weak priorities and incomparability, allowing the decision-maker to remain unaware of their preferences. In particular, when considering animal behavior and welfare, such uncertainties arise due to the subjective perception of some parameters. In addition to this potential mechanism for coping with uncertainties, the choice of the MCDA methodology involved represents another possibility for improvement. According to Cinelli et al. [52], the selection of appropriate MCDA methods for each decision problem is challenging. Considering this research, it may be of significant importance to review alternative appropriate MCDA methods that could be assigned to the presented framework. By way of example, an extension may include further preference ranking or outranking methods, such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [53] and the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [54].

The selected indicators in this framework are limited to those for which standardized on-farm data collection is feasible and consistent across farming systems. As a result, more subjective or behaviorally nuanced indicators—such as affective state or the quality of enrichment use—were not prioritized. While this allows for comparability and implementation in real-world contexts, it inevitably narrows the scope of the welfare picture. We recognize that such constraints can introduce bias toward production-relevant metrics and suggest that future adaptations incorporate complementary qualitative assessments or fuzzy logic systems.

In completing the assessment that must follow the current study, it is essential to ensure that the characteristics of the indicators are consistent with the nominal scale. The entire classification system is relevant, as it provides the basis for calculating the animal welfare score of the system being assessed. The characteristics must be assigned to the scale in a way that ensures that they are detectable, visible, distinguishable, and, when possible, numerically determinable. To this end, the classification shall be based on an appropriate number of expert judgements.

5. Conclusions

The assessment of animal welfare is undoubtedly a contentious and multifaceted issue that requires careful consideration. The framework presented in this study takes a novel approach by identifying a set of hierarchically structured indicators and weighting them using expert judgement to provide a comprehensive assessment of welfare considerations. Single animal observation and feed intake are the main criteria that significantly influence the underlying indicators. Influenced by its assigned main criterion, single animal observation, the fitness condition indicator is one of the highest rated indicators. However, another indicator that attracts attention receives almost the same weight, namely animal losses, which underlines the overall finding that an animal health-centered approach is preferred when assessing animal welfare. These retrieved indicators should then be translated into numerical values, giving them a level of quantifiability not commonly found in the literature reviewed. One of the distinctive aspects of our methodology is its commitment to maintaining the validity of these measurements. This not only distinguishes it but also underlines its practicality for practitioners and, ultimately, consumers throughout the livestock value chain. To overlook this dimension when conducting environmental assessments in the livestock sector would be to miss a crucial component of sustainability. We acknowledge that translating the multidimensional concept of animal welfare into a single numerical score entails reductionist compromises. While this format is useful for comparability and integration into broader LCA models, it may obscure important qualitative nuances. Transparency in score composition and maintaining traceability to individual indicators are therefore central principles of the presented framework.

Our framework aims to realize the vision of a holistic sustainability assessment by introducing a new impact category that incorporates animal welfare into the LCA framework. In doing so, it paves the way for a more comprehensive assessment of sustainability in the livestock sector, where both environmental and social factors are given their due importance. The impact category is explained using a score based on an equivalent, which serves as a means of summarizing the overall results of this category. This score must be classified and interpreted in relation to the other LCA results in order to obtain a holistic sustainability assessment. Once an animal welfare score has been calculated, it is essential to have a methodology in place for evaluating the different categories under consideration and consolidating them into a final score. This approach should encompass all the results and provide a qualitative assessment of their interrelationships. In this sense, the integration of animal welfare into LCA also supports the One Health approach, which emphasizes the interconnection among human, animal, and environmental health [16]. This implementation is in line with van der Werf et al. [11], who emphasized the importance of including social aspects in the LCA of the livestock industry in order to increase the robustness of the assessment.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su17104677/s1, Table S1: Review of animal welfare based on [9,12,17–25,33,40,43,47,50,55–70]. Document S2: AHP execution [40,43,68–70].

Author Contributions: N.T.: writing—review and editing, writing—original draft, validation, methodology, investigation, formal analysis, data curation, and conceptualization. E.N.: writing—review and editing, writing—original draft, validation, and methodology. F.S.: writing—review and editing and funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: This project was supported by the German Federal Ministry of Food and Agriculture (BMEL), along with the project SPECK (Systemic optimization of the meat value chain using pig farming as an example through the development and embedding of digital tools), under grant number 281A502B19.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; the collection, analyses, or interpretation of data; the writing of the manuscript; or the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
AHP	Analytic Hierarchy Process
MCDA	Multi-Criteria Decision Analysis
CR	Critical Ratio
AFPR	Animal–Feeding Place Ratio
ADPR	Animal–Drinking Place Ratio

Appendix A

Table A1. Assignment of the 15 indicators to the four main criteria with explanations of the indicators' features and their possible measurability.

Main Criterion	Indicator	Explanation	Measurability
Husbandry conditions	Space per animal	Average area per animal per farming section.	easily measurable factor (m^2) the legal standard is specified
	Access to outdoor areas	Presence of an outlet.	easy to measure (presence yes/no) area not decisive
	Floor	Soil conditions per section.	easily measurable factor (type, material) a classification of whether compatibility with the respective development stage of the animals is sought
	Litter	Presence of straw.	easily measurable (presence yes/no) the legal standard for sows enables species-typical behavior
	Employment material	Nature of the material, such as a stationary chain or a loose object. Edibility and accessibility.	easily measurable (type, edibility yes/no) differences in materials legal standard as a minimum assessment
Feed intake	Animal–feeding place ratio (AFPR)	Ratio of usable feeding places to the average number of animals per section of housing.	easily measurable (#:#) at the same time, accessibility is a decisive criterion for inclusion
	Feeding technology	Eating is facilitated by built-in technology.	easily measurable (type, species) ad libitum, liquid, solid, etc. possible evaluation according to the species-appropriateness of the feeding method
	Animal–drinking place ratio (ADPR)	Ratio of usable drinking places to the average number of animals per section of housing.	easily measurable (#:#) at the same time, accessibility is a decisive criterion for inclusion
	Drinking situation	Water absorption is facilitated by installed technology.	easily measurable (type, species) accessibility, cleanliness, species appropriateness

Table A1. *Cont.*

Main Criterion	Indicator	Explanation	Measurability
Operation-specific parameters	Animal losses	This factor should be recorded in a posture section.	easily measurable (%) sow planner fattening pigs, piglets (born alive, <8 kg), piglet rearing (8–30 kg)
	Daily weight gain	This factor is intended to record posture-specific deviations with comparable basic criteria.	easily measurable (weight in kg) define deviations based on feed intake and performance
	Lactation period	This factor is intended to determine the duration of the piglets' intake of the mothers' milk.	easy to measure (duration in weeks)
Single animal observation	Fitness condition	This factor is intended to record the external fitness level of the animals.	difficult to measure (body condition score, subjective) classification from 1 to 5 activity, reactions, weight
	External integrity	This factor is intended to reflect semi-annual monitoring.	difficult to measure (subjective) skin (wounds)
	Lying behavior	This factor should allow conclusions to be drawn about the well-being associated with each section of the husbandry.	difficult to measure (abnormalities, subjective) show clear abnormalities (cluster vs. total isolation)

= Number.

Table A2. Identified indicators for the presented framework and their appearance in the assessed literature.

Main Criteria	Indicators	Bartlett et al. [19]	Bonneau et al. [9]	Dolman et al. [47]	Röös et al. [55]	Ruckli et al. [24]	Scherer et al. [17]	Zira et al. [12]
Husbandry conditions	Space per animal	x				x	x	x
	Floor	x				x		x
	Litter	x				x		x
	Access to outdoor areas	x			x	x	x	x
	Employment material	x	x			x		x
Feed intake	Animal–feeding place ratio	x	x					
	Feeding technology	x	x					
	Animal–drinking place ratio	x	x			x		
	Watering situation	x	x			x		
Operation-specific parameters	Animal losses		x	x		x		x
	Daily weight gain							
	Lactation period					x		
Single animal observation	Fitness condition	x						
	External integrity	x				x		x
	Lying behavior	x						

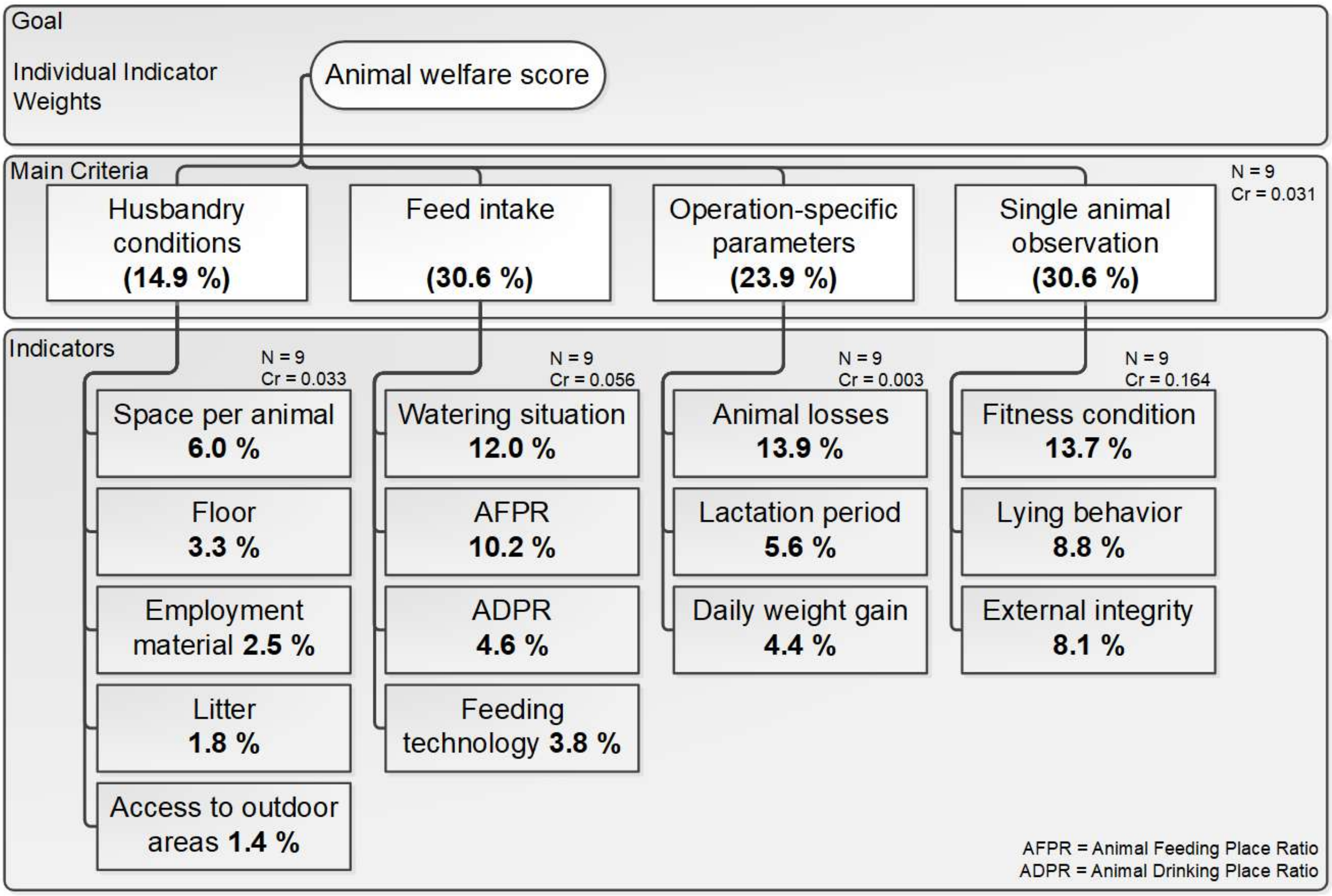


Figure A1. Individual indicator weights derived using the AHP survey.

References

1. Benton, T.; Bieg, C.; Harwatt, H.; Pudasaini, R.; Wellesley, L. The Royal Institute of International Affairs. In *Food System Impacts on Biodiversity Loss: Three Levers for Food System Transformation in Support of Nature*; Chatham House: London, UK, 2021.
2. McAuliffe, G.A.; Chapman, D.V.; Sage, C.L. A Thematic Review of Life Cycle Assessment (LCA) Applied to Pig Production. *Environ. Impact Assess. Rev.* **2016**, *56*, 12–22. [CrossRef]
3. Pelletier, N.; Audsley, E.; Brodt, S.; Garnett, T.; Henriksson, P.; Kendall, A.; Kramer, K.J.; Murphy, D.; Nemecek, T.; Troell, M. Energy Intensity of Agriculture and Food Systems. *Annu. Rev. Environ. Resour.* **2011**, *36*, 223–246. [CrossRef]
4. Tilman, D.; Clark, M. Global Diets Link Environmental Sustainability and Human Health. *Nature* **2014**, *515*, 518–522. [CrossRef]
5. Xu, X.; Sharma, P.; Shu, S.; Lin, T.-S.; Ciais, P.; Tubiello, F.N.; Smith, P.; Campbell, N.; Jain, A.K. Global Greenhouse Gas Emissions from Animal-Based Foods Are Twice Those of Plant-Based Foods. *Nat. Food* **2021**, *2*, 724–732. [CrossRef]
6. De Luca, A.I.; Iofrida, N.; Leskinen, P.; Stillitano, T.; Falcone, G.; Strano, A.; Gulisano, G. Life Cycle Tools Combined with Multi-Criteria and Participatory Methods for Agricultural Sustainability: Insights from a Systematic and Critical Review. *Sci. Total Environ.* **2017**, *595*, 352–370. [CrossRef] [PubMed]
7. Gislason, S.; Birkved, M.; Maresca, A. A Systematic Literature Review of Life Cycle Assessments on Primary Pig Production: Impacts, Comparisons, and Mitigation Areas. *Sustain. Prod. Consum.* **2023**, *42*, 44–62. [CrossRef]
8. Basset-Mens, C.; van der Werf, H.M.G. Scenario-Based Environmental Assessment of Farming Systems: The Case of Pig Production in France. *Agric. Ecosyst. Environ.* **2005**, *105*, 127–144. [CrossRef]
9. Bonneau, M.; Klauke, T.N.; Gonzàlez, J.; Rydhmer, L.; Ilari-Antoine, E.; Dourmad, J.Y.; de Greef, K.; Houwers, H.W.J.; Cinar, M.U.; Fàbrega, E.; et al. Evaluation of the Sustainability of Contrasted Pig Farming Systems: Integrated Evaluation. *Animal* **2014**, *8*, 2058–2068. [CrossRef]
10. Dourmad, J.Y.; Ryschawy, J.; Trousson, T.; Bonneau, M.; Gonzàlez, J.; Houwers, H.W.J.; Hviid, M.; Zimmer, C.; Nguyen, T.L.T.; Morgensen, L. Evaluating Environmental Impacts of Contrasting Pig Farming Systems with Life Cycle Assessment. *Anim. Int. J. Anim. Biosci.* **2014**, *8*, 2027–2037. [CrossRef]

11. van der Werf, H.M.G.; Knudsen, M.T.; Cederberg, C. Towards Better Representation of Organic Agriculture in Life Cycle Assessment. *Nat. Sustain.* **2020**, *3*, 419–425. [CrossRef]
12. Zira, S.; Rydhmer, L.; Ivarsson, E.; Hoffmann, R.; Röös, E. A Life Cycle Sustainability Assessment of Organic and Conventional Pork Supply Chains in Sweden. *Sustain. Prod. Consum.* **2021**, *28*, 21–38. [CrossRef]
13. Florindo, T.J.; Bom De Medeiros Florindo, G.I.; Ruviaro, C.F.; Pinto, A.T. Multicriteria Decision-Making and Probabilistic Weighing Applied to Sustainable Assessment of Beef Life Cycle. *J. Clean. Prod.* **2020**, *242*, 118362. [CrossRef]
14. Broom, D.M. Animal Welfare: An Aspect of Care, Sustainability, and Food Quality Required by the Public. *J. Vet. Med. Educ.* **2010**, *37*, 83–88. [CrossRef]
15. Webster, J. Animal Welfare: Freedoms, Dominions and A Life Worth Living. *Animals* **2016**, *6*, 35. [CrossRef]
16. FAO; UNEP; WHO; WOAH. *One Health Joint Plan of Action (2022–2026): Working Together for the Health of Humans, Animals, Plants and the Environment*, 1st ed.; World Health Organization: Rome, Italy, 2022; ISBN 978-92-4-005913-9.
17. Scherer, L.; Tomasik, B.; Rueda, O.; Pfister, S. Framework for Integrating Animal Welfare into Life Cycle Sustainability Assessment. *Int. J. Life Cycle Assess.* **2018**, *23*, 1476–1490. [CrossRef]
18. Lanzoni, L.; Whatford, L.; Atzori, A.S.; Chincarini, M.; Giammarco, M.; Fusaro, I.; Vignola, G. Review: The Challenge to Integrate Animal Welfare Indicators into the Life Cycle Assessment. *Anim. Int. J. Anim. Biosci.* **2023**, *17*, 100794. [CrossRef]
19. Bartlett, H.; Balmford, A.; Holmes, M.A.; Wood, J.L.N. Advancing the Quantitative Characterization of Farm Animal Welfare. *Proc. R. Soc. B* **2023**, *290*, 20230120. [CrossRef] [PubMed]
20. Rocchi, L.; Paolotti, L.; Rosati, A.; Boggia, A.; Castellini, C. Assessing the Sustainability of Different Poultry Production Systems: A Multicriteria Approach. *J. Clean. Prod.* **2019**, *211*, 103–114. [CrossRef]
21. Tallentire, C.W.; Edwards, S.A.; van Limbergen, T.; Kyriazakis, I. The Challenge of Incorporating Animal Welfare in a Social Life Cycle Assessment Model of European Chicken Production. *Int. J. Life Cycle Assess.* **2019**, *24*, 1093–1104. [CrossRef]
22. Ziegler, F.; Nilsson, K.; Levermann, N.; Dorph, M.; Lyberth, B.; Jessen, A.A.; Desportes, G. Local Seal or Imported Meat? Sustainability Evaluation of Food Choices in Greenland, Based on Life Cycle Assessment. *Foods* **2021**, *10*, 1194. [CrossRef]
23. Head, M.; Sevenster, M.; Odegard, I.; Krutwagen, B.; Croezen, H.; Bergsma, G. Life Cycle Impacts of Protein-Rich Foods: Creating Robust yet Extensive Life Cycle Models for Use in a Consumer App. *J. Clean. Prod.* **2014**, *73*, 165–174. [CrossRef]
24. Ruckli, A.K.; Hörtenhuber, S.J.; Ferrari, P.; Guy, J.; Helmerichs, J.; Hoste, R.; Hubbard, C.; Kasperczyk, N.; Leeb, C.; Malak-Rawlikowska, A.; et al. Integrative Sustainability Analysis of European Pig Farms: Development of a Multi-Criteria Assessment Tool. *Sustainability* **2022**, *14*, 26. [CrossRef]
25. Castellini, C.; Boggia, A.; Paolotti, L.; Thoma, G.; Kim, D. Environmental Impacts and Life Cycle Analysis of Organic Meat Production and Processing. In *Organic Meat Production and Processing*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2012; pp. 113–136.
26. Statista Konsum von Fleisch Weltweit Nach Fleischart Bis. 2024. Available online: https://de.statista.com/statistik/daten/studie/296612/umfrage/konsum-von-fleisch-weltweit-nach-fleischart/ (accessed on 11 March 2024).
27. Halpern, B.S.; Frazier, M.; Verstaen, J.; Rayner, P.-E.; Clawson, G.; Blanchard, J.L.; Cottrell, R.S.; Froehlich, H.E.; Gephart, J.A.; Jacobsen, N.S.; et al. The Environmental Footprint of Global Food Production. *Nat. Sustain.* **2022**, *5*, 1027–1039. [CrossRef]
28. FAO Global Statistical Yearbook, FAO Regional Statistical Yearbooks. Available online: https://www.fao.org/faostat/en/#data/QCL/visualize (accessed on 11 March 2024).
29. Mellor, D.J.; Beausoleil, N.J.; Littlewood, K.E.; McLean, A.N.; McGreevy, P.D.; Jones, B.; Wilkins, C. The 2020 Five Domains Model: Including Human–Animal Interactions in Assessments of Animal Welfare. *Animals* **2020**, *10*, 1870. [CrossRef] [PubMed]
30. Webster, J. *Animal Welfare: Limping towards Eden: A Practical Approach to Redressing the Problem of Our Dominion over the Animals*; UFAW Animal Welfare Series; Blackwell Pub: Oxford, UK; Ames, IA, USA, 2005; ISBN 0-470-75110-X.
31. Dalmau, A.; Velarde, A.; Scott, K.; Edwards, S.; Butterworth, A.; Veissier, I.; Keeling, L.; van Overbeke, G.; Bedaux, V. *Welfare Quality® Welfare Quality® Assessment Protocol for Pigs (Sows and Piglets, Growing and Finishing Pigs)*; Welfare Quality® Consortium: Lelystad, The Netherlands, 2009.
32. Webster, A.J. Farm Animal Welfare: The Five Freedoms and the Free Market. *Vet. J.* **2001**, *161*, 229–237. [CrossRef] [PubMed]
33. Petit, G.; Sablayrolles, C.; Yannou-Le Bris, G. Combining Eco-Social and Environmental Indicators to Assess the Sustainability Performance of a Food Value Chain: A Case Study. *J. Clean. Prod.* **2018**, *191*, 135–143. [CrossRef]
34. van Nieuwamerongen, S.E.; Soede, N.M.; van der Peet-Schwering, C.M.C.; Kemp, B.; Bolhuis, J.E. Gradual Weaning during an Extended Lactation Period Improves Performance and Behavior of Pigs Raised in a Multi-Suckling System. *Appl. Anim. Behav. Sci.* **2017**, *194*, 24–35. [CrossRef]
35. Ahrens, F.; Pollmüller, T.; Sünkel, Y.; Bussemas, R.; Weißmann, F.; Erhard, M.H. Prolonged Suckling Period in Organic Piglet Production—Effects on Some Performance and Health Aspects. In *Cultivating the Future Based on Science, Volume 2—Livestock, Socio-Economy and Cross Disciplinary Research in Organic Agriculture, Proceedings of the Second Scientific Conference of the International Society of Organic Agriculture Research (ISOFAR), Modena, Italy, 18 June 2008*; International Society of Organic Agricultural Research (ISOFAR): Bonn, Germany, 2008; pp. 142–145.

36. Saaty, T.L. How to Make a Decision: The Analytic Hierarchy Process. *Eur. J. Oper. Res.* **1990**, *48*, 9–26. [CrossRef]
37. Dong, Y.; Xu, Y.; Li, H.; Dai, M. A Comparative Study of the Numerical Scales and the Prioritization Methods in AHP. *Eur. J. Oper. Res.* **2008**, *186*, 229–242. [CrossRef]
38. Finan, J.S.; Hurley, W.J. Transitive Calibration of the AHP Verbal Scale. *Eur. J. Oper. Res.* **1999**, *112*, 367–372. [CrossRef]
39. Ishizaka, A.; Balkenborg, D.; Kaplan, T. Influence of Aggregation and Measurement Scale on Ranking a Compromise Alternative in AHP. *J. Oper. Res. Soc.* **2011**, *62*, 700–710. [CrossRef]
40. Ji, P.; Jiang, R. Scale Transitivity in the AHP. *J. Oper. Res. Soc.* **2003**, *54*, 896–905. [CrossRef]
41. Lootsma, F.A. Scale Sensitivity in the Multiplicative AHP and SMART. *J. Multi-Criteria Decis. Anal.* **1993**, *2*, 87–110. [CrossRef]
42. Salo, A.A.; Hämäläinen, R.P. On the Measurement of Preferences in the Analytic Hierarchy Process. *J. Multi-Criteria Decis. Anal.* **1997**, *6*, 309–319. [CrossRef]
43. Saaty, R.W. The Analytic Hierarchy Process—What It Is and How It Is Used. *Math. Model.* **1987**, *9*, 161–176. [CrossRef]
44. Saaty, T.L. Group Decision Making and the AHP. In *The Analytic Hierarchy Process*; Springer: Berlin/Heidelberg, Germany, 1989; pp. 59–67.
45. *ISO 14044 Standard*; Environmental Management–Life Cycle Assessment–Requirements and Guidelines. ISO Beuth Verlag GmbH: Berlin, Germany, 2018.
46. haltungsform.de Mindestanforderungen Für Programme, Die Kriterien Für Betriebe Mit Schweinemast Festlegen. Available online: https://www.haltungsform.de/im-ueberblick/ (accessed on 23 May 2024).
47. Dolman, M.A.; Vrolijk, H.C.J.; Boer, I.J.M. Exploring Variation in Economic, Environmental and Societal Performance among Dutch Fattening Pig Farms. *Livest. Sci.* **2012**, *149*, 143–154. [CrossRef]
48. Doyle, R.E.; Groat, J.; Wynn, P.C.; Holyoake, P.K. Physiological and Nonphysiological Indicators of Body Condition Score in Weaner Pigs. *J. Anim. Sci.* **2015**, *93*, 1887–1895. [CrossRef]
49. Pietrosemoli, S.; Tang, C. Animal Welfare and Production Challenges Associated with Pasture Pig Systems: A Review. *Agriculture* **2020**, *10*, 34. [CrossRef]
50. Zira, S.; Röös, E.; Ivarsson, E.; Hoffmann, R.; Rydhmer, L. Social Life Cycle Assessment of Swedish Organic and Conventional Pork Production. *Int. J. Life Cycle Assess.* **2020**, *25*, 1957–1975. [CrossRef]
51. Liu, Y.; Eckert, C.M.; Earl, C. A Review of Fuzzy AHP Methods for Decision-Making with Subjective Judgements. *Expert Syst. Appl.* **2020**, *161*, 113738. [CrossRef]
52. Cinelli, M.; Burgherr, P.; Kadziński, M.; Słowiński, R. Proper and Improper Uses of MCDA Methods in Energy Systems Analysis. *Decis. Support Syst.* **2022**, *163*, 113848. [CrossRef]
53. Hwang, C.-L.; Yoon, K. Methods for Multiple Attribute Decision Making. In *Multiple Attribute Decision Making*; Beckmann, M., Künzi, H.P., Hwang, C.-L., Yoon, K., Eds.; Lecture Notes in Economics and Mathematical Systems; Springer: Berlin/Heidelberg, Germany, 1981; pp. 58–191. ISBN 978-3-540-10558-9.
54. Landry, M.; Nadeau, R. *L'Aide à La Décision: Nature, Instruments et Perspectives D'avenir*; Sciences de l'administration; Presses de l'Université Laval: Québec, QC, Canada, 1986; Volume 2, ISBN 978-2-7637-7084-0.
55. Röös, E.; Ekelund, L.; Tjärnemo, H. Communicating the Environmental Impact of Meat Production: Challenges in the Development of a Swedish Meat Guide. *J. Clean. Prod.* **2014**, *73*, 154–164. [CrossRef]
56. Boggia, A.; Paolotti, L.; Antegiovanni, P.; Fagioli, F.F.; Rocchi, L. Managing Ammonia Emissions Using No-Litter Flooring System for Broilers: Environmental and Economic Analysis. *Environ. Sci. Policy* **2019**, *101*, 331–340. [CrossRef]
57. Dolman, M.A.; Sonneveld, M.P.W.; Mollenhorst, H.; Boer, I.J.M. Benchmarking the Economic, Environmental and Societal Performance of Dutch Dairy Farms Aiming at Internal Recycling of Nutrients. *J. Clean. Prod.* **2014**, *73*, 245–252. [CrossRef]
58. Geß, A.; Viola, I.; Miretti, S.; Macchi, E.; Perona, G.; Battaglini, L.; Baratta, M. A New Ap-proach to LCA Evaluation of Lamb Meat Production in Two Different Breeding Systems in Northern Italy. *Front. Vet. Sci.* **2020**, *7*, 651. [CrossRef]
59. Haas, G.; Wetterich, F.; Köpke, U. Comparing Intensive, Extensified and Organic Grassland Farming in Southern Germany by Process Life Cycle Assessment. *Agric. Ecosyst. Environ.* **2001**, *83*, 43–53. [CrossRef]
60. Mas, K.; Pardo, G.; Galán, E.; Del Prado, A. Assessing Dairy Farm Sustainability Using Whole-Farm Modelling and Life Cycle Analysis. *Adv. Anim. Biosci.* **2016**, *7*, 259–260. [CrossRef]
61. Mollenhorst, H.; Berentsen, P.B.M.; Boer, I.J.M. On-Farm Quantification of Sustainability Indicators: An Application to Egg Production Systems. *Br. Poult. Sci.* **2006**, *47*, 405–417. [CrossRef]
62. Müller-Lindenlauf, M.; Deittert, C.; Köpke, U. Assessment of Environmental Effects, Animal Welfare and Milk Quality among Organic Dairy Farms. *Livest. Sci.* **2010**, *128*, 140–148. [CrossRef]
63. Rocchi, L.; Cartoni Mancinelli, A.; Paolotti, L.; Mattioli, S.; Boggia, A.; Papi, F.; Castellini, C. Sustainability of Rearing System Using Multicriteria Analysis: Application in Commercial Poultry Production. *Anim. Open Access J.* **2021**, *11*, 3483. [CrossRef]
64. Turner, I.; Heidari, D.; Widowski, T.; Pelletier, N. Development of a Life Cycle Impact As-sessment Methodology for Animal Welfare with an Application in the Poultry Industry. *Sustain. Prod. Consum.* **2023**, *40*, 30–47. [CrossRef]

65. van Asselt, E.D.; Capuano, E.; van der Fels-Klerx, H.J. Sustainability of Milk Production in the Netherlands—A Comparison between Raw Organic, Pasteurised Organic and Conventional Milk. *Int. Dairy J.* **2015**, *47*, 19–26. [CrossRef]
66. van Asselt, E.D.; van Bussel, L.G.J.; van Horne, P.; van der Voet, H.; van der Heijden, G.W.A.M.; van der Fels-Klerx, H.J. Assessing the Sustainability of Egg Production Systems in The Netherlands. *Poult. Sci.* **2015**, *94*, 1742–1750. [CrossRef] [PubMed]
67. Zucali, M.; Battelli, G.; Battini, M.; Bava, L.; Decimo, M.; Mattiello, S.; Povolo, M.; Brasca, M. Multi-Dimensional Assessment and Scoring System for Dairy Farms. *Ital. J. Anim. Sci.* **2016**, *15*, 492–503. [CrossRef]
68. Liu, F.; Peng, Y.; Zhang, W.; Pedrycz, W. On Consistency in AHP and Fuzzy AHP. *J. Syst. Sci. Inf.* **2017**, *5*, 128–147. [CrossRef]
69. Cho, F. Ahpsurvey: Analytic Hierarchy Process for Survey Data 2019. Available online: https://cran.r-project.org/web/packages/ahpsurvey/index.html (accessed on 9 April 2025).
70. Saaty, T.L. A Scaling Method for Priorities in Hierarchical Structures. *J. Math. Psychol.* **1977**, *15*, 234–281. [CrossRef]

Paper C

Assessing sustainability in the pork value chain: A multi-objective approach

Reference

Treml N, Rudi A, Schultmann F (2026b) Assessing sustainability in the pork value chain: A multi-objective approach. *Submitted to a Scientific Journal*.

Abstract

Purpose Animal-based food production remains a cornerstone of global nutrition, yet improving its sustainability is a complex challenge with far-reaching societal implications. Multi-objective optimization of meat value chains typically lacks assessing sustainability dimensions beyond economic performance and CO_2 emission minimization.

Methods This study designs a multi-objective optimization model covering four sustainability dimensions - environmental, economic, social, and animal welfare. Those dimensions are operationalized through quantitative indicators to evaluate a real-world multi-echelon pork value chain constructed from German case studies. The model is solved based on the augmented ε-constraint approach creating a pareto optimal set of points.

Results and discussion The results highlight the decisive influence of economic profitability on overall sustainability and its positive alignment with environmental and animal welfare objectives. In contrast, the social indicators diverge from other dimensions and, when optimized, worsen their performance.

Conclusions These findings underline the importance of evaluating sustainability at the level of entire value chains and demonstrate the novelty of integrating four sustainability dimensions into a unified optimization model.

1. Introduction

Over the last decade, the environmental impacts of pork production have been extensively environmentally examined through the method of life cycle assessment (LCA) (Gislason et al. 2023). While several studies provide valuable insights, they largely neglect other key dimensions of sustainability. According to the well-established "triple bottom line" perspective, sustainability encompasses not only environmental, but also social and economic aspects (Cordella et al. 2023). Economic viability remains a decisive factor for livestock systems: without profitability, environmental and social goals cannot be sustained in practice. Furthermore, the affordability of the meat product itself plays a significant role for its social and economic acceptance. Ideally, synergies between these dimensions exist, but in reality, trade-offs are frequent and difficult to align. To address this broader perspective, life cycle sustainability assessment (LCSA) has been proposed as an integrative framework that extends traditional LCA by incorporating social life cycle assessment (SLCA) (Kloepffer, 2008; Moltesen et al., 2018; Rosenbaum et al., 2015) and life cycle costing (LCC) (Kreith 1981; Zhang et al. 2014; Niembro-García et al. 2022). Despite progress, methodological inconsistencies remain, particularly regarding indicator selection and the joint evaluation of multiple sustainability pillars (Bubicz et al. 2019). Although case studies have explored different approaches, a lack of harmonized guidelines and standardization persists (Wulf et al. 2019; Costa et al. 2019). Most livestock-related LCSA studies treat the three sustainability dimensions independently, presenting results side by side without integrating them into a single evaluative framework (Zira et al. 2021; Ruckli et al. 2022). A major obstacle is the heterogeneity of metrics and units across dimensions, which complicates aggregation and interpretation. Multi-objective optimization (MOO) - a subfield of Multi-Criteria Decision Analysis (MCDA) - provides the opportunity to simultaneously optimize several sustainability objectives under defined constraints and support to identify relationships between the sustainability dimensions (Bubicz et al. 2019). Several works address MOO in the context of logistics with meat supply chains as application area. The focus of these studies predominantly lies in the design of a logistic system and in planning the supply chain (Soysal et al. 2014; Mohammed and Wang 2017; Mohebalizadehgashti et al. 2020). Besides cost-minimization, the integration of environmental factors represents a twist to comparable research, changing the topic to green supply chain management (Srivastava 2007). The integration of GHG emissions as minimization objective is the typical way to include environmental factors as an objective (Oglethorpe 2010; Aramyan et al. 2011; Soysal et al. 2014; Eskandarpour et al. 2015; Mohammed and Wang 2017; Mohebalizadehgashti et al. 2020). However, the expansion of the environmental consideration beyond GHG emissions can be delivered by implementing a bigger variety of LCA impact categories to the objective. Furthermore, only limited attempts have been made to apply integrated optimization approaches to food value chains that explicitly consider the environmental, economic, and social pillars of sustainability (Eskandarpour et al. 2015; Yadav et al. 2022). The combination of LCSA objectives and MOO with goal programming was performed by Oglethorpe (2010) for a pork supply chain. The study is based on survey-data and integrates the three sustainability dimensions within five goals: return on sales; GHG emissions; water use; fat content of products; and number of jobs. The author changes the weights of the goals to investigate how this leads to change in the strategic decisions, starting with equal weighting (Oglethorpe 2010). Besides that, in particular, animal welfare remains underrepresented in sustainability assessments of meat value chains. Moreover, no scientific studies have been identified that conduct a comprehensive LCSA of an entire pig value chain while simultaneously considering animal welfare and embedding these dimensions within a mathematical optimization model. Addressing this gap, the present study develops a MOO model that seeks to (i) minimize environmental impacts, (ii) maximize economic profitability, (iii) minimize socially negative implications, and (iv) reduce negative effects on animal welfare and find an optimal way through a network of six German case studies. It demonstrates a novel methodological approach to integrating heterogeneous sustainability indicators through mathematical optimization and provides empirical insights into the sustainability performance of real-world elements of the German pig sector.

2. Materials and methods

2.1. Life cycle sustainability assessment

LCSA provides a comprehensive framework for evaluating the environmental, economic, and social impacts of products and processes (Ren 2020). Initially conceptualized by Zhou et al. (2007) and formally introduced by Kloepffer (2008), LCSA operationalizes the “triple bottom line” approach to sustainability (Cinelli et al. 2014). The framework is commonly expressed as: LCSA = LCA + LCC + SLCA, where LCA denotes environmental life cycle assessment, LCC represents life cycle costing, and SLCA refers to social life cycle assessment. Kloepffer (2008) originally emphasized that results should not be aggregated. Nevertheless, subsequent studies have proposed and applied a variety of aggregation techniques, underscoring the ongoing methodological debate in this field (Costa et al. 2019). Despite such challenges, LCSA has been recognized as a valuable tool for supporting decision making in sustainability transitions (Fauzi et al. 2019; Berticelli et al. 2020).

In this study, LCSA serves as the overarching framework for assessing sustainability in the pig value chain. Building on this foundation, we extend the dimensions by integrating a MOO approach to simultaneously address environmental, economic, social, and animal welfare dimensions.

2.2. *Multi-objective optimization*

MOO provides a structured approach to address problems involving multiple, often conflicting, objectives (Nickel et al. 2022). The solution space is defined by several objective functions subject to system constraints, where no single solution can simultaneously optimize all objectives (Farahani et al. 2010). Among various solution techniques, the ε-constraint is the most widely employed solution method in MOO models (Eskandarpour et al. 2015; Babbar and Amin 2018; Zhu et al. 2018). The literature for food supply chain optimization – emphasizing the application of MOO models – is covered by reviews from Eskandarpour et al. (2015), Zhu et al. (2018) and Yadav et al. (2022). Relevant MOO studies optimizing especially meat supply chains are listed in Table 1.

Table 1. Recent studies that optimize meat supply chains respecting economic and environmental objectives.

Study	**Model**	**Solution methods**	**Economic**	**Environmental**
(Soysal et al. 2014)	MOLP[a]	ε-constraint	logistic cost	GHG emissions in transportation
(Mohammed and Wang 2017)	FMOPM[b]	LP[c]-metrics, ε-constraint, goal programming	cost of transportation and implementation	CO_2 emissions in transportation
(Mohebalizadehgashti et al. 2020)	MILP[d]	augmented ε-constraint	cost	CO_2 emissions from transportation

[a] multi-objective linear programming
[b] FMOPM = fuzzy multi-objective programming model
[c] LP = linear programming
[d] MILP = mixed-integer linear programming

Soysal et al. (2014) sets the focus mainly on the logistical issues concerning beef supply. The model is applied by assessing a case study on a real-life logistic chain from Brazil to Europe. Mohammed and Wang (2017) develop a three-echelon meat supply chain network considering CO_2 emissions as environmental factor and compared the results from three different solving methods. The distribution planning problem was applied to a case study and determined the number of facilities and obtained a trade-off among the objectives. The best performing solution approach was retrieved by the ε-constraint method (Mohammed and Wang 2017). In the most recent study, Mohebalizadehgashti et al. (2020) approach a similar challenge in designing a green meat supply chain network for a region in Canada. The authors apply the augmented ε-constraint method and incorporate a broader cost portfolio into their assessment expanding beyond transportation related costs.

2.3. Network configuration

In this study, a multi-objective linear programming (MOLP) model is designed to analyze and optimize a livestock-based supply chain in Germany. The supply chain extends from farms (F1, F2, F3) to a slaughterhouse (M), to processors (P1, P2), and finally to retail (R). The structure of the network is illustrated in Figure 1. The system is modeled as a directed graph composed of three types of nodes: supply nodes (farms), conversion nodes (slaughterhouse and processors), and a dummy demand node (retail outlet, not represented by a case study).

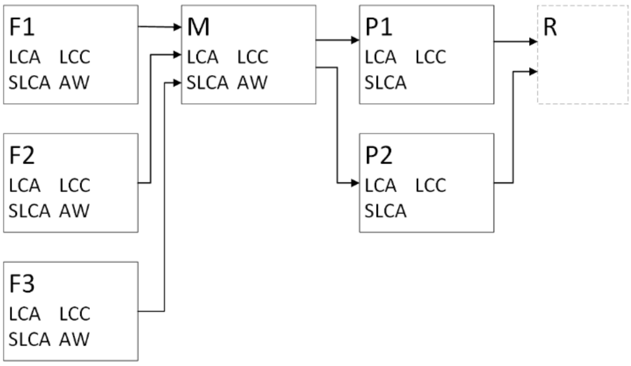


Fig. 1 Schematic representation of the supply network model for pork production. The directed graph illustrates material flows from farms (F1, F2, F3) through slaughter (M) and processing stages (P1, P2), to the final retail node (R). Arcs represent logistic distances between the facilities. The goals (LCA, LCC, SLCA, AW) are assigned to the nodes for which data is collected, reflecting the environmental, economic, social, and animal welfare impacts throughout the supply chain.

The underlying empirical basis of the model draws on six German case studies representing links of the pork value chain. These studies were covered by the research project SPECK and therefore present a comprehensive data foundation for the assessment. Especially the use of original data in the performed optimization should emphasize the practical feasibility of the methodological approach.

The following descriptions reflect the actual operations and characteristics of the case study's associated value chain stage (see also Supplementary S1); they provide empirical context but do not imply a real-world representation of the modeled value chain. Three farms, one slaughterhouse, and two processors are selected to represent different production systems along the pig value chain. Farms F1 and F3 operate under conventional systems, whereas F2 represents an organic production system with a lower production capacity. Farm F1 is the largest producer, integrating both breeding/rearing and fattening facilities located at different sites, which necessitates transport of piglets. Farm F2, with the smallest production volume, provides detailed data availability and thus serves as a valuable benchmark for organic production. Farm F3 operates a stable with outdoor climate housing, thereby improving its animal welfare classification relative to conventional standards. Its production volume lies between that of F1 and F2. The slaughterhouse (M) serves as the first conversion node, processing animals supplied by the farms and delivering carcasses to processors. While it predominantly handles smaller quantities from organic systems, its overall throughput is high relative to individual farms. The two processors differ in scale and production focus: P1 processes mainly organic meat in relatively small volumes, whereas P2 is a large-scale facility specializing in conventional meat. The retail node R serves as a dummy demand node that anchors the optimization but does not correspond to a specific case study. It ensures that all upstream supply chain activities are directed toward fulfilling a defined demand. Without R, the model would lack a fixed endpoint, and production flows could be unrealistically allocated without reference to a final consumer.

Data for the assessment was collected from primary farm and facility records where available and complemented with secondary data and targeted web searches for cost and social indicators. Animal welfare data was restricted to farm-level operations, as animals are no longer present in the subsequent processing stages.

The MOLP model simultaneously optimizes four conflicting objectives to find the optimal flow through the network: (1) Minimization of environmental impact (LCA) – including normalized life cycle assessment results and transport-related emissions; (2) Maximization of economic value (LCC) – measured as facility-level revenues derived from costs and product prices; (3) Minimization of animal welfare burden (AW) – based on animal losses, husbandry conditions, and transport distances; (4) Minimization of social impacts (SLCA) – operationalized through indicators such as unemployment rates and consumer prices. The indicators - listed in Table 2 - are calculated and normalized for one kilogram of product, in accordance with the integrated LCA's functional unit (Treml et al. 2025b). This ensures intracomparability inside the objective functions. The model inputs are listed alongside case study characteristics in Supplementary S1. The final optimization is performed for the demand of one kilogram of product at the retail node.

Table 2. Set of indicators that builds the foundation of the objectives for the optimization problem.

Objective	Indicator	Original unit
environmental	global warming	kg CO_2 eq
	terrestrial acidification	kg SO_2 eq
	freshwater eutrophication	kg PO_4 eq
	land use	m^2a
	impact of transportation	kg SO_2 eq / kg CO_2 eq per km
economic	revenue	€
animal welfare	animal losses	%
	husbandry condition	1-5
	transportation distance	km
social	unemployment rate	%
	consumer price	€

2.3.1. Environmental objective

In the literature, MOO approaches are often based on assessing CO_2 emissions as the environmental aspect (Soysal et al. 2014; Bortolini et al. 2016; Mohammed and Wang 2017). This, while addressing one of the most relevant climate threats, covers just a small part of environmentally impactful issues. Though, some studies use the LCA methodology to consider a broader range of impacts (Eskandarpour et al. 2015). Furthermore, leaving behind the exclusively logistic problem design, Soysal et al. (2014) suggest an extension to respect environmental impacts from whole production stages like livestock management, including e.g. resource and energy use. Accordingly, the environmental objective is based on results from LCA’s conducted for the six case studies (Treml et al. 2025b). The underlying life cycle inventory is described in detail by Treml et al. (2025b). The associated indicators and their original units are displayed in Table 2. Based on the impact assessment method ReCiPe midpoint 2016 (H) the impact categories of global warming, land use, freshwater eutrophication and terrestrial acidification are examined as these categories are typically used to evaluate agricultural process emissions (Huijbregts et al. 2017; Gislason et al. 2023). The results are min-max normalized and assigned to each node of the value chain. In addition to these node-based impacts, transportation-related burdens are incorporated (1). In the literature, emissions for transportation are considered predominantly rather than for production processes, foremost respecting complex transportation capacity calculations and even modes of transport (Soysal et al. 2014; Mohebalizadehgashti et al. 2020). In this study, transport emissions are calculated using the ecoinvent dataset for lorry transport (Ecoinvent Association 2023). Transport impacts solely contribute to the categories of global warming and terrestrial acidification, are weighted by distance between the facilities of the value chain stages and normalized alongside the production process impacts.

2.3.2. Economic objective

Reviewing MOO of supply chains, the most examined sustainability dimension is the economic one (Yadav et al. 2022). Transportation, production and maintenance act as cost drivers and as for every process economic feasibility is a key dimension – also for livestock production systems. In the pork sector, profitability depends on the balance between revenues and production costs. In 2021, the industry faced a significant crisis as declining demand and oversupply depressed pig prices, particularly affecting conventional systems characterized by high volumes and limited welfare differentiation (BLE 2022). In this study, the economic objective is represented by the revenue, defined as the difference between the selling price per kilogram of product and the associated production costs (2). Price and cost data are consistently expressed per kilogram at the facility gate, enabling comparability across stages. The dataset combines primary data from farm management records with secondary information from official statistics, complemented by values reported in market studies and industry publications (see Supplementary S1). Farm-level parameters are primarily based on direct farm records, while midstream and processing stages draw on secondary sources, particularly for organic and conventional pork prices. This mixed-source approach ensures robustness and transparency while also highlighting areas where additional data collection is needed. The indicator values are min-max normalized based on the calculated revenue results of the facilities before being introduced to the objective function.

2.3.3. Animal welfare objective

The representation of animal welfare in MOO models for meat supply chains is missing in recent studies (Eskandarpour et al. 2015; Zhu et al. 2018; Yadav et al. 2022). Though, the integration of animal-related indicators into the evaluation of livestock value chains is reasonable and is becoming more relevant. The extension of sustainability assessment to gather a complete picture of processes also includes the deliberation to include the life of the animal representing the base product. Therefore, we assess animal welfare using three indicators selected on the basis of Treml et al. (2025b) and adapted to the available dataset (Table 2). The indicators capture impacts over the animals' lifetime. While animal losses and husbandry conditions are gathered through farm management data, the transportation distance is complementing the assessment (2).

The first indicator, animal losses, refers to mortality rates recorded at the farm level and serves as a proxy for overall herd health. As demonstrated by Treml et al. (2025a), this parameter is among the most relevant measures of welfare in pig production systems, reflecting both management practices and biological resilience. The second indicator, husbandry conditions, is evaluated using the classification system established by major German retail chains (haltungsform.de 2024). This system ranks production practices along a five-level scale, ranging from the minimum regulatory standard to certified organic farming. The indicator integrates multiple aspects of welfare, including housing, feeding regimes, and general animal care, thereby providing a multidimensional representation of living conditions. The third indicator, transportation distance, captures the cumulative distance traveled by animals between different production stages and to the slaughterhouse. Transport is considered a critical factor because it exposes animals to stressors and procedures that lie outside their daily routines, thereby influencing welfare outcomes (Petit et al. 2018). To enable comparability and integration into the MOO model, all three indicators are min-max normalized prior to inclusion in the model.

2.3.4. Social objective

In the context of livestock production, social factors are particularly relevant, given the importance of safeguarding farm workers, ensuring fair treatment of stakeholders, and meeting consumer expectations. Recent research has operationalized social dimensions through SLCA, providing quantitative insights into stakeholder well-being (Neugebauer et al. 2014; Zira et al. 2020; Aranda et al. 2021; Møller et al. 2024). The inclusion into MOO of meat supply chains is only performed by Olgethorpe (2010) with consideration of the objectives hours of employment and retail price. Though, social sustainability is more challenging to operationalize than environmental or economic dimensions because of its inherent subjectivity, yet it remains indispensable for a comprehensive assessment (Bubicz et al. 2019). In this study, social performance is represented by two quantifiable indicators (Table 2). The first, the regional unemployment rate, reflects the contribution of facilities to local employment opportunities. Higher unemployment rates are weighted positively within the model, as the establishment or continuation of facilities in such regions can be assumed to have greater relative benefits for job creation. The second indicator, the consumer price, serves as a proxy for affordability and accessibility of pork products. By integrating consumer price into the optimization and minimizing it, the analysis acknowledges the importance of ensuring economic access for consumers alongside sustainability objectives. Together, these two indicators represent both producer-oriented and consumer-oriented aspects of social performance, thereby enabling a more balanced consideration of societal impacts within the optimization model (4). Prior to implementation into the objective function these indicators are min-max normalized.

2.3.5. Model formulation and calculation

The MOO model is formulated as a linear program in the General Algebraic Modeling System (GAMS 50.1.0) (GAMS Dev. Corp. 2023) to evaluate sustainable configurations across the value chain. Please refer to Supplementary S2 for the code. Table 3 introduces the decision variables and the corresponding nomenclature. To address the multiple objectives, the four sustainability dimensions - environmental impact (1), economic performance (2), animal welfare (3) and social impact (4) - are formulated as single objective functions.

Table 3. Description of model nomenclature.

Variables	
$x_{ij} \in \mathbb{R}_0^+$	flow of product from node i to node j.
$z_c \in \mathbb{R}_0^+$	objective functions ($c = lca, lcc, aw, slca$)
$z_{c_{norm}} \in \mathbb{R}_0^+$	normalized objective function values ($c = lca, lcc, aw, slca$)
Sets	
N	all nodes: $N = \{F1, F2, F3, M, P1, P2, R\}$.
$S \subset N$	supply nodes: $S = \{F1, F2, F3\}$.
$C \subset N$	conversion nodes: $C = \{M, P1, P2\}$.
$D \subset N$	demand nodes: $D = \{R\}$.
$A \subset N \times N$	set of arcs (directed edges) between nodes: $(i,j) \in A = \{(F1, M), (F2, M), (F3, M), (M, P1), (M, P2), (P1, R), (P2, R)\}$.
Parameters	
e_c	parameters for the right-hand side for the specific iteration drawn from the grid points of the objective functions c ($c = lcc, aw, slca$).
eps	$eps \in [10^{-6}, 10^{-3}]$
s_c	slack or surplus variables, ($c = lcc, aw, slca$)
r_c	range of the c-th objective function, ($c = lcc, aw, slca$)
α_{ij}	conversion coefficient from node i to node j.
$supply_i$	supply capacity at node $i \in S$.
$demand_j$	demand requirement at node $j \in D$.
lca_i	LCA impact at node i.
$transportLCA_{ij}$	transport-related LCA impact from i to j.
$revenue_i$	economic revenue at node i.
$animallosses_i$, $husbandrycond_i$, $distaw_i$	animal welfare indicators at node i.
$unemployment_i$	unemployment rate at node i.
$consprice_i$	consumer price at node i.

The MOO is performed using the augmented ε-constraint method, an advanced variant of the classical ε-constraint approach that ensures the generation of only pareto-efficient solutions. In this method, one objective function is optimized while the remaining objective functions are implemented as constraints (5). The implementation follows the formulations of Mavrotas (2009) and Mavrotas and Florios (2013), enabling the exact identification of pareto-optimal configurations for the presented LP. Following Marler and Arora (2010), the resulting objective function values for the pareto points are min-max normalized, as formulated in (9) and (10), to ensure comparability by transforming them into a common [0,1] range. This normalization allows to express the relative objective value of each sustainability dimension and enabling exploration of trade-offs between environmental, economic, social, and animal welfare objectives (Greco et al. 2016). Therefore, each objective is optimized beforehand applying the weighted sum method individually to obtain the best and worst values, which serve as boundaries for the min-max normalization of the pareto points. For interpretability, a composite overall objective is derived post-optimization as an equally weighted aggregation of the normalized individual objectives per point. Generally, the model is solved using the CPLEX 22.1.2 solver.

$$z_{lca} = \sum_{(i,j)\,\in\,A} x_{ij} \cdot \left(lca_i + transportLCA_{ij}\right) \tag{1}$$

$$z_{lcc} = \sum_{(i,j)\,\in\,A} x_{ij} \cdot revenue_i \tag{2}$$

$$z_{aw} = \sum_{i\,\in\,S} x_{ij} \cdot (animallosses_i + husbandrycond_i + distaw_i) \quad \forall j \in M \tag{3}$$

$$z_{slca} = \sum_{(i,j)\,\in\,A} x_{ij} \cdot (consprice_i - \ unemployment_i) \tag{4}$$

$$\begin{aligned} &\min(z_{lca} - eps \ \cdot (\frac{s_{lcc}}{r_{lcc}} + 10^{-1} \cdot \frac{s_{aw}}{r_{aw}} + 10^{-2} \cdot \frac{s_{slca}}{r_{slca}})) \\ &s.t. \\ &\qquad z_{lcc} - s_{lcc} = e_{lcc} \\ &\qquad z_{aw} + s_{aw} = e_{aw} \\ &\qquad z_{slca} + s_{slca} = e_{slca} \\ &\qquad s_c \in \mathbb{R}^+ \end{aligned} \tag{5}$$

$$\sum_{j \in A} x_{ij} \leq supply_i \quad \forall i \in S \tag{6}$$

$$\sum_{i \in A} x_{ij} = demand_j \quad \forall j \in D \tag{7}$$

$$\sum_{i \in A} x_{ik} \cdot \alpha_{ik} = \sum_{j \in A} x_{kj} \quad \forall k \in C \tag{8}$$

$$z_{c_{norm}} = \frac{z_{c_{opt}} - z_{c_{min}}}{z_{c_{max}} - z_{c_{min}}}, c \in lca, aw, slca \tag{9}$$

$$z_{c_{norm}} = \frac{z_{c_{max}} - z_{c_{opt}}}{z_{c_{max}} - z_{c_{min}}}, c \in lcc \tag{10}$$

The system constraints (6), (7), (8) regulate product flows and ensure mass balance throughout the network. Constraints (6) and (7) guarantee that supply capacities are not exceeded and that the specified demand is satisfied. To maintain comparability, the demand is fixed at a specific weight of product delivered to the retail node (R). Equation (8), the conversion constraint, ensures that yield factors are respected at each processing stage, thereby linking inputs and outputs consistently across the value chain.

3. Results

The results highlight the inherent trade-offs between the sustainability objectives within the livestock-based value chain network (Figure 2). The visualization of the 538 pareto efficient points underscores the discrete characteristic of the problem. The augmented ε-constraint method works well by producing only efficient (non-dominant) solutions. The method is calculated alongside the LCA objective (5), therefore, its resulting graph is the one with consistent increase without outliers.

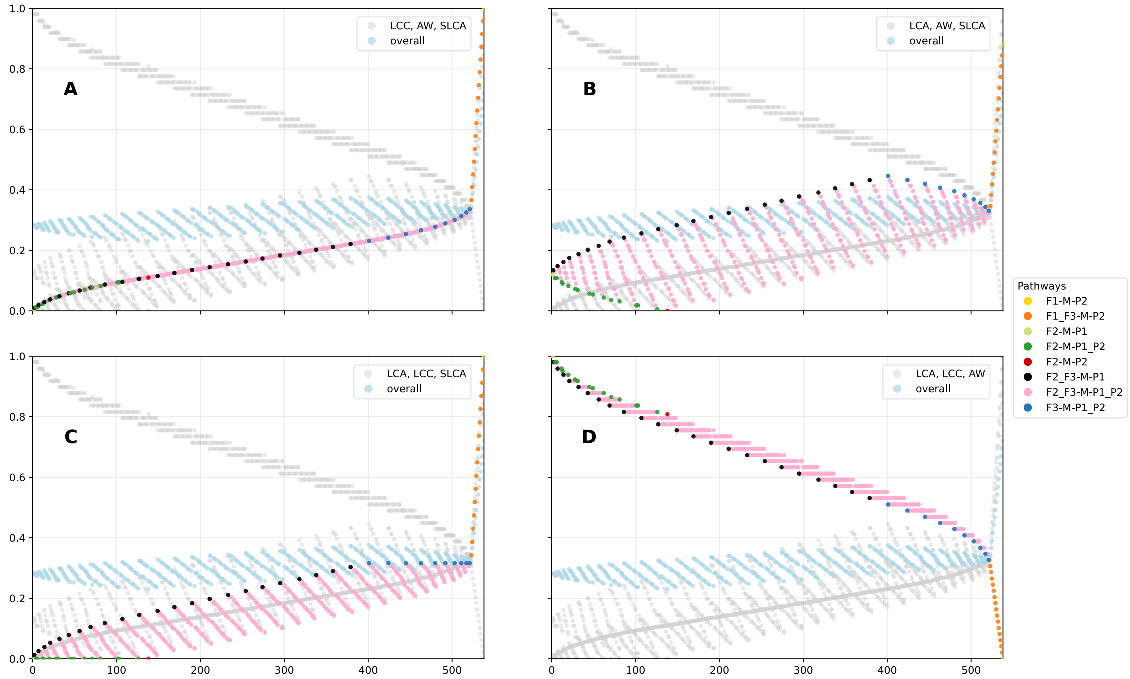


Fig. 2 Visualization of the normalized objective function values alongside the pareto points. The optimal pathways through the network are highlighted by color for every individual objective (A=LCA, B=LCC, C=AW, D = SLCA). The overall equally weighted sum of objectives is displayed in light blue (overall). Values near zero indicate good performance following the performed minimization.

The dimensions LCA, LCC and AW represent a relatively similar trend alongside the pareto points (Figure 2). Contradictory, the SLCA results counteract against the other objectives. For reference as a possible stakeholder rating, an overall graph (light blue) is displayed representing equal weighting of objectives. Generally, Figure 2 indicates some outstanding points regarding pathway changes highlighted by color codes. Especially, the sudden spike must be emphasized where the graphs systematically change to linear shape and one specific pathway (F1_F3-M-P2, orange) declines overall but improves SLCA results. This region typically signals the pareto knee, where some objectives deteriorate sharply while one improves (Lee et al. 2018; Cuate and Schütze 2020). The knee point is identified at pareto point 522. Up to this point, improvements across dimensions occurred relatively proportionally, representing balanced sustainability trade-offs. Beyond point 522, however, further improvement in the SLCA objective required substantial sacrifices in environmental, economic, and animal welfare performance. This inflection thus represents the most efficient compromise solution on the pareto frontier ($z_{lca_{norm}}$= 0.337, $z_{lcc_{norm}}$= 0.323, $z_{aw_{norm}}$= 0.312, $z_{slca_{norm}}$= 0.327). Besides, the F2_F3-M-P1_P2 (pink) pathway representing farms F2 and F3 and delivery to P1 and P2 is the dominating pareto optimal solution. The scenario is chosen in 472 points, apparent in Figure 2. Altogether, from the first point F2-M-P1 (light green), the F2-M-P1_P2 (green) and F2_F3-M-P1 (black) pathways alternate with the pink one from the start. Then the F2-M-P2 (red point) with the overall best solution ends the green pathways occurrence while black and pink stay till the F3-M-P1_P2 (blue) pathway enters the curve. Blue and pink alternate until being substituted by the orange pathway that ends all the other pathways. The last point represents the F1-M-P2 (yellow) pathway.

3.1. Environmental performance

Figure 2A visualizes the development of the pareto points alongside the LCA objective function. In the process, the LCA objective's results are successively worsened resulting in an ascending curve in the diagram. The first pareto point (light green) equals the best environmental outcome with farm F2, the slaughterhouse M, and processor P1 forming the optimal route. This configuration achieves the best possible environmental performance ($z_{lca_{norm}}$ = 0) while simultaneously delivering optimal results for animal welfare ($z_{aw_{norm}}$ = 0). However, this comes at the expense of economic ($z_{lcc_{norm}}$ = 0.12) and social ($z_{slca_{norm}}$ = 1) performance losses. Typically, reduced economic outcomes in organic systems can be attributed to lower production volumes and higher costs, which limit revenue generation compared with conventional large-scale farms. In this study, however, the organic farm (F2) outperforms the conventional alternatives, and the observed economic curtailment is instead linked to the processing facility P2 selected in the optimal pathway. The unfavorable social performance is largely driven by the higher consumer prices associated with organic products and the limited potential for regional employment improvements offered by the chosen facilities.

The strong alignment between environmental and animal welfare outcomes indicates that these objectives are positively dependent within the model structure. In particular, production systems that minimize environmental impacts also appear to reduce animal welfare burdens, likely due to overlapping attributes such as shorter transport distances, reduced resource inputs, and more animal-friendly housing. The predominance of organic systems in the selected route reinforces this interpretation.

3.2. Economic performance

The economic performance is displayed in Figure 2B, showing high volatility alongside the rising LCA curve. The best combination of pathways to meet economic goals is reached with red, green and pink as they tend to represent the lowest values.

When filtering for the best economic performance – searching for the lowest value of LCC – the normalized objective score reaches zero, reflecting the optimal attainment of the economic goal, but other dimensions are compromised. The resulting objective values ($z_{lca_{norm}}$ = 0.11; $z_{lcc_{norm}}$ = 0; $z_{aw_{norm}}$ = 0; $z_{slca_{norm}}$ = 0.808) are identical to those obtained for the best overall (equally weighted) pareto point ($z_{overall}$ = 0.230), underlining the strong alignment between economic and the overall sustainability objective within the modeled system. Identifiable as a red dot at pareto point 138 in Figure 2, the network configuration includes farm F2 as the supplier and routes the flow through M and processor P2 to R. This outcome mirrors the best overall case and demonstrates that the same combination of an organic farm and a high-volume processor simultaneously secures economic viability and animal welfare optimization. The results illustrate the relative robustness of organic farming against conventional production in economic terms for the considered case studies. Although farm F1 and farm F3 are excluded due to lower revenues, the unique selling point of organic pork provides greater stability under volatile market conditions, supported by production processes that are inherently more sustainable.

3.3. *Animal welfare performance*

The green and red pathways represent the best outcome for animal welfare as they implement solely F2 (Figure 2C). Finding the best pareto point for animal welfare produces 19 results that set the normalized objective to zero – including two pink points. Since animal welfare indicators are restricted to the farming stage and transport distances to the slaughterhouse, the optimal route terminates there (M) (Figure 2). The model selects farm F2, despite its comparatively higher animal loss rates, because it performs better in terms of husbandry conditions and transport-related welfare. Taking a closer look at the two pink points, the delivery from F3 is negligibly low, underscoring the aforementioned observations. Some resulting pathways match the economic ($z_{lcc_{norm}}$ = [0, 0.12]) and the environmentally ($z_{lca_{norm}}$ = [0, 0.11]) best point and achieve optimal scores for animal welfare ($z_{aw_{norm}}$ = 0). However, this comes at a cost: the social objective operates near the worst possible value ($z_{slca_{norm}}$ = [0.808, 1]).

3.4. *Social performance*

The social objective reveals the strongest divergence across objectives (Figure 2D). When minimizing SLCA impacts, the model achieves perfect social performance as expected ($z_{slca_{norm}}$ = 0) at the yellow point, but at a considerable cost to the other dimensions. Environmental ($z_{lca_{norm}}$ = 1) and animal welfare ($z_{aw_{norm}}$ = 1) outcomes both deteriorate to their worst levels, while economic performance also performs poorly ($z_{lcc_{norm}}$ = 0.879). The optimal flow includes farm F1, routed through M and processor P2 to R. This configuration reflects the influence of lower consumer prices and higher regional unemployment rates, which improve social indicators but simultaneously worsens environmental, welfare, and economic outcomes for the considered case studies. These findings suggest that, within the modeled approach, socially favorable decisions are structurally misaligned with environmental, animal welfare, and economic sustainability goals.

4. Discussion and Outlook

Despite the studies novelty, several limitations must be acknowledged. The model currently relies on eight parameters influencing the overall objective, meaning its comprehensiveness is constrained by available data. While the environmental dimension is well established through life cycle assessment (Gislason et al. 2023; Treml et al. 2025b), social sustainability remains insufficiently captured, as unemployment rates and consumer prices do not adequately represent complex social realities (Bubicz et al. 2019). Similarly, economic data are partly based on heterogeneous sources, and animal welfare indicators remain limited in their quantifiability. Expanding and refining indicator sets across all dimensions would strengthen both reliability and robustness.

The central contribution of this study lies in demonstrating that this MOO model can be applied to livestock systems under realistic conditions. While the included facilities reflect real case studies, not all are directly linked in practice. By embedding empirical case studies, the analysis shows that real-world data can be systematically incorporated into the framework, revealing both synergies – such as the alignment between economic, environmental and animal welfare objectives – and trade-offs, particularly regarding social outcomes. These results illustrate how the model could support decision-making at farm, processing, or policy level by testing different value chain configurations. As a next step, applying the model to fully connected supply chains with comprehensive datasets would enhance its relevance and provide stronger guidance for practical implementation.

The findings underline the importance of weight setting in sustainability assessments: equal weighting did not produce a balanced compromise but instead privileged economic performance, with animal welfare outcomes improving and social factors lagging behind. This highlights the need for deliberate stakeholder-driven calibration of preferences when applying multi-criteria optimization. Importantly, the observed convergence of profitability, environmental performance, and animal welfare suggests that synergies are achievable under specific structural conditions, particularly when organic production and cost-efficient processing are combined. By contrast, persistent weaknesses in the social dimension point to the necessity of more representative indicators and supportive policy instruments.

5. Conclusion

This study demonstrates the feasibility of applying MOO for comprehensive sustainability assessment of livestock production by operationalizing a model that integrates environmental, economic, social, and animal welfare indicators. Using six German case studies as inputs, the framework shows how diverse and partly conflicting dimensions can be systematically combined into an aggregated sustainability objective. While sustainability dimensions have often been assessed separately (Zira et al. 2021; Ruckli et al. 2022), this study provides, to our knowledge, the first application of such an holistic optimization model to the pork sector. The model not only visualizes trade-offs but also identifies facility configurations that create synergies across sustainability criteria, thereby illustrating its potential as a decision-support tool for value chain design.

The results reveal clear trade-offs: economic, environmental and animal welfare objectives often align, while social performance remains structurally misaligned due to limited and insufficiently representative indicators. Limitations remain, particularly in the quantification of social and animal welfare aspects and the assumption of virtual linkages among facilities. Future research should enrich the indicator set, improve the representation of qualitative dimensions, and extend the framework to fully connected value chains and other sectors.

Supplementary S1. GAMS code implementing the multi-objective optimization model for sustainability assessment of pork production, including equations, constraints, and solution procedures for environmental, economic, social, and animal welfare objectives.

Supplementary S2. Supplementary material containing additional case study characteristics, Input data for the optimization model, the overall results and the resulting pathways.

CRediT authorship contribution statement

Nina Treml: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andreas Rudi:** Validation, Methodology, Writing – review & editing. **Frank Schultmann:** Writing – review & editing, Funding acquisition.

Data availability statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The project was supported by the German Federal Ministry of Food and Agriculture (BMEL), with the project SPECK (Systemic optimization of the meat value chain using pig farming as an example through the development and embedding of digital tools), grant number 281A502B19.

References

Aramyan L, Hoste R, Van Den Broek W, Groot J, Soethoudt H, Nguyen TL, Hermansen J, Van Der Vorst J (2011) Towards sustainable food production: a scenario study of the European pork sector. J Chain Netw Sci 11(2):177–189. https://doi.org/10.3920/jcns2011.qpork8

Aranda J, Zambrana-Vásquez D, Del-Busto F, Círez F (2021) Social Impact Analysis of Products under a Holistic Approach: A Case Study in the Meat Product Supply Chain. Sustainability 13(21):12163. https://doi.org/10.3390/su132112163

Babbar C, Amin SH (2018) A multi-objective mathematical model integrating environmental concerns for supplier selection and order allocation based on fuzzy QFD in beverages industry. Expert Syst Appl 92:27–38. https://doi.org/10.1016/j.eswa.2017.09.041

Berticelli R, Pandolfo A, Reichert GA, Salazar RFDS, Kalil RM (2020) Support system for decision-making processes related to municipal solid waste management by taking into consideration a sustainable life cycle assessment: review on environmental, economic and social aspects. Int J Environ Waste Manag 26(2):147. https://doi.org/10.1504/IJEWM.2020.108812

BLE (2022) Bericht zur Markt- und Versorgungslage mit Fleisch 2022. Bundesanstalt für Landwirtschaft und Ernährung, Bonn

Bortolini M, Faccio M, Ferrari E, Gamberi M, Pilati F (2016) Fresh food sustainable distribution: cost, delivery time and carbon footprint three-objective optimization. J Food Eng 174:56–67. https://doi.org/10.1016/j.jfoodeng.2015.11.014

Bubicz ME, Barbosa-Póvoa APFD, Carvalho A (2019) Incorporating social aspects in sustainable supply chains: Trends and future directions. J Clean Prod 237:117500. https://doi.org/10.1016/j.jclepro.2019.06.331

Cinelli M, Coles SR, Kirwan K (2014) Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol Indic 46:138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

Cordella M, Horn R, Hong SH, Bianchi M, Isasa M, Harmens R, Sonderegger T, Pihkola H (2023) Addressing sustainable development goals in life cycle sustainability assessment: Synergies, challenges and needs. J Clean Prod 415:137719. https://doi.org/10.1016/j.jclepro.2023.137719

Costa D, Quinteiro P, Dias AC (2019) A systematic review of life cycle sustainability assessment: Current state, methodological challenges, and implementation issues. Sci Total Environ 686:774–787. https://doi.org/10.1016/j.scitotenv.2019.05.435

Cuate O, Schütze O (2020) Pareto Explorer for Finding the Knee for Many Objective Optimization Problems. Mathematics 8(10):1651. https://doi.org/10.3390/math8101651

Ecoinvent Association (2023) Ecoinvent Version 3.9.1 APOS

Eskandarpour M, Dejax P, Miemczyk J, Péton O (2015) Sustainable supply chain network design: An optimization-oriented review. Omega 54:11–32. https://doi.org/10.1016/j.omega.2015.01.006

Farahani RZ, SteadieSeifi M, Asgari N (2010) Multiple criteria facility location problems: A survey. Appl Math Model 34(7):1689–1709. https://doi.org/10.1016/j.apm.2009.10.005

Fauzi RT, Lavoie P, Sorelli L, Heidari MD, Amor B (2019) Exploring the Current Challenges and Opportunities of Life Cycle Sustainability Assessment. Sustainability 11(3):636. https://doi.org/10.3390/su11030636

GAMS Dev. Corp. (2023) General Algebraic Modeling System (GAMS)

Gislason S, Birkved M, Maresca A (2023) A systematic literature review of life cycle assessments on primary pig production: Impacts, comparisons, and mitigation areas. Sustain Prod Consum 42:44–62. https://doi.org/10.1016/j.spc.2023.09.005

Greco S, Ehrgott M, Figueira JR (eds) (2016) Multiple criteria decision analysis: State of the art surveys, Second edition. Springer, New York; Heidelberg; Dordrecht; London

haltungsform.de (2024) Mindestanforderungen für Programme, die Kriterien für Betriebe mit Schweinemast festlegen. In: Haltungsform.de. https://www.haltungsform.de/im-ueberblick/. Accessed 23 May 2024

Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22(2):138–147. https://doi.org/10.1007/s11367-016-1246-y

Kloepffer W (2008) Life cycle sustainability assessment of products: (with Comments by Helias A. Udo de Haes, p. 95). Int J Life Cycle Assess 13(2):89–95. https://doi.org/10.1065/lca2008.02.376

Kreith F (1981) PRINCIPLES OF ECONOMICS FOR SOLAR ENERGY INVESTMENTS. In: Solar Energy Conversion II. Elsevier, pp 497–515

Lee J, Lee S-I, Ahn J, Choi H-L (2018) Pareto front generation with knee-point based pruning for mixed discrete multi-objective optimization. Struct Multidiscip Optim 58(2):823–830. https://doi.org/10.1007/s00158-018-1926-2

Marler RT, Arora JS (2010) The weighted sum method for multi-objective optimization: new insights. Struct Multidisc Optim 41(6):853–862. https://doi.org/10.1007/s00158-009-0460-7

Mavrotas G (2009) Effective implementation of the ε-constraint method in Multi-Objective Mathematical Programming problems. Appl Math Comput 213(2):455–465. https://doi.org/10.1016/j.amc.2009.03.037

Mavrotas G, Florios K (2013) An improved version of the augmented ε-constraint method (AUGMECON2) for finding the exact pareto set in multi-objective integer programming problems. Appl Math Comput 219(18):9652–9669. https://doi.org/10.1016/j.amc.2013.03.002

Mohammed A, Wang Q (2017) The fuzzy multi-objective distribution planner for a green meat supply chain. Int J Prod Econ 184:47–58. https://doi.org/10.1016/j.ijpe.2016.11.016

Mohebalizadehgashti F, Zolfagharinia H, Amin SH (2020) Designing a green meat supply chain network: A multi-objective approach. Int J Prod Econ 219:312–327. https://doi.org/10.1016/j.ijpe.2019.07.007

Møller H, Rydhmer L, Christensen T, Poulsen LK, Olsen HF (2024) Social life cycle assessment in current and future Norwegian livestock production. Int J Life Cycle Assess. https://doi.org/10.1007/s11367-024-02345-3

Moltesen A, Bonou A, Wangel A, Bozhilova-Kisheva KP (2018) Social Life Cycle Assessment: An Introduction. In: Hauschild MZ, Rosenbaum RK, Olsen SI (eds) Life Cycle Assessment. Springer International Publishing, Cham, pp 401–422

Neugebauer S, Fischer D, Bach V, Finkbeiner M (2014) Social indicators for meat production – addressing workers, local communities, consumers and animals. 9th International Conference LCA of Food. San Francisco

Nickel S, Rebennack S, Stein O, Waldmann K-H (2022) Operations Research. Springer Berlin Heidelberg, Berlin, Heidelberg

Niembro-García J, Alfaro-Martínez P, Marmolejo-Saucedo JA (2022) Life cycle cost and life cycle assessment: an approximation to understand the real impacts of the Electricity Supply Industry. In: Advances of Artificial Intelligence in a Green Energy Environment. Elsevier, pp 83–110

Oglethorpe D (2010) Optimising Economic, Environmental, and Social Objectives: A Goal-Programming Approach in the Food Sector. Environ Plan A 42(5):1239–1254. https://doi.org/10.1068/a42292

Petit G, Sablayrolles C, Yannou-Le Bris G (2018) Combining eco-social and environmental indicators to assess the sustainability performance of a food value chain: A case study. J Clean Prod 191:135–143. https://doi.org/10.1016/j.jclepro.2018.04.156

Ren J (2020) Integrated data envelopment analysis, weighting method and life cycle thinking: A quantitative framework for life cycle sustainability improvement. In: Life Cycle Sustainability Assessment for Decision-Making. Elsevier, pp 329–344

Rosenbaum E, Mancini, L, Vasta, A, Sala, S, Dewulf, J (2015) Social life cycle assessment – State of the art and challenges for product policy support. Publications Office, Commission of the European Union. Joint Research Centre., LU

Ruckli AK, Hörtenhuber SJ, Ferrari P, Guy J, Helmerichs J, Hoste R, Hubbard C, Kasperczyk N, Leeb C, Malak-Rawlikowska A, Valros A, Dippel S (2022) Integrative Sustainability Analysis of European Pig Farms: Development of a Multi-Criteria Assessment Tool. Sustainability 14(5988):26. https://doi.org/10.3390/su14105988

Soysal M, Bloemhof-Ruwaard JM, van der Vorst JGAJ (2014) Modelling food logistics networks with emission considerations: The case of an international beef supply chain. Int J Prod Econ 152:57–70. https://doi.org/10.1016/j.ijpe.2013.12.012

Srivastava SK (2007) Green supply-chain management: A state-of-the-art literature review. Int J Manag Rev 9(1):53–80. https://doi.org/10.1111/j.1468-2370.2007.00202.x

Treml N, Naber E, Schultmann F (2025a) Towards an Animal Welfare Impact Category: Weighting Indicators in Pig Farming. Sustainability 17(10):4677. https://doi.org/10.3390/su17104677

Treml N, Rudi A, Schultmann F (2025b) Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany. J Clean Prod 503(145408). https://doi.org/10.1016/j.jclepro.2025.145408

Wulf C, Werker J, Ball C, Zapp P, Kuckshinrichs W (2019) Review of Sustainability Assessment Approaches Based on Life Cycles. Sustainability 11(20):5717. https://doi.org/10.3390/su11205717

Yadav VS, Singh AR, Gunasekaran A, Raut RD, Narkhede BE (2022) A systematic literature review of the agro-food supply chain: Challenges, network design, and performance measurement perspectives. Sustain Prod Consum 29:685–704. https://doi.org/10.1016/j.spc.2021.11.019

Zhang J, Li H, Yang S, Li X, Qian Y (2014) Investigation on Life-cycle Cost of Coal-based Synthetic Natural Gas (SNG). In: Computer Aided Chemical Engineering. Elsevier, pp 991–996

Zhou Z, Jiang H, Qin L (2007) Life cycle sustainability assessment of fuels. Fuel 86(1):256–263. https://doi.org/10.1016/j.fuel.2006.06.004

Zhu Z, Chu F, Dolgui A, Chu C, Zhou W, Piramuthu S (2018) Recent advances and opportunities in sustainable food supply chain: a model-oriented review. Int J Prod Res 56(17):5700–5722. https://doi.org/10.1080/00207543.2018.1425014

Zira S, Röös E, Ivarsson E, Hoffmann R, Rydhmer L (2020) Social life cycle assessment of Swedish organic and conventional pork production. Int J Life Cycle Assess 25(10):1957–1975. https://doi.org/10.1007/s11367-020-01811-y

Zira S, Rydhmer L, Ivarsson E, Hoffmann R, Röös E (2021) A life cycle sustainability assessment of organic and conventional pork supply chains in Sweden. Sustain Prod Consum 28:21–38. https://doi.org/10.1016/j.spc.2021.03.028

Paper D

Meat versus microbial protein—a life cycle assessment of present-day value chains

Reference

Treml N, Minden S, Grünberger A, Volk R, Rudi A, Schultmann F, Kaster A (2026a) Meat versus microbial protein—a life cycle assessment of present-day value chains. The International Journal of Life Cycle Assessment 31(5):65. https://doi.org/10.1007/s11367-026-02637-w.

The International Journal of Life Cycle Assessment (2026) 31:65
https://doi.org/10.1007/s11367-026-02637-w

LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Meat versus microbial protein–a life cycle assessment of present-day value chains

Nina Treml[1] · Steven Minden[2] · Alexander Grünberger[3] · Rebekka Volk[1] · Andreas Rudi[1] · Frank Schultmann[1] · Anne-Kristin Kaster[2,4]

Received: 25 August 2025 / Accepted: 1 April 2026

Abstract

Purpose Replacing meat-based protein with more sustainable options is a pivotal strategy towards the fulfillment of the United Nations Sustainable Development Goals. An ever-increasing global demand for protein-rich nutrition has to be satisfied.

Methods This study conducts a comparative life cycle assessment of two contemporary value chains—pork meat and bioreactor-based microbial protein—to evaluate their environmental impact. Pork meat production is examined based on primary data from German manufacturers, including two consecutive pig production facilities and one slaughterhouse. Microbial protein production is based on literature data covering a commercialized process and estimates are derived from process simulations. Both production processes are assessed for their impact on global warming, land use, water use, and non-renewable energy demand based on 1 kg protein output as functional unit.

Results and discussion The results indicate that microbial protein production offers reductions in land and water use by 94% and 70%, respectively. In addition, microbial protein production shows slightly higher impacts for global warming and a three-fold increase in non-renewable energy demand, mostly resulting from the glucose syrup feedstock and energy for medium sterilization. Furthermore, the global warming impact of pork production benefits from offsets through biogas credits. A Monte Carlo simulation provides uncertainty estimators for both production chains which shows, in particular, that it is not possible to draw conclusive statements about the impact on global warming.

Conclusion Microbial protein demonstrates significant reductions in land and water use compared to pork, indicating strong potential for improved sustainability. However, its overall advantage depends on reducing energy demand and sourcing low-impact carbon feedstocks, which are critical prerequisites for achieving a truly sustainable profile.

Communicated by Arnaud Hélias.

✉ Steven Minden
minden@kit.edu

✉ Anne-Kristin Kaster
kaster@kit.edu

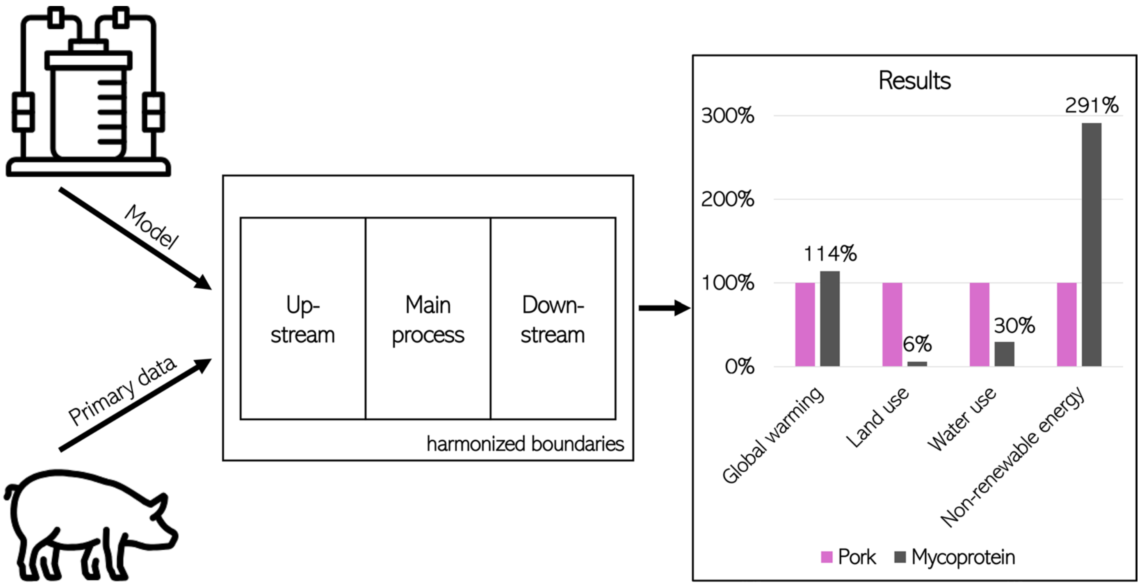
[1] Institute for Industrial Production (IIP), Karlsruhe Institute of Technology (KIT), Hertzstraße 16, 76187 Karlsruhe, Germany

[2] Institute for Biological Interfaces 5 (IBG-5), Biotechnology and Microbial Genetics, Karlsruhe Institute of Technology (KIT), Hermann-von- Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

[3] Microsystems in Bioprocess Engineering (μBVT), Institute of Process Engineering in Life Sciences (BLT), Karlsruhe Institute of Technology (KIT), Fritz-Haber-Weg 2, 76131 Karlsruhe, Germany

[4] Institute of Applied Biosciences (IAB), Karlsruhe Institute of Technology (KIT), Fritz-Haber-Weg 4, 76131 Karlsruhe, Germany

Graphical Abstract



Keywords Pork · Mycoprotein · Comparative LCA · Fermentation · Bioreactor · Livestock · Pig farming

1 Introduction

Human population growth and climate change are two megatrends that impose a challenge on the current way food is produced. Population growth increases food demand, and rising global living standards, particularly the adoption of protein-rich diets, are projected to drive a 2% compound annual growth rate (CAGR) in global protein consumption through 2050 (Noorman 2023). Yet, food production directly contributes to one third of anthropogenic greenhouse gas (GHG) emissions primarily driven by agricultural land-use—a fact that will require disruptions in how food is produced in the future. (Crippa et al. 2021; Tubiello et al. 2022). Moreover, land use and water use are further heavy impacts of conventional agriculture and in particular meat-based protein production (Gislason et al. 2023). Rising temperatures, extreme weather events, water scarcity, and biodiversity loss threaten agricultural supply chains, with crop yields projected to decline by 35 to 50% under a business-as-usual policy until 2100 (Scheelbeek et al. 2018; Tigchelaar et al. 2018). Moreover, our current trajectory pushes the planetary boundaries beyond critical thresholds, calling for a profound reformation toward sustainable and secure food production (Halpern et al. 2022; Richardson et al. 2023).

While several strategies exist to reduce emissions and increase the robustness of meat- and plant-derived protein supply chains, their mitigation potential is limited (Hong et al. 2025; Kyttä et al. 2025; Springmann et al. 2018). Fermentation-based microbial protein (MP) as protein-rich food is currently gaining popularity in global markets as sustainable alternative protein (Pereira et al. 2024). Cellular agriculture-derived dairy products and myco- or single cell protein as representatives of MP in meat-like formulations are produced in balanced bioreactors in contrast to the traditional agricultural systems that are subject to constant fluctuations. Using microbes instead of meat or plant systems further offers the advantage of superior feedstock efficiencies, increased production rates, and decreased ethical concerns (Choi et al. 2022; Matassa et al. 2016; Shepon et al. 2016). Most importantly, microbial foods offer innovation potential for land- and climate-independent production chains via e.g. CO_2 valorization and could significantly reduce environmental impacts, achieving order-of-magnitude improvements over meat- and plant-based protein (Minden et al. 2024; Pikaar et al. 2018). However, MP production also faces challenges, such as cost of production, scalability, consumer acceptance, market entry, and regulation (Hartmann et al. 2022; Sturme et al. 2025; Synonym Biotechnologies 2023; World Economic Forum 2019).

Comprehensive environmental sustainability assessment is critical for informed policy, process design, and business decisions toward fulfilling the United Nations Sustainable Development Goals (SDGs) (Sinkko et al. 2023). In that regard, life cycle assessment (LCA) studies provide a rich literature base for comparing different food systems, including mycoprotein (e.g., Cellura et al. 2022; Detzel et al. 2022; Smetana et al. 2015). On the one hand, the cited studies and others strongly demonstrate that most MP products are more environmentally friendly than meat products. On the other hand, literature lacks a systematic comparison of scaled meat- and microbial protein value chains representing the *status quo* as a metric for future decision making. Available studies are either anticipatory of not yet developed or scaled technology or value chains are not comparable due to different underlying methodologies (e.g., functional units, or system boundaries), assumptions, and research goals (Roßmann et al. 2021). For example, the sustainability assessment of Quorn™ production, one of the few industrially scaled food MP processes to date, employs a set of impact categories that does not include cumulative energy demand, reflecting the methodological boundaries of the study (Finnigan et al. 2024). Because energy demand is central to bioprocess evaluation in this study, we address this gap using harmonized system boundaries and functional units.

The aim of this work is to provide a LCA benchmark by contrasting two representative value chains for commercialized meat-derived protein and MP products. The first value chain assesses meat-derived protein production via pork production, selected as a representative of one of the most consumed meat types on a global scale (Gislason et al. 2023), utilizing primary data as detailed in Treml et al. (2025). The data covers the breeding, fattening, and slaughtering of animals based on case studies from Germany, one of the largest pig producers in the world (FAO, 2023). In Germany, the pig industry consolidated from smaller farms to integrated factory farms in the last decade, which is considered by the representative meat production system in this study (Federal Statistical Office of Germany, 2024). The second value chain examines mycoprotein as an example of MP production. Data originates from process simulations based on the well-documented Quorn™ process, representing the largest and most established MP production for human consumption, with commercial sales in 20 countries since 1985 (Finnigan et al. 2017, 2024; Meyer et al. 2020). Both value chains are analyzed within a cradle-to-gate scope, adhering to consistent system boundaries to ensure comparability. Uncertainties arising from different data sources are accounted for by Monte Carlo simulations (Mendoza Beltran et al. 2018). The environmental impacts are evaluated across four key categories: global warming, water use, land use, and non-renewable energy demand, providing a comprehensive assessment of the environmental profiles of these protein production systems.

2 Materials and methods

The environmental impacts of the different protein sources, pork and mycoprotein, are assessed by evaluating the production systems using the LCA methodology. This study is based on the ISO 14,040 and 14,044 standards for LCA (ISO, 2018, 2009) modeled in openLCA. Although both case studies vary qualitatively in their material streams and unit operations, the functional unit (FU) and system boundaries allow comparability between the livestock-based value chain and bioreactor-derived MP production since the products are harmonized based on their quality as a protein source in food.

2.1 Functional unit

The FU enables a sound comparison of the production systems under investigation based on their common property as a protein source (Heller et al. 2013; Nijdam et al. 2012; Shrivastava et al. 2025; Sillman et al. 2020; Sonesson et al. 2017; Ye et al. 2018). In contrast to conventional LCA studies, the FU focuses not only on the mass of the product, but specifically on the nutritional ingredient protein. This approach has already been preferred in previous LCAs of mycoprotein (Järviö et al. 2021a; Kobayashi et al. 2023; Smetana et al. 2023). Figures 1 and 2 visualize how the FU is assembled for both case studies to yield 1 kg of protein. The red arrows indicate the assembly of the functional unit at each stage, showing how much product from each step contributes to achieving the final functional unit of 1 kg of protein for both pork and mycoprotein production. This breakdown helps clarify the processes and amounts required to reach the functional unit for comparison in the LCA study. The blue arrows ensure comprehensiveness by visualizing the mass of the products of the value chain steps in relation to the final product. The FU expresses the protein mass fraction of the cut meat and formulated mycelium for the pork and mycoprotein systems, respectively. Formulated mycelium describes the output after the product formulation step with a 48% water content that is ready for further valorization and comparable to unprocessed meat. The respective protein content is stated as 13.4%, based on Finnigan et al. (2024). For the conversion of the slaughterhouse product (slaughter halves) to pork meat, studies are consulted that investigated the yield of pork meat from pigs (Dourmad et al. 2015; Laisse et al. 2018; Schinckel et al. 2001). Laisse et al. (2018) reported a protein content of 21.5% in pork meat, which was used for calculations in this study as it corresponds to the slaughter weight recorded in the farm management data for the case study.

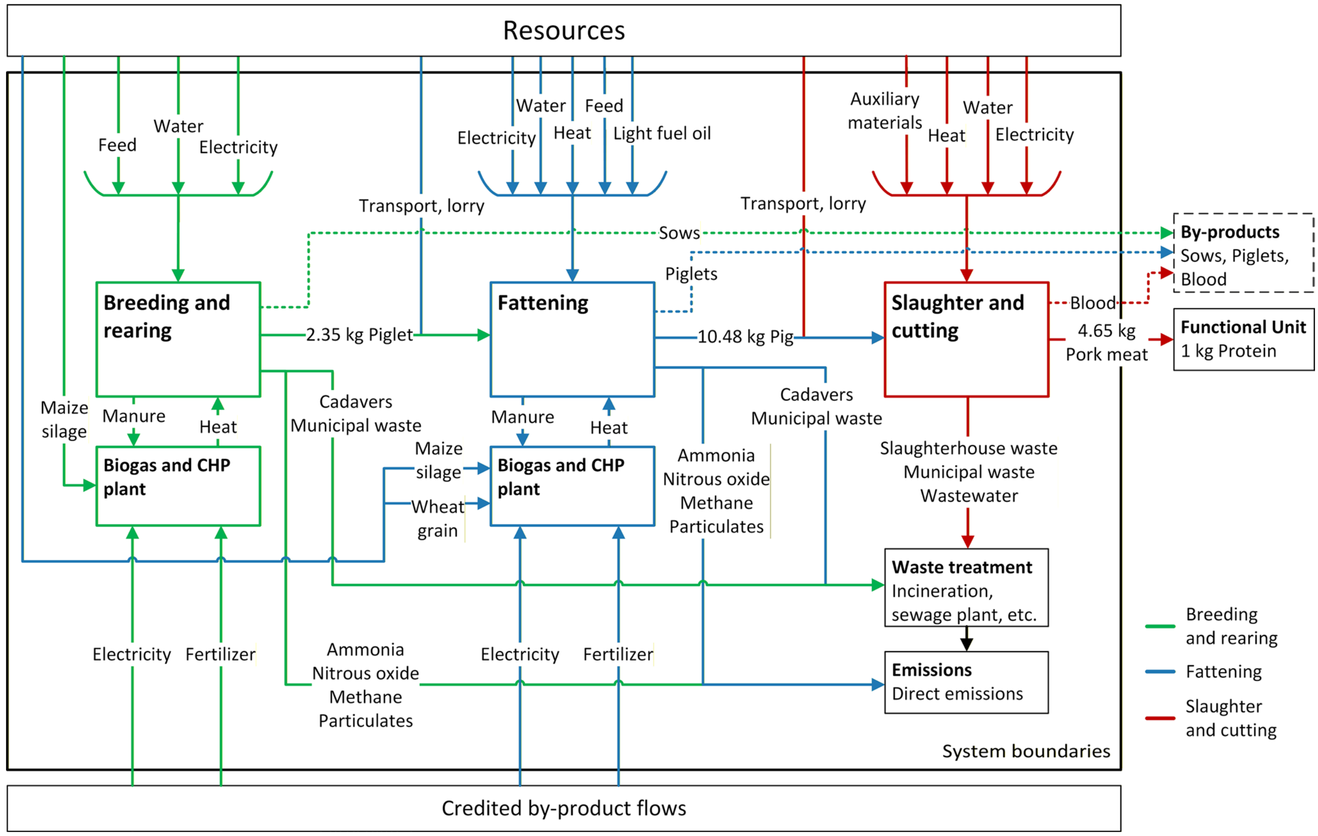


Fig. 1 System boundaries for the pork meat production encompassing the breeding and rearing farm, the fattening farm and the slaughter facility. Each facility exists as modeled. The functional unit is defined as 1 kg of protein. Reference flows for production correspond to the total input mass required to obtain this FU. The colors indicate the affiliation of the process in- and outputs to the different value chain links. The dashed lines indicate by-products that are excluded by allocation

2.2 System boundaries

The analysis considers a cradle-to-gate approach, which encompasses the resource procurement, transportation, and production phases of the products being compared, while excluding factors such as buildings and machinery. As previously described, the two value chains under investigation build upon contrasting settings.

The core unit operation of the pork value chain is raising pigs as living creatures. As shown in Fig. 1, pork production consists of three facilities representing three steps in the value chain: the breeding and rearing farm, the fattening farm, and the slaughterhouse. These facilities are connected by truck transport, and the life cycle inventories are based primarily on data from the factories (see Sect. 2.3 and Treml et al. 2025). The main production step in the pig value chain is fattening, provided by breeding and rearing, followed by slaughter. Pig farm systems integrate the production and use of biogas from manure and emerging credits, as these factors significantly impact LCA considerations and represent a standard practice on German pig farms (Treml et al. 2025). The assessment also covers feed production as a determining input. The by-products indicated by dashed lines are excluded from calculations by mass-allocation (see Sect. 2.4). The connections between production processes are labeled with masses that result in the functional unit.

Mycoprotein is produced from fungal growth in a balanced bioreactor system located at the site indicated in Fig. 2. Similar to how pigs metabolize feed, the fermentation process requires a feedstock to enable fungal growth. In this study, glucose syrup is used as the carbon source for the fermentation process, aligning with the findings of Upcraft et al. (2021). Glucose is one of the components of the fermentation medium and is used as an input for the medium preparation step (see Sect. 2.3 for details). To improve comparability, the mycoprotein production process is divided into three steps: upstream, fermentation, and downstream. Fermentation is the main production step in mycoprotein production and is highlighted in blue. This step is accompanied by upstream and downstream processing. Displaying the product mass required for producing the functional unit should demonstrate the potential of such a facility compared to the evaluated meat production case study.

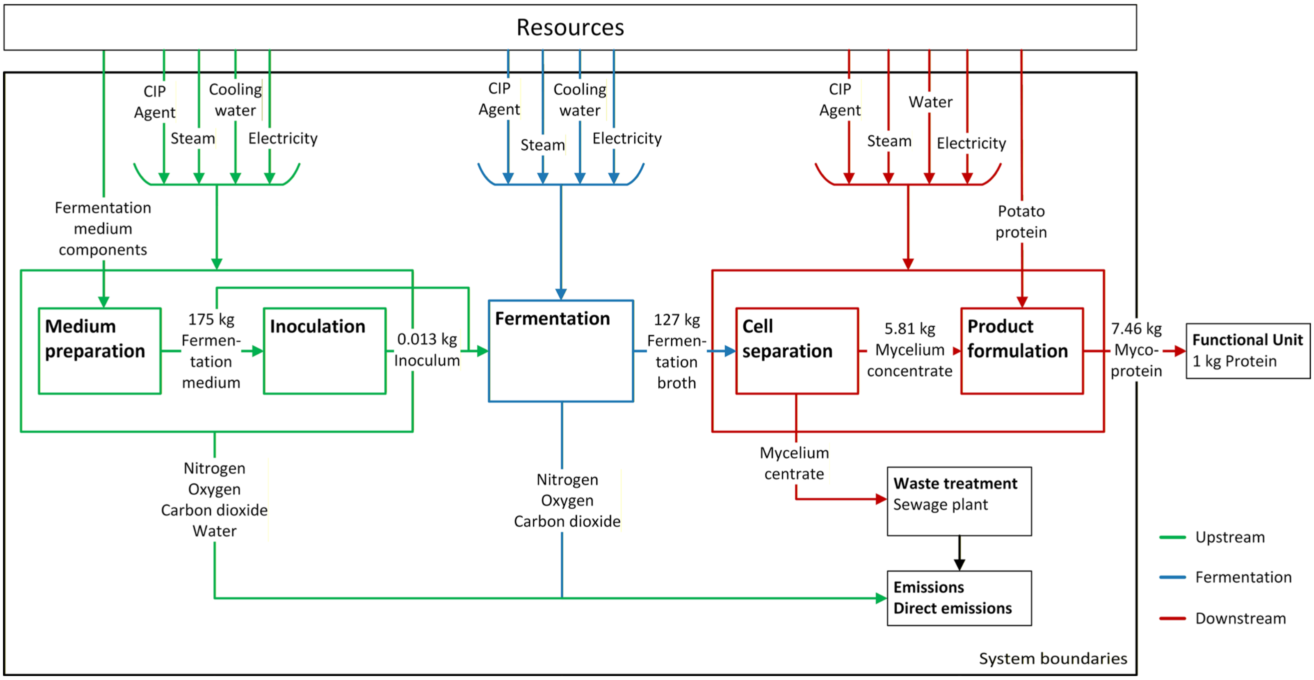


Fig. 2 System boundaries for the modeled mycoprotein production and the distinct production steps based on literature data. Reference flows for production correspond to the total input mass required to obtain this FU. The colors indicate the affiliation of the process in- and outputs to the different value chain links. Upstream and downstream processes are color-coded together to improve readability

Table 1 Inventory for the pig production process including the transfer of piglets to the fattening farm on the level of value chain links based on the output of 1 kg of protein (FU)

Inputs/Outputs	Amount	Unit	Provider	Data source
Inputs				
Pig	8.13	kg	Fattening	a
Piglets	2.35	kg	Breeding and Rearing	a
Transport	2.35 · 95	kg·km	market for transport, freight, lorry 16–32 metric ton, EURO5/6 | APOS, U - RER	a, b
Output				
Fattened Pig	10.48	kg		a

a Treml et al. (2025)

b Ecoinvent (2023)

For both systems (Figs. 1 and 2), waste treatment is carried out within the boundaries and direct emissions have been identified and considered in the assessment (scope 1). Moreover, electricity is considered with the current energy mix in Germany (scope 2).

2.3 Inventory and data

A thorough overview of the inventory data is provided with the supplementary material (Appendix A). Both systems are modeled as German case studies to remove location-dependent effects. When primary data for Germany was unavailable, sources most closely aligned with Germany's geographic context were prioritized. All primary inventory data is matched to the databases of ecoinvent in version 3.9.1 and agribalyse in version 3.1 (ADEME, 2023; Ecoinvent Association 2023).

The pork production process is covered by primary data from the farm and facility operators of the three pork production steps and completed with qualified estimates for the combination of the pig production steps with the slaughterhouse operations. The data for the pork production sites as standalone systems is provided by Treml et al. (2025). The pig production (see Table 1) describes an existing value chain operated in Germany. This process comprises the two steps "breeding and rearing" and "fattening" from the presented system boundaries (Fig. 1). In contrast, the slaughterhouse under consideration in the case study is not, in fact, supplied by the fattening pig farm that was previously examined. However, in order to provide a realistic scenario of pork production in Germany based on primary data, these facilities are combined as shown in Table 2. This approach is feasible considering that the slaughtering process is only a minor contributor to the environmental impact of pork (Cherubini et al. 2015; McAuliffe et al. 2017; Nguyen et al. 2011; Reckmann et al. 2013; Treml et al. 2025; Yu et al. 2024). The transports considered in the value chain represent the actual distances between the pig breeding and fattening farm and the slaughterhouse. All transports are modeled based on the ecoinvent data sets for lorry transport from 16

Table 2 Inventory for the pork production process including the transfer of the pigs to the slaughterhouse and the cutting of the slaughter halves to pork meat on the level of value chain links based on the output of 1 kg of protein (FU)

Inputs/Outputs	Amount	Unit	Provider	Data source
Inputs				
Fattened pig	10.48	kg	Pig Production	a
Carcass	8.39	kg	Slaughter	a
Cutting	8.39	kg	Cutting, carcasses, Pork loin, industrial production, French production mix, at plant, 1 kg Pork loin (POUi)	b
Transport	10.48 · 320	kg·km	market for transport, freight, lorry 16–32 metric ton, EURO5/6 | APOS, U - RER	see Table 1
Output				
Pork meat	4.56	kg		c, d, e

a Treml et al. (2025)

b ADEME (2023)

c Dourmad et al. (2015)

d Laisse et al. (2018)

e Schinckel et al. (2001)

to 32 tons of EURO 5 and 6 (see Tables 1 and 2) (Ecoinvent Association 2023). The considered livestock facilities (piglets and pigs) are factory farms with comparatively large production capacities above the German average. The feed composition for both farms is detailed in an OpenLCA readable zip-file in the supplementary material (Appendix B), as including it here would exceed the scope of the text. The considered slaughterhouse focuses on the slaughter of organically reared animals and has a low production volume (carcasses) compared to the three large slaughter factories that hold most of the market share in Germany (ISN, 2024). Those factories produce the yearly output of pork carcasses from the presented value chain link in approximately two weeks (Stephan 2020).

Mycoprotein production data is primarily derived from process simulation using the software Superpro Designer™ (version 14, Intelligen, USA). Simulations are based on the published process model file for mycoprotein production from Da Gama Ferreira et al. (2023). The model was adapted according to literature covering the Quorn® process from Marlow Foods (UK) wherever possible (Finnigan et al. 2017, 2024; Fletcher et al. 2024; Nevalainen 2020; Risner et al. 2023; Trinci 1992). Major changes made to the original process model file include removal of water recycling and fertilizer production from the centrate, which is the mycoprotein-deriched liquid phase after cell separation (more detail can be found in the supplementary material: Appendix A). In brief, the entire process chain involves medium preparation, inoculation, fermentation, and cell separation (see Fig. 2). Table 3 lists the components of a hypothetical fermentation medium designed based on the Rank-Hovis medium recipe due to its documented history in the Quorn® inoculation process (Whittaker 2022) (see also Fig. 2). Minor modifications to the original recipe stem from LCA-database limitations, such as absent biotin which is substituted by a vitamin mix. To ensure completeness and comprehensibility, flows that could not be assigned to match the database are listed as elementary flows. Comparable approximate data for the elementary flows was identified to match the database and examined in terms of the influence to the calculation. There was no influence on any impact category observable, therefore the flows were not inserted in the model. The core process involves three 160 m^3 bioreactors operated continuously delivering 24×10^3 t of product annually with underlying reaction kinetics from the original process model file.

2.4 Allocation procedure

The utilization of allocation rules is imperative within the context of the pork production chain, encompassing the individual by-products for each process step. In the context of pork production, the environmental impacts are allocated by mass to the by-products, namely sows, piglets and blood, because their mass fraction is negligible in comparison to the main product. The primary product is the pig, though manure can also be considered a valuable co-product. Processes involving energy production or yielding co-products that are used beyond the system boundaries are addressed using system expansion to avoid allocation. In accordance with ISO (2018) standards, the allocation of manure is avoided, and system expansion is applied for manure treatment via biogas plants and to avoid fertilizer production. With regard to digestate and manure, the production of appropriate fertilizers is selected, guided by nutrient composition data provided by the farms. Furthermore, the electricity generated is credited against the German electricity production mix, following system expansion principles. The mycoprotein process does not necessitate allocation since it does not yield any by-products.

2.5 Life cycle impact assessment

The calculation of environmental impacts is performed with the software OpenLCA with the impact assessment methods ReCiPe 2016 Midpoint (H), AWARE 1.2 and Cumulative Energy Demand (HHV). The examination focuses on the impact categories global warming, land use, water use and non-renewable energy demand (NRE) because these categories display decisive differences in impacts of the two

Table 3 Inventory for the fermentation medium components for the production of 1 kg of fermentation medium in the medium preparation step. Alongside the amount of each ingredient the provider from the according LCA-respective database is listed

Inputs	Amount	Unit	Provider*	Database
Glucose syrup	31.15	g	Market for glucose | glucose | APOS, U - GLO	E
Ammonia (anhydrous)	1.38	g	Market for ammonia, anhydrous, liquid | ammonia, anhydrous, liquid | APOS, U - RER	E
Magnesium sulfate	0.708	g	Market for magnesium sulfate | magnesium sulfate | APOS, U - GLO	E
Citric acid	1.197	g	Market for citric acid | citric acid | APOS, U - GLO	E
Sodium phosphate	0.913	g	Market for sodium phosphate | sodium phosphate | APOS, U - RER	E
Potassium phosphate	2.91	g	Elementary flow	E
Calcium chloride	0.198	g	Market for calcium chloride | calcium chloride | APOS, U - RER	E
Iron sulfate	0.0076	g	Market for iron sulfate | iron sulfate | APOS, U - RER	E
Zinc monosulfate	0.0029	g	Market for zinc monosulfate | zinc monosulfate | APOS, U - RER	E
Manganese sulfate monohydrate	0.0047	g	Market for manganese sulfate | manganese sulfate | APOS, U - GLO	E
Cupric chloride dihydrate	0.0006	g	Elementary flow	E
Boric acid	0.0013	g	Market for boric acid, anhydrous, powder | boric acid, anhydrous, powder | APOS, U - GLO	E
Molybdenum	0.0003	g	market for molybdenum | molybdenum | APOS, U - GLO	E
Vitamin mix	0.0026	g	Vitamin, animal feed, at retailer gate - FR	A
Choline chloride	0.0003	g	Elementary flow	E
Air	273.50	g	Elementary flow	E
Water	687.72	g	Market for water, deionised | water, deionised | APOS, U - Europe without Switzerland	E

* Entries reproduced from database

A = Agribalyse (2023)

APOS = Allocation at point of substitution

E = Ecoinvent (2023)

FR = France

GLO = Global

RER = Europe

U = Unit process

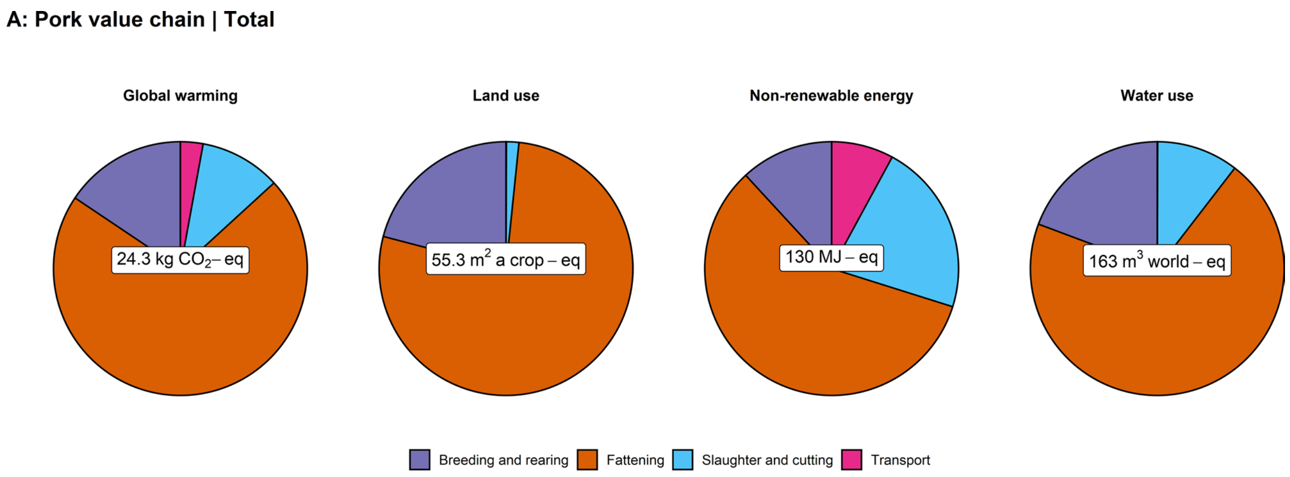
systems. While global warming is the most common category to assess environmental issues, land use is a limited resource that plays an important role regarding the layout of the systems considered. These categories are also evaluated by recent studies about mycoprotein or other APs, enabling broader comparability to our assessment (Bakman et al. 2024; Järviö et al. 2021a, b; Kobayashi et al. 2023; Mazac et al. 2023; Mogensen et al. 2020; Smetana et al. 2015, 2021, 2023; Upcraft et al. 2021). Additionally, most of the aforementioned studies assess water use categories because of the water-intensive fermentation process during mycoprotein production (Bakman et al. 2024; Järviö et al. 2021a, b; Kobayashi et al. 2023; Mazac et al. 2023; Röder et al. 2022; Smetana et al. 2023). In the study at hand, the water use category is calculated based on the AWARE 1.2 impact assessment method, a method that is developed especially to assess the relative availability of water remaining in a watershed after meeting human and ecosystem demands, with values normalized to the global average to indicate the potential for water deprivation (Boulay et al. 2018). The characterization factors multiply water usage in the system with specific factors to gain an overall result based on the water scarcity in the specific regions that correspond to the employed flows. The selection of NRE is driven by the energy-intensive nature of mycoprotein production, particularly in the context of heating tasks.

The reliability of the results is tested via sensitivity and scenario analyses. The sensitivity analysis covers the reduction of the most influential input flow for both systems. For Mycoprotein production, the replacement of this input with a valid substitution material is calculated as a scenario analysis.

An uncertainty analysis was implemented with the Monte Carlo approach incorporated into the OpenLCA software. The simulation was conducted for all considered data sets over 1000 iterations with a logarithmic normal distribution and uncertainty factors were calculated for each input and output data points considering a lognormal distribution and utilizing the pedigree matrix (Bakman et al. 2024; Ciroth et al. 2016; Smetana et al. 2021). This analysis was performed to evaluate the range of results, especially for the mycoprotein case because its data was derived from literature and assumptions. The data quality was assessed for every unit process by the data collectors and builds the basis for the simulation to show if the retrieved results are reasonable. Statistical significance between pork and mycoprotein cases was assessed using Welch's t-test, which accounts for unequal variances between groups.

3 Results and discussion

The pork production chain is a well-evaluated reference for comparing animal-based diets with any other given diet. The evaluation in this study is based on a review of case studies (Treml et al. 2025). Those studies were combined as described in Sect. 2.3 and calculated for the FU of 1 kg protein. For comparison, mycoprotein is evaluated as an alternative protein source from a submerged fermentation process with filamentous fungi. The results for the four selected environmental impact categories, presented in Figs. 3A and 4A, show that mycoprotein has a slightly higher global warming impact of 14%, while pork uses 94% more land and 70% more water. In contrast, mycoprotein exhibits a markedly higher NRE demand of 291%. The pork results serve as baseline for the percentage values. The relative and absolute influence of the processes for every impact



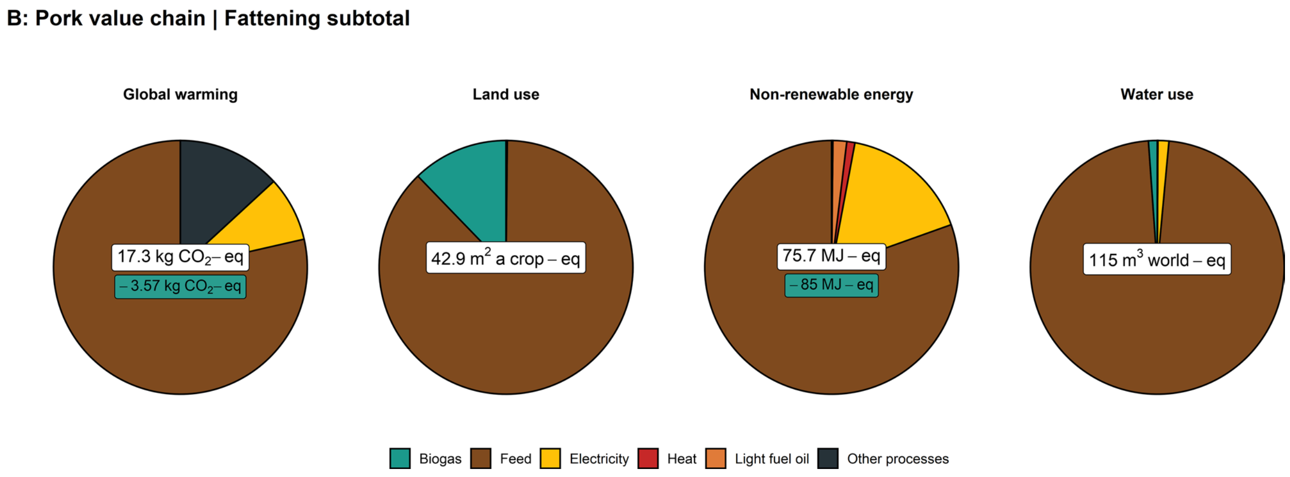


Fig. 3 Environmental impact assessment of pork meat production. (**A**) shows percentages of impact allocations per process with the sum as an absolute value label tag in the center of each pie chart. (**B**) disaggregates the most impactful process "fattening" into its sub-processes with negative values resulting from credits depicted as an additional value tag in the respective process color. Sub-processes contributing < 1% to the sum are conflated to "other processes"

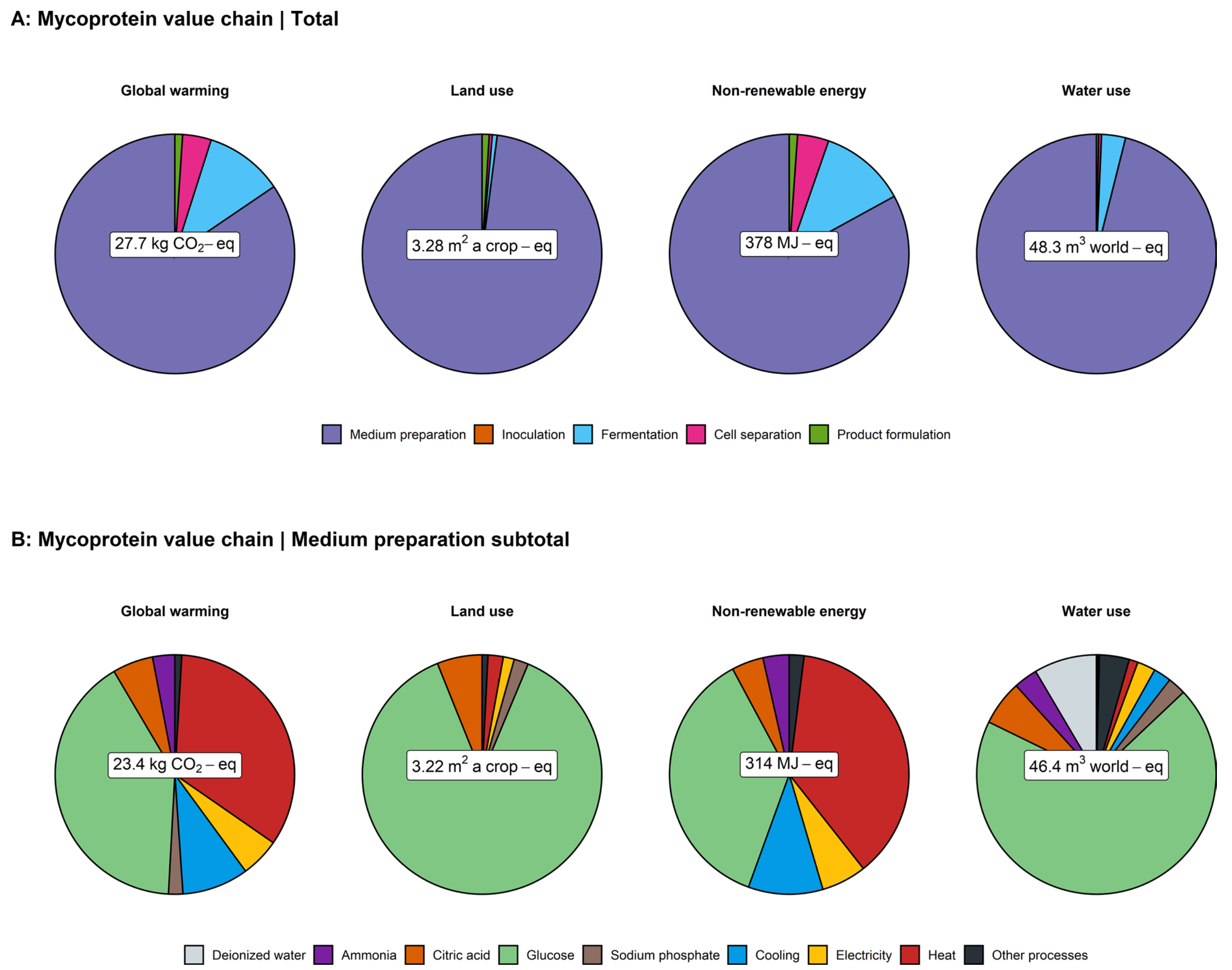


Fig. 4 Environmental impact assessment of mycoprotein production. (**A**) shows percentages of impact allocations per process with the sum as an absolute value label tag in the center of each pie chart. (**B**) disaggregates the most impactful process "medium preparation" into its sub-processes with those contributing < 1% to the sum conflated to "other processes"

category is reported in the supplementary material (Appendix A).

3.1 Global warming

The results indicate that mycoprotein production has 14% higher global warming impact than pork production for 1 kg of protein. In mycoprotein production, the global warming impact is mainly driven by the medium preparation step, which contributes to the largest share of the emissions with roughly 84%, with a distinct part also attributed to the fermentation process with 11%. Glucose, as the considered carbon source and heat from natural gas, accounts for about 75% of the CO_2-eq of the medium preparation with assigned shares around 30%. This highlights that the upstream or preparatory stages of mycoprotein production, including the provision of raw materials and energy, have a major impact on the overall carbon footprint. The fermentation contributes 11%, while cell separation and product formulation together contribute less than 5%, and inoculum production is negligible as its impact is less than 1%. Energy related inputs like electricity, cooling energy and steam account for 54% of global warming for mycoprotein. In comparison, the global warming impact of pork production shows a share wise similar distribution alongside the value chain with one overshooting contribution of 85% coming from the fattening step. Overall, the consumed feed represents the most substantial impact with over 85%. When searching for explanations of this impact distribution focusing on the feedstocks, the production of glucose from corn for mycoprotein processes and the wheat (~22%), barley (~28%) and soybean (~42%) components of the feed mix for the pigs are mostly based on agricultural processes that cause the largest impacts (Treml et al. 2025). On the other hand, for the pork case, the production and use of biogas from pig production creates a creditable output, leading to a positive influence on global warming and NRE mainly through the electricity fed to the grid (Treml et al. 2025). The slaughter stage has less impact (10%) than the breeding and rearing stages (16%), and transport (3%) of the live pig has the least impact.

3.2 Land use

The results of the land use impact category show a considerable difference between the two protein production systems—the mycoprotein system results in just 6% of the results for pork. The cause of the difference is grounded in the agricultural land use of the systems and the calculation basis of the impact category with the characterization factor "agricultural land occupation potential" (Huijbregts et al. 2017). While the pork system relies heavily on agricultural systems for pig feed production (87%), mycoprotein production relies almost exclusively on glucose (86%) from corn as an agricultural input. The impacts for barley (~36%), wheat (~32%), and soy (~24%) stand out once again in contributing to the fattening feed. For mycoprotein production, the land use impacts are relatively low, with the main contribution coming from the medium preparation stage with 98% impact. Therefore, land use displays the main differentiator of both systems. This difference reflects the feedstock efficiencies of both systems as the modeled mycoprotein production is approximately nine times more feed efficient in comparison to pork production based on the feedstock-to-product yield (excluding water) in this study. Another notable impact for the pig production phases is the production of maize silage and wheat for the use in the biogas plant as a co-substrate accounting for 11%. This land requirement indicates the high environmental cost of land resources in intensive livestock production. In comparison to the other categories, the credits associated with the biogas production and use do not apply, because the credited flows do not influence the land use category.

3.3 Non-renewable energy

The Cumulative Energy Demand impact assessment method allows to examine the NRE content in production processes. Based on literature consensus (Minden et al. 2024), this category is a known challenge of fermentation-derived process chains. Hence, an energy demand of mycoprotein surpassing that of pork production by a factor of three (291%) should not come as a surprise. The medium preparation contributes more than 80% to the overall NRE consumption. Glucose provision and heat supply, e.g., for medium sterilization, account for 30% and 35%, respectively, of the overall result. The fermentation accounts for 12% emerging mostly from cooling energy (11%). Improvements could be achieved through increasing the implementation of renewable energy production sources and changing the carbon source into a more sustainable option. For pork production, the consumed feed accounts for 128% of the NRE content. Focusing on feed provided to fattening, the major impacts are divided among soybean (~36%), barley (~15%), and wheat (~22%) components. The slaughter and transport processes have a greater impact than the other impact categories with 30%, but more than half of the impact stems from the fattening process. Looking more closely at the on-farm processes, it becomes evident that production and use of biogas is a substantial negative contributor by cutting the total NRE result by more than half—improving the fattening process by 85 MJ-eq (-66%) and the breeding process by 31 MJ-eq (-24%). The biogas plant primarily provides heating for the pig production steps, which reduces the results in this category because no additional heating is required. The environmental impacts of the slaughter process are responsible for more than 20% of the total emissions in this category and stem from two main factors: the treatment of slaughterhouse waste (10%) and the energy consumption (9%) associated with the slaughter process. An important remark is that when biogas production and use and therefore the credits would be erased, the pork results elevate to 246 MJ-eq and mycoprotein production results are only 1.5 times increased. As the heating supply is also covered by biogas conversion, another source of impact is not even considered in this scenario. Talking about the scenario, it is relevant also to reflect on biogas production as the standard manure treatment representing a reference for pig production in Germany. This fact justifies integrating credits in our study.

3.4 Water use

For the water use impact assessment, the AWARE 1.2 impact assessment method is applied as an international representative technique to assess water use worldwide (Boulay et al. 2018). The results further emphasize the importance of considering the resource requirements of agricultural production processes. Pork production uses more than three times as much water as mycoprotein production (338% more). The fattening phase represents the largest share of influence (70%), while feed production for complete pig production accounts for 89%—mainly from barley and wheat. This is due to the water consumption of the agricultural processes used to produce the feed. Furthermore, water utilization in the treatment of slaughterhouse waste, which accounts for 10% of the overall impact, is a primary factor influencing the impact of slaughter processes (10%). Although water is an important ingredient and process material for mycoprotein production, water use is limited compared to pork production. Medium preparation is the primary contributor, accounting for nearly 96% of the identified water use. Specifically, glucose production contributes to 67% of the total impact. Similar to pork feed, the main source of water consumption here is the agricultural process used to produce corn, the raw material used to make glucose. Deionized water, which is used in production processes, also plays a significant role, contributing 8% to the results.

3.5 Sensitivity analysis

The two feedstocks, feed and glucose, have the greatest influence on the examined impact categories. Reducing these flows' input by 10% allows us to analyze the sensitivity created when their efficiency improves and less material is needed. Figure 5 shows how the overall results for the examined impact categories change. The most prominent reduction is seen in the NRE category in the pork case with more than 12%. Overall, the reductions in the pork case are more pronounced. The least improvement is achieved in the NRE category for mycoprotein production followed closely by the corresponding global warming impact.

By comparing the results to the LCA results, the margin of reduction can be allocated. Feed has a major impact on every category of pork production's LCA, which explains the high levels of improvement achieved. The exceptional reduction in NRE further emphasizes the energy intensity of feed production, particularly the substantial proportion of grains. Treml et al. (2025) stated that feed efficiency is optimized to the maximum extent possible over the last decades and therefore only feed composition respecting efficiency changes and origin of components can be adapted.

Although glucose has the strongest overall impact on mycoprotein production, its relative influence is much lower than the impact change when reducing feed in pork production. As the impact of land and water use for glucose is quite important, their larger reductions can be associated with agricultural processes connected to glucose production. Figure 4 shows that the influence of glucose is relatively small for global warming and NRE in comparison. Therefore, impact reductions are obviously smaller. To improve mycoprotein production substantially, a combination of reducing feedstock and energy consumption could be a viable

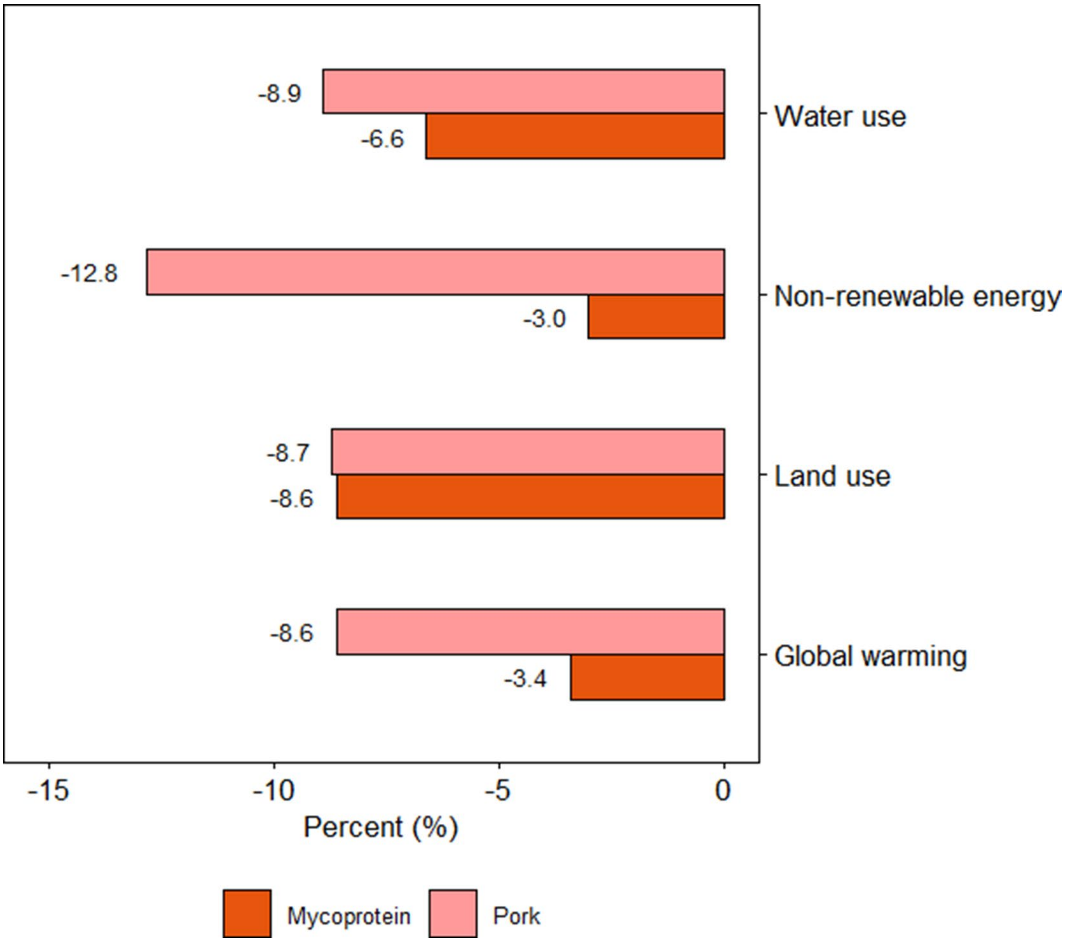


Fig. 5 Sensitivity analysis results of the four impact categories representing calculations with 10% reduced feed and glucose input for the pork and mycoprotein case, respectively

strategy. While the optimization potential of industrial animal meat production in terms of energy demand is mostly expended, anticipatory LCAs of bioreactor-derived protein sources promise up to 5-fold ameliorations versus the herein reported 378 MJ-eq, e.g. by shifting from purified glucose syrup to molasses as a by-product from the sugar industry (Smetana et al. 2015; Tubb & Seba, 2019). Accordingly, an optional replacement of glucose with sugar beet molasses is discussed in Sect. 3.6.

3.6 Scenario analysis

The proposed assessment of the replacement of glucose syrup with molasses for mycoprotein production in our LCA model is conducted as a scenario analysis. The results indicate that the change reduces the outcomes for global warming, water use, land use, and NRE by 32%, 59%, 67%, and 29%, respectively. The drastic change arises foremost from the applied economic allocation for the beet sugar production that produces molasses as co-product and allocates impacts with factor 4.5% to molasses.

In comparison with pork, the scenario results indicate that mycoprotein production yields 23%, 98%, and 88% lower global warming, land use, and water use impacts, respectively. The demand for NRE is higher, exceeding the pork case by 107%. Overall, the scenario amplifies the differences observed in land use, water use, and non-renewable energy demand, largely in favor of mycoprotein. Notably, mycoprotein production also outperforms pork with respect to global warming impacts by 23%, representing the most pronounced improvement in the scenario.

3.7 Uncertainty evaluation

The Monte Carlo simulation of each impact category is visualized in Fig. 6 and reported in detail in Appendix A. Significance levels of all four impact categories fall below 1×10^{-3} indicating that both case studies differ from one another on a high level of confidence. Negative values for water use and global warming result from the underlying default uncertainty factors applied together with the pedigree matrix, serving as multiplicators contributing to the geometric standard deviation (Ciroth et al. 2016). The aim of this simulation is to analyze the variance of the deterministic results, especially from mycoprotein production, and to evaluate whether the associated values remain in a reasonable range.

Regarding global warming, the deterministic LCA model yields a 14% higher value for mycoprotein compared to pork production. When modeling uncertainty through the Monte Carlo simulation, however, the pork system exhibits an 18-fold higher variance (154 *versus* 8) in global warming results compared to mycoprotein. This elevated variance arises from several highly variable inventory flows within the pig production system, such as interactions related to biogas use and feed production, which received higher uncertainty factors in the pedigree matrix (see Fig. 1). These uncertainty factors propagate through the Monte Carlo sampling, resulting in a wider distribution, including some negative values. The broader distribution also causes a shift in the median impact (Fig. 6), which explains why the Monte Carlo median for pork exceeds that of mycoprotein, despite the deterministic result showing the opposite. Given the substantial uncertainty, the global warming results should therefore be regarded as inconclusive, as the relative magnitudes of the two systems cannot be reliably distinguished. The simulation results for the NRE, land and water use categories are trend-wise consistent with the LCA results and the variances of the values for both systems are comparable. For NRE, the previously gathered results surpass the IQR of the simulation results. However, the IQRs of the water use category support the LCA results, while there are some outliers that extend the scale. These outliers are influenced by the high uncertainty factors retrieved by the pedigree matrix as contemplated above, related to feed production in the pork case as well as water cooling and deionization for the mycoprotein case.

The limitations of this study are therefore outlined in the following, as addressing them can improve transferability. Foremost, the data for the mycoprotein case offers room for

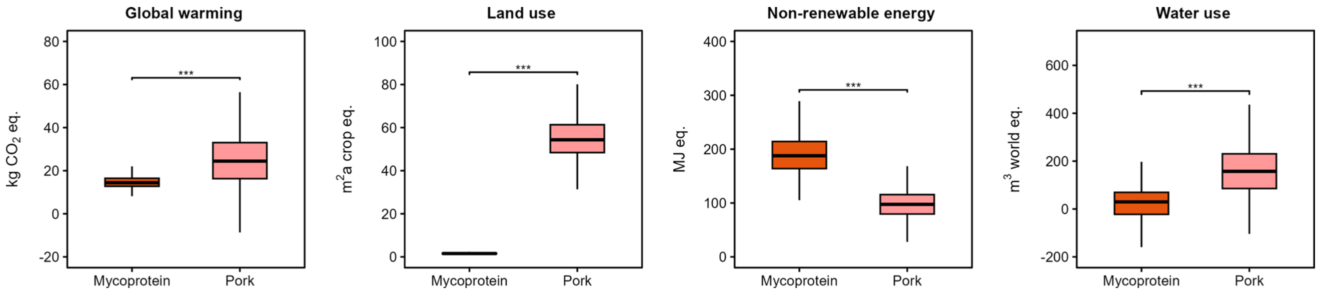


Fig. 6 Uncertainty analysis based on Monte-Carlo simulations for pork and mycoprotein. The upper and lower hinges of the boxplots span the interquartile range (IQR), with the whiskers extended to a maximum of 1.5 times the IQR in both directions. The median is displayed. Outliers are not plotted. ***, p-value < 1 × 10−3

Table 4 Comparison of this study to cradle-to-gate LCAs from literature. Pork and mycoprotein literature data originates from 36 and 12 LCA studies, respectively and is harmonized to a per kg protein basis using the conversion factors from de Vries and de Boer (2010) for pork (0.53 kg edible product/kg live weight; 0.19 kg protein/kg edible product) and Finnigan et al. (2017) for mycoprotein (0.15 kg protein/kg mycoprotein). The raw data and literature sources are available in Appendix A

Case	Impact category	Unit	Mean	Median	Sd	Min	Max	*N*	This study
Pork	Global Warming	kg CO_2-eq.	28.2	26.2	11.7	6	67	60	24.3
	Land Use	m^2	94.5	44.9	209.7	20.9	1251.2	32	55.3
	Non-Renewable Energy	MJ-eq.	157.5	144	77.2	67.5	348.6	24	130
	Water Use	m^3	111.1	0.8	279.7	0.1	859.1	15	163
Mycoprotein	Global Warming	kg CO_2-eq.	17.6	15.6	8.7	4.7	34.5	10	27.7
	Land Use	m^2	9.7	6.5	7.6	1.9	24.1	7	3.28
	Non-Renewable Energy	MJ-eq.	241.5	205	189	30	560	5	378
	Water Use	m^3	13.6	9.2	10.8	0.5	34.5	7	48.3

Sd = Standard deviation

N = Number of data points

improvement as only simulated data was available. For the calculation, it is important to keep in mind that we assess a specific pork case against a unified mycoprotein case, which leaves potential for deviations in differing cases. Additionally, for LCA applications in general, the mapping of data to match database flows must be acknowledged as a typical limitation. We address this by disclosing our modeling foundations in detail (Supplementary material: Appendix A).

3.8 Comparison with literature data

Multiple LCA studies indicate that mycoprotein production can dramatically reduce GHG emissions compared to pork. For example, Derbyshire (2020) reports a carbon footprint of only ~ 0.8 kg CO_2-eq per kg of mycoprotein, versus ~ 8.3 kg CO_2-eq per kg for pork. Similarly, a recent systematic review by Shahid et al. (2024) found mycoprotein's GHG emissions to be lower than those of plant-based proteins (0.73 kg CO_2-eq/kg for mycoprotein *versus* 1.21–1.91 for soy/pea) and lower compared to meat. Notably, even when including downstream stages, mycoprotein products may cut GHG emissions by ~ 90% relative to beef and ~ 75–95% relative to pork with the range reflecting different regions and system boundaries (Lee et al. 2025). Some studies caution that if intensive energy inputs or certain formulation ingredients are accounted for, mycoprotein's GHG emissions can approach 5.6–6.2 kg CO_2-eq/kg, in the same order as or slightly above emissions from chicken or pork production (Lee et al. 2025).

In contrast to our global warming results, the overall consensus is that mycoprotein offers significantly lower climate impacts than traditional pork, as illustrated in the literature review in Table 4. This study's pork global warming impact (24.3 kg CO_2-eq.) aligns with the central tendency metrics of literature data while the impact of mycoprotein resides 58 and 78% above the literature mean and median, respectively. This discrepancy relates to literature data from the lower end of the interval investigating more environmentally friendly sugar sources, and varying cradle-to-gate boundaries, e.g. ending with the fermentation step (Brancoli et al., 2021; Smetana et al. 2015). In addition, the Monte Carlo simulation-based uncertainty analysis places the overall GHG emission of mycoprotein production within 5% of the literature median. Such peculiarities, partial non-uniform definition of impact categories, and different sample sizes render the comparison of literature data unreliable due to contextual heterogeneity. Hence, literature values spanning one to four orders of magnitude from minimum to maximum further corroborate the motivation of this study to provide a benchmark comparison between the two value chains.

Concerning land occupation, literature comparisons strongly favor mycoprotein over conventional pork. Smetana et al. (2015) and others show that producing 1 kg of mycoprotein requires only on the order of 2 to 4 m^2 of land. In one assessment, mycoprotein had the lowest land footprint among proteins at 1.8×10^{-4} ha/kg, whereas pork was about 1.2×10^{-3} ha/kg (Derbyshire 2020). This implies an 85% to 90% reduction in land use. These results are echoed by Rubio et al. (2020), who found mycoprotein requires far less agricultural area than both chicken or pork systems. Our land use estimates for pork and mycoprotein are in close agreement with these data, corroborating that fungi-based protein can dramatically spare land. This is an important validation: as noted in one review, mycoprotein uses on order of magnitude less land compared to meat (Lee et al. 2025). Minor differences in absolute values can be attributed to geographic specifics, but overall, the order-of-magnitude gap in land footprint is consistently observed.

Most results still fall within the range of prior studies except for water use of mycoprotein displaying a new maximum. Although mycoprotein uses 3-fold less water compared to pork production, the absolute value of 48.4 m^3 is 8-fold above the reported value from an independent impact assessment of the

Quorn™ process (Finnigan et al. 2017). Disaggregation of water use contribution is similar in this study and the cited reference, with 70% of water allocated to glucose production. Thus, a systematic difference in determining water use is the most likely explanation. Indeed, this work contrasts from the presented literature data on mycoprotein by applying the AWARE 1.2 methodology for water use (Boulay et al. 2018). Another distinguishing factor is the underlying calculation and interpretation of water use, which results in divergent outcomes. Most studies either present only an inventory value or do not reflect deeply on the data collection approach. However, published LCAs unanimously conclude the water footprint of mycoprotein to be substantially lower than that of pork. Pork production can consume approximately 6 m^3 per kg (driven largely by feed crop irrigation), whereas mycoprotein needs only a few hundred liters. Our results closely match this disparity. Water use for pork is an order of magnitude higher than for the fungal protein, which aligns with literature values in both magnitude and ratio. Rubio et al. (2020) similarly observed that the water requirement of mycoprotein production is below that of even plant-based protein and far below livestock benchmarks. Some scenarios (e.g. using cellulosic feedstock) could increase the process water demand of MP production in general, but even a worst-case estimate found its water use would only approach that of beef, and beef is considerably more water-intensive than pork (Lee et al. 2025).

One area where mycoprotein can show a trade-off is energy demand. It is the category where bioreactor-derived food production performs significantly worse than animal systems. The fermentation process is energy-intensive, which several studies note can somewhat offset its other environmental gains (Rubio et al. 2020; Smetana et al. 2015). Strikingly, the difference in non-renewable energy demand of mycoprotein production in this study is twice as high as the central tendency of previous reports suggest. The pork value chain is credited with 85 MJ equivalent from anaerobic digestion during the fattening process (Fig. 3), widening the gap between both protein production methods compared to literature. Yet, this discrepancy is also an indicator for the contrasting development stage of both value chains as exemplarily evidenced in the sensitivity analysis of this work regarding the optimization of primary substrates. In addition, it is worth noting that if low-impact carbon sources are used, the climate impact resulting from a higher energy demand can be mitigated, as evidenced by the low global warming figures cited above for mycoprotein facilities making the shift to molasses. For instance, replacing glucose syrup with molasses in our LCA model reduces the assessed impact categories. This reinforces the interpretation that while fungal protein uses more non-renewable energy, it still yields net environmental benefits when considering the full impact profile.

Taken together, the central tendencies apparent from the current literature are mostly confirmed by this study. However, the absolute differences between the investigated value chains, with a dedicated focus on the current state-of-the-art, vary substantially underpinning the importance of context-dependent comparative LCA.

4 Conclusion

The comparative LCA of pork and mycoprotein production systems reveals critical insights into their environmental profiles, addressing the urgent need for informed decision-making regarding rising global protein demand, sustainable use of (agricultural) land, and supply chain pressure from climate change. Our analysis demonstrates that the current state of mycoprotein production already offers significant environmental advantages over pork in land use and water use, with reductions of approximately 94% and 70%, respectively. These benefits stem from the balanced bioreactor system's increased efficiency regarding agricultural inputs compared to the extensive feed requirements for pork. Yet, mycoprotein exhibits a slightly higher global warming potential and a substantially elevated energy demand—nearly three times that of pork—driven by glucose syrup production and the energy-intensive medium preparation and fermentation processes. This might offer further research potential for improvement. The pork value chain, while resource-intensive, benefits from biogas credits, which partially offset its environmental footprint, particularly in global warming and energy demand categories.

The Monte Carlo simulation confirms the robustness of each system's absolute LCA result when assessed separately, although it does not support the deterministic ranking between them within the global warming category. The low variance observed for mycoprotein reflects the high data quality of its process-based inventory, whereas the greater variability in pork impacts arises from complex agricultural interactions. These outcomes align with the literature's central tendencies but highlight contextual discrepancies, such as elevated water use for mycoprotein when assessed with the AWARE 1.2 methodology. This study establishes a benchmark for comparing animal and microbial protein value chains, emphasizing the trade-offs between resource efficiency and energy demand. Future innovations in microbial protein production, such as transitioning to low-impact feedstocks, could further enhance its environmental sustainability, while optimizations in pork production may face diminishing returns due to its mature industrial state. Ultimately, this comparative LCA underscores the potential of microbial proteins to reshape sustainable food systems, and addressing energy-related challenges could further align production with United Nations SDGs 6 ('Clean Water and Sanitation') and 15 ('Life on Land') through informed policy and industry strategies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11367-026-02637-w.

Acknowledgements The authors acknowledge the German Federal Ministry of Food and Agriculture (BMEL) for funding this work, which is embedded in the project SPECK (Systemic optimization of the meat value chain using pig farming as an example through the development and embedding of digital tools), grant number 281A502B19. Additional funding was received from the Helmholtz Association via the research program "Materials Systems Engineering", topic "Adaptive and Bioinstructive Materials Systems" (grant number 43.33.11) and the KIT via strategy funding (grant number FE.5207.0014.0800).

Author contribution Nina Treml: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. Steven Minden: Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation, Supervision. Alexander Grünberger: Writing – review & editing. Rebekka Volk: Writing – review & editing. Andreas Rudi: Writing – review & editing. Frank Schultmann: Writing – review & editing, Funding acquisition. Anne-Kristin Kaster: Writing – review & editing. Funding acquisition.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data availability Data will be made available on request.

Declarations

Generative AI and AI-assisted technologies in the writing process During the preparation of this work the authors used DeepL in order to mitigate grammatical errors and improve language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Competing interest The authors declare no competing interests.

References

ADEME (2023) Agribalyse Database (Version 3.1) (Datenbank). ADEME (Agence de la transition écologique), Angers, France

Mendoza Beltran A, Prado V, Vivanco F, Henriksson D, Guinée PJG, Heijungs JB, R (2018) Be Concluded? Environ Sci Technol 52:2152–2161. https://doi.org/10.1021/acs.est.7b06365. Quantified Uncertainties in Comparative Life Cycle Assessment: What Can

Bakman T, Hoffmann BS, Portugal-Pereira J (2024) A recipe for change: Analyzing the climate and ecosystem impacts of the Brazilian diet shift. Sci Total Environ 930:172568. https://doi.org/10.1016/j.scitotenv.2024.172568

Boulay A-M, Bare J, Benini L, Berger M, Lathuillière MJ, Manzardo A, Margni M, Motoshita M, Núñez M, Pastor AV, Ridoutt B, Oki T, Worbe S, Pfister S (2018) The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int J Life Cycle Assess 23:368–378. https://doi.org/10.1007/s11367-017-1333-8

Brancoli P, Gmoser R, Taherzadeh MJ, Bolton, K (2021) The use of life cycle assessment in the support of the development of fungal food products from surplus bread. Fermentation 7(3):173. https://doi.org/10.3390/fermentation7030173

Cellura M, Cusenza MA, Longo S, Luu LQ, Skurk T (2022) Life Cycle Environmental Impacts and Health Effects of Protein-Rich Food as Meat Alternatives: A Review. Sustain 14:979. https://doi.org/10.3390/su14020979

Cherubini E, Zanghelini GM, Alvarenga RAF, Franco D, Soares SR (2015) Life cycle assessment of swine production in Brazil: a comparison of four manure management systems. J Clean Prod 87:68–77. https://doi.org/10.1016/j.jclepro.2014.10.035

Choi KR, Yu HE, Lee SY (2022) Microbial food: microorganisms repurposed for our food. Microb Biotechnol 15:18–25. https://doi.org/10.1111/1751-7915.13911

Ciroth A, Muller S, Weidema B, Lesage P (2016) Empirically based uncertainty factors for the pedigree matrix in ecoinvent. Int J Life Cycle Assess 21:1338–1348. https://doi.org/10.1007/s11367-013-0670-5

Crippa M, Solazzo E, Guizzardi D, Monforti-Ferrario F, Tubiello FN, Leip A (2021) Food systems are responsible for a third of global anthropogenic GHG emissions. Nat Food 2:198–209. https://doi.org/10.1038/s43016-021-00225-9

Da Gama Ferreira R, Misailidis N, Demetri Petrides (2023) Meat-like fungi protein (Mycoprotein) production via fermentation – process modeling and Techno-Economic Assessment (TEA) using SuperPro designer. https://doi.org/10.13140/RG.2.2.24718.13127

Derbyshire E.J. (2020) Is There Scope for a Novel Mycelium Category of Proteins alongside Animals and Plants? Foods 9:1151. https://doi.org/10.3390/foods9091151

Detzel A, Krüger M, Busch M, Blanco-Gutiérrez I, Varela C, Manners R, Bez J, Zannini E (2022) Life cycle assessment of animal-based foods and plant-based protein-rich alternatives: an environmental perspective. J Sci Food Agric 102:5098–5110. https://doi.org/10.1002/jsfa.11417

De Vries M, De Boer IJM (2010) Comparing environmental impacts for livestock products: A review of life cycle assessments. Livest Sci 128:1–11. https://doi.org/10.1016/j.livsci.2009.11.007

Dourmad J-Y, Nassy G, Salaün Y, Riquet J, Lebret B (2015) Estimation des pertes alimentaires dans la filière porcine entre la sortie de l'élevage et la commercialisation des produits. Innov Agron 48:115–125. https://doi.org/10.15454/1.4622710500090479E12

Ecoinvent Association (2023) Ecoinvent Database (Version 3.9.1) (Datenbank). Ecoinvent Association, Zurich, Switzerland

FAO, FAO Regional Statistical Yearbooks [WWW Document] (2023) Global Statistical Yearbook,. FAOSTAT. URL https://www.fao.org/faostat/en/#data/QCL/visualize (accessed 3.11.24)

Federal Statistical Office of Germany (2024) Holdings with pigs: Germany, reference month, pig categories. URL https://www-genes is.destatis.de/datenbank/online/table/41313-0001/search/s/NDEzMTMtMDAwMQ== (accessed 17.04.25)

Finnigan TJA, Theobald HE, Bajka B (2024) Mycoprotein: A Healthy and Sustainable Source of Alternative Protein-Based Foods. Annu Rev Food Sci Technol. https://doi.org/10.1146/annurev-food-111523-121802

Finnigan T, Needham L, Abbott C (2017) Mycoprotein. Sustainable Protein Sources. Elsevier, pp 305–325. https://doi.org/10.1016/B978-0-12-802778-3.00019-6

Fletcher AJ, Smith NW, Hill JP, McNabb WC (2024) Modeling the feasibility of fermentation-produced protein at a globally relevant scale. Front Sustain Food Syst 8:1419259. https://doi.org/10.3389/fsufs.2024.1419259

Gislason S, Birkved M, Maresca A (2023) A systematic literature review of life cycle assessments on primary pig production: Impacts, comparisons, and mitigation areas. Sustain Prod Consum 42:44–62. https://doi.org/10.1016/j.spc.2023.09.005

Halpern BS, Frazier M, Verstaen J, Rayner P-E, Clawson G, Blanchard JL, Cottrell RS, Froehlich HE, Gephart JA, Jacobsen NS, Kuempel CD, McIntyre PB, Metian M, Moran D, Nash KL, Többen J, Williams DR (2022) The environmental footprint of global food production. Nat Sustain 5:1027–1039. https://doi.org/10.1038/s41893-022-00965-x

Hartmann C, Furtwaengler P, Siegrist M (2022) Consumers' evaluation of the environmental friendliness, healthiness and naturalness of meat, meat substitutes, and other protein-rich foods. Food Qual Prefer 97:104486. https://doi.org/10.1016/j.foodqual.2021.104486

Hong C, Zhong R, Xu M, He P, Mo H, Qin Y, Shi D, Chen X, He K, Zhang Q (2025) Interactions Among Food Systems, Climate Change, and Air Pollution. Rev Eng 44:215–233. https://doi.org/10.1016/j.eng.2024.12.021

Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M, Zijp M, Hollander A, van Zelm R (2017) ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess 22:138–147. https://doi.org/10.1007/s11367-016-1246-y

ISN (2024) ISN-Schlachthofranking 2023: Konsolidierung in der Schlachtbranche setzt sich fort [WWW Document]. Interessengemeinschaft der Schweinehalter Deutschlands e V. URL https://www.schweine.net/news/isn-schlachthofranking-2023-konsolidierung-setzt.html (accessed 5.13.25)

ISO (2009) ISO 14040 Standard

ISO (2018) ISO 14044 Standard

Järviö N, Maljanen N-L, Kobayashi Y, Ryynänen T, Tuomisto HL (2021a) An attributional life cycle assessment of microbial protein production: A case study on using hydrogen-oxidizing bacteria. Sci Total Environ 776:145764. https://doi.org/10.1016/j.scitotenv.2021.145764

Järviö N, Parviainen T, Maljanen N-L, Kobayashi Y, Kujanpää L, Ercili-Cura D, Landowski CP, Ryynänen T, Nordlund E, Tuomisto HL (2021b) Ovalbumin production using Trichoderma reesei culture and low-carbon energy could mitigate the environmental impacts of chicken-egg-derived ovalbumin. Nat Food 2:1005–1013. https://doi.org/10.1038/s43016-021-00418-2

Kobayashi Y, EL-Wali M, Guðmundsson H, Guðmundsdóttir EE, Friðjónsson ÓH, Karlsson EN, Roitto M, Tuomisto HL (2023) Life-cycle assessment of yeast-based single-cell protein production with oat processing side-stream. Sci Total Environ 873:162318. https://doi.org/10.1016/j.scitotenv.2023.162318

Reckmann K, Traulsen I, Krieter J (2013) Ger Livest Sci 157:586–596. https://doi.org/10.1016/j.livsci.2013.09.001. Life Cycle Assessment of pork production: A data inventory for the case of

Kyttä V, Ghani HU, Pellinen T, Kårlund A, Kolehmainen M, Pajari A-M, Tuomisto HL, Saarinen M (2025) Integrating nutrition into environmental impact assessments reveals limited sustainable food options within planetary boundaries. Sustain Prod Consum 56:142–155. https://doi.org/10.1016/j.spc.2025.03.018

Laisse S, Baumont R, Dusart L, Gaudré D, Rouillé B, Benoit M, Veysset P, Rémond D, Peyraud J-L (2018) L'efficience nette de conversion des aliments par les animaux d'élevage: une nouvelle approche pour évaluer la contribution de l'élevage à l'alimentation humaine. INRA Prod Anim 31:269–288. https://doi.org/10.20870/productions-animales.2018.31.3.2355

Lee DY, Mariano E, Choi Y, Park JM, Han D, Kim JS, Park JW, Namkung S, Li Q, Li X, Venter C, Hur SJ (2025) Environmental Impact of Meat Protein Substitutes: A Mini-Review. Food Sci Anim Resour 45:62–80. https://doi.org/10.5851/kosfa.2024.e109

Matassa S, Boon N, Pikaar I, Verstraete W (2016) Microbial protein: future sustainable food supply route with low environmental footprint. Microb Biotechnol 9:568–575. https://doi.org/10.1111/1751-7915.12369

Mazac R, Järviö N, Tuomisto HL (2023) Environmental and nutritional Life Cycle Assessment of novel foods in meals as transformative food for the future. Sci Total Environ 876:162796. https://doi.org/10.1016/j.scitotenv.2023.162796

McAuliffe GA, Takahashi T, Mogensen L, Hermansen JE, Sage CL, Chapman DV, Lee MRF (2017) Environmental trade-offs of pig production systems under varied operational efficiencies. J Clean Prod 165:1163–1173. https://doi.org/10.1016/j.jclepro.2017.07.191

Heller MC, Keoleian GA, Willett WC (2013) Rev Environ Sci Technol 47:12632–12647. https://doi.org/10.1021/es4025113. Toward a Life Cycle-Based, Diet-level Framework for Food Environmental Impact and Nutritional Quality Assessment: A Critical

Meyer V, Basenko EY, Benz JP, Braus GH, Caddick MX, Csukai M, de Vries RP, Endy D, Frisvad JC, Gunde-Cimerman N, Haarmann T, Hadar Y, Hansen K, Johnson RI, Keller NP, Kraševec N, Mortensen UH, Perez R, Ram AFJ, Record E, Ross P, Shapaval V, Steiniger C, van den Brink H, van Munster J, Yarden O, Wösten HAB (2020) Growing a circular economy with fungal biotechnology: a white paper. Fungal Biol Biotechnol 7:5. https://doi.org/10.1186/s40694-020-00095-z

Minden S, Grünberger A, Van Der Schaaf U, Neumann A, Rösch C, Sauer J, Kaster A-K (2024) Producing food from CO2 using microorganisms: Lots to do, little to lose! Trends Food Sci Technol 154:104778. https://doi.org/10.1016/j.tifs.2024.104778

Mogensen L, Heusale H, Sinkko T, Poutanen K, Sözer N, Hermansen JE, Knudsen MT (2020) Potential to reduce GHG emissions and land use by substituting animal-based proteins by foods containing oat protein concentrate. J Clean Prod 274:122914. https://doi.org/10.1016/j.jclepro.2020.122914

Nevalainen H (ed) (2020) Grand Challenges in Fungal Biotechnology, Grand Challenges in Biology and Biotechnology. Springer International Publishing, Cham. https://doi.org/10.1007/978-3-030-29541-7

Nguyen TLT, Hermansen JE, Mogensen L (2011) Environmental assessment of danish pork

Nijdam D, Rood T, Westhoek H (2012) The price of protein: Review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37:760–770. https://doi.org/10.1016/j.foodpol.2012.08.002

Noorman H (2023) Net zero carbon protein: The cornerstone of a sustainable food system [WWW Document]. dsm-firmenich. URL https://www.dsm-firmenich.com/anh/news/feed-talks/articles/net-zero-carbon-protein.html (accessed 4.17.25)

Pereira A, Delmoitié B, Sakarika M (2024) Understanding the Potential of Microbial Protein as a more Sustainable Food Source. Food Sci Nutr Cases 2024(fsncases20240008). https://doi.org/10.1079/fsncases.2024.0008

Pikaar I, Matassa S, Bodirsky BL, Weindl I, Humpenöder F, Rabaey K, Boon N, Bruschi M, Yuan Z, van Zanten H, Herrero M, Verstraete

W, Popp A (2018) Decoupling Livestock from Land Use through Industrial Feed Production Pathways. Environ Sci Technol 52:7351–7359. https://doi.org/10.1021/acs.est.8b00216

Röder H, Kumar K, Füchsl S, Sieber V (2022) Ex-ante life cycle assessment and scale up: A protein production case study. J Clean Prod 376:134329. https://doi.org/10.1016/j.jclepro.2022.134329

Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF, Drüke M, Fetzer I, Bala G, von Bloh W, Feulner G, Fiedler S, Gerten D, Gleeson T, Hofmann M, Huiskamp W, Kummu M, Mohan C, Nogués-Bravo D, Petri S, Porkka M, Rahmstorf S, Schaphoff S, Thonicke K, Tobian A, Virkki V, Wang-Erlandsson L, Weber L, Rockström J (2023) Earth beyond six of nine planetary boundaries. Sci Adv 9:eadh2458. https://doi.org/10.1126/sciadv.adh2458

Risner D, McDonald KA, Jones C, Spang ES (2023) A techno-economic model of mycoprotein production: achieving price parity with beef protein. Front Sustain Food Syst 7. https://doi.org/10.3389/fsufs.2023.1204307

Roßmann M, Stratmann M, Rötzer N, Schäfer P, Schmidt M (2021) Comparability of LCAs — Review and Discussion of the Application Purpose. In: Albrecht S, Fischer M, Leistner P, Schebek L (eds) Progress in Life Cycle Assessment 2019. Springer International Publishing, Cham, pp 213–225. https://doi.org/10.1007/978-3-030-50519-6_15

Rubio NR, Xiang N, Kaplan DL (2020) Plant-based and cell-based approaches to meat production. Nat Commun 11:6276. https://doi.org/10.1038/s41467-020-20061-y

Scheelbeek P.F.D., Bird F.A., Tuomisto H.L., Green R., Harris F.B., Joy E.J.M., Chalabi Z., Allen E., Haines A., Dangour A.D. (2018) Effect of environmental changes on vegetable and legume yields and nutritional quality. Proc Natl Acad Sci 115:6804–6809. https://doi.org/10.1073/pnas.1800442115

Schinckel AP, Wagner JR, Forrest JC, Einstein ME (2001) Evaluation of alternative measures of pork carcass composition. J Anim Sci 79:1093. https://doi.org/10.2527/2001.7951093x

Shahid M, Shah P, Mach K, Rodgers-Hunt B, Finnigan T, Frost G, Neal B, Hadjikakou M (2024) The environmental impact of mycoprotein-based meat alternatives compared to plant-based meat alternatives: A systematic review. Future Foods 10:100410. https://doi.org/10.1016/j.fufo.2024.100410

Shepon A, Eshel G, Noor E, Milo R (2016) Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. Environ Res Lett 11:105002. https://doi.org/10.1088/1748-9326/11/10/105002

Shrivastava S, Gudjónsdóttir M, Thorkelsson G, Ögmundarson Ó (2025) Shifting units, shifting views: how product mass and protein content influence environmental impact of Icelandic lamb. Int J Life Cycle Assess 30:491–510. https://doi.org/10.1007/s11367-024-02411-w

Sillman J, Uusitalo V, Ruuskanen V, Ojala L, Kahiluoto H, Soukka R, Ahola J (2020) A life cycle environmental sustainability analysis of microbial protein production via power-to-food approaches. Int J Life Cycle Assess 25:2190–2203. https://doi.org/10.1007/s11367-020-01771-3

Sinkko T, Sanyé-Mengual E, Corrado S, Giuntoli J, Sala S (2023) The EU Bioeconomy Footprint: Using life cycle assessment to monitor environmental impacts of the EU Bioeconomy. Sustain Prod Consum 37:169–179. https://doi.org/10.1016/j.spc.2023.02.015

Smetana S, Mathys A, Knoch A, Heinz V (2015) Meat alternatives: life cycle assessment of most known meat substitutes. Int J Life Cycle Assess 20:1254–1267. https://doi.org/10.1007/s11367-015-0931-6

Smetana S, Profeta A, Voigt R, Kircher C, Heinz V (2021) Meat substitution in burgers: nutritional scoring, sensorial testing, and Life Cycle Assessment. Future Foods 4:100042. https://doi.org/10.1016/j.fufo.2021.100042

Smetana S, Ristic D, Pleissner D, Tuomisto HL, Parniakov O, Heinz V (2023) Meat substitutes: Resource demands and environmental footprints. Resour Conserv Recycl 190:106831. https://doi.org/10.1016/j.resconrec.2022.106831

Sonesson U, Davis J, Flysjö A, Gustavsson J, Witthöft C (2017) Protein quality as functional unit – A methodological framework for inclusion in life cycle assessment of food. J Clean Prod 140:470–478. https://doi.org/10.1016/j.jclepro.2016.06.115

Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky BL, Lassaletta L, de Vries W, Vermeulen SJ, Herrero M, Carlson KM, Jonell M, Troell M, DeClerck F, Gordon LJ, Zurayk R, Scarborough P, Rayner M, Loken B, Fanzo J, Godfray HCJ, Tilman D, Rockström J, Willett W (2018) Options for keeping the food system within environmental limits. Nat 562:519–525. https://doi.org/10.1038/s41586-018-0594-0

Stephan R (2020) Vion: Tierbestände gehen spürbar zurück. Bauernzeitung URL https://www.bauernzeitung.de/news/vion-tierbestaende-gehen-spuerbar-zurueck/ (accessed 5.15.25).

Sturme M, van der Berg JP, Kleter G (2025) Precision fermentation. FAO, Rome, Italy. https://doi.org/10.4060/cd4448en

Synonym Biotechnologies (2023) State of Global Fermentation Capacity. Ind Biotechnol 19:62–68. https://doi.org/10.1089/ind.2023.29304.syn

Tigchelaar M, Battisti DS, Naylor RL, Ray DK (2018) Future warming increases probability of globally synchronized maize production shocks. Proc Natl Acad Sci 115:6644–6649. https://doi.org/10.1073/pnas.1718031115

Treml N, Rudi A, Schultmann F (2025) Evaluating environmental impacts of pork production: a life cycle assessment of seven case studies in Germany. J Clean Prod 145408. https://doi.org/10.1016/j.jclepro.2025.145408

Trinci APJ (1992) Myco-protein: A twenty-year overnight success story. Mycol Res 96:1–13. https://doi.org/10.1016/S0953-7562(09)80989-1

Tubb C, Seba T. (2019) Rethinking food and agriculture 2020-2030: the second domestication of plants and animals, the disruption of the cow, and the collapse of industrial livestock farming. RethinkX. https://doi.org/10.61322/IJIP9096

Tubiello FN, Karl K, Flammini A, Gütschow J, Obli-Laryea G, Conchedda G, Pan X, Qi SY, Halldórudóttir Heiðarsdóttir H, Wanner N, Quadrelli R, Souza R, Benoit L, Hayek P, Sandalow M, Mencos Contreras D, Rosenzweig E, Moncayo CR, Conforti J, Torero P, M (2022) Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. Earth Syst Sci Data 14:1795–1809. https://doi.org/10.5194/essd-14-1795-2022

Upcraft T, Tu W-C, Johnson R, Finnigan T, Hung NV, Hallett J, Guo M (2021) Protein from renewable resources: mycoprotein production from agricultural residues. Green Chem 23:5150–5165. https://doi.org/10.1039/D1GC01021B

Whittaker JA (2022) Sugar, Soil and Sequencing: Studies in Fusarium venenatum (Doctor of Philosophy). University of Nottingham

World Economic Forum (2019) Alternative Proteins. W.E.Forum. The Future Series, Meat

Ye C, Mu D, Horowitz N, Xue Z, Chen J, Xue M, Zhou Y, Klutts M, Zhou W (2018) Life cycle assessment of industrial scale production of spirulina tablets. Algal Res 34:154–163. https://doi.org/10.1016/j.algal.2018.07.013

Yu Y, Li Q, Bao Y, Fu E, Chen Y, Ni T (2024) Research on the Measurement and Influencing Factors of Carbon Emissions in the Swine Industry from the Perspective of the Industry Chain. Sustain 16:2199. https://doi.org/10.3390/su16052199