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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

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

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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.

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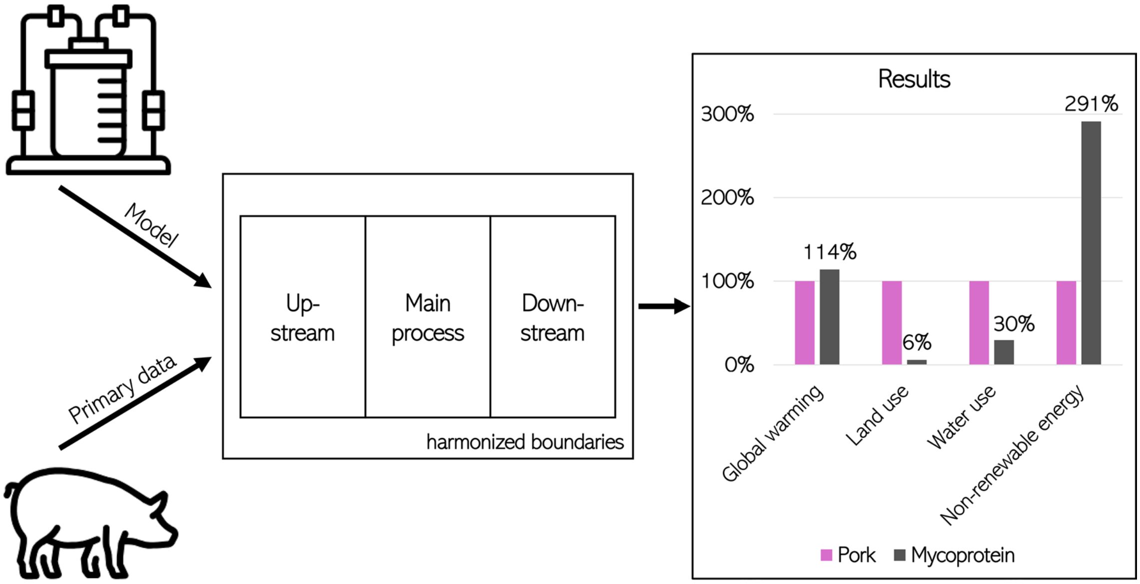
Graphical Abstract



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.

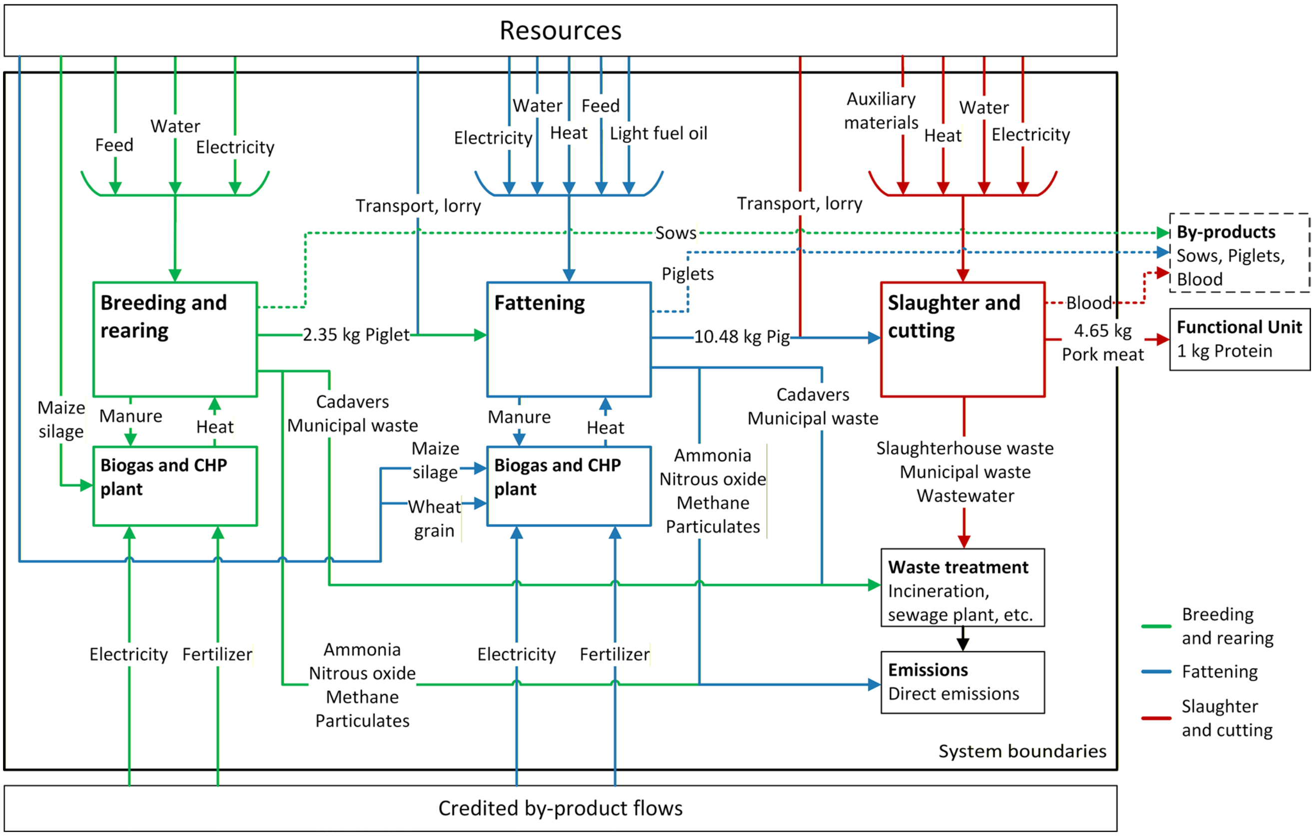


Fig. 1 System boundaries for the pork meat production encompassing the breeding and rearing farm, the fattening farm and the slaughter facility. Each facility exists as modeled. The functional unit is defined as 1 kg of protein. Reference flows for production correspond to the total input mass required 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.

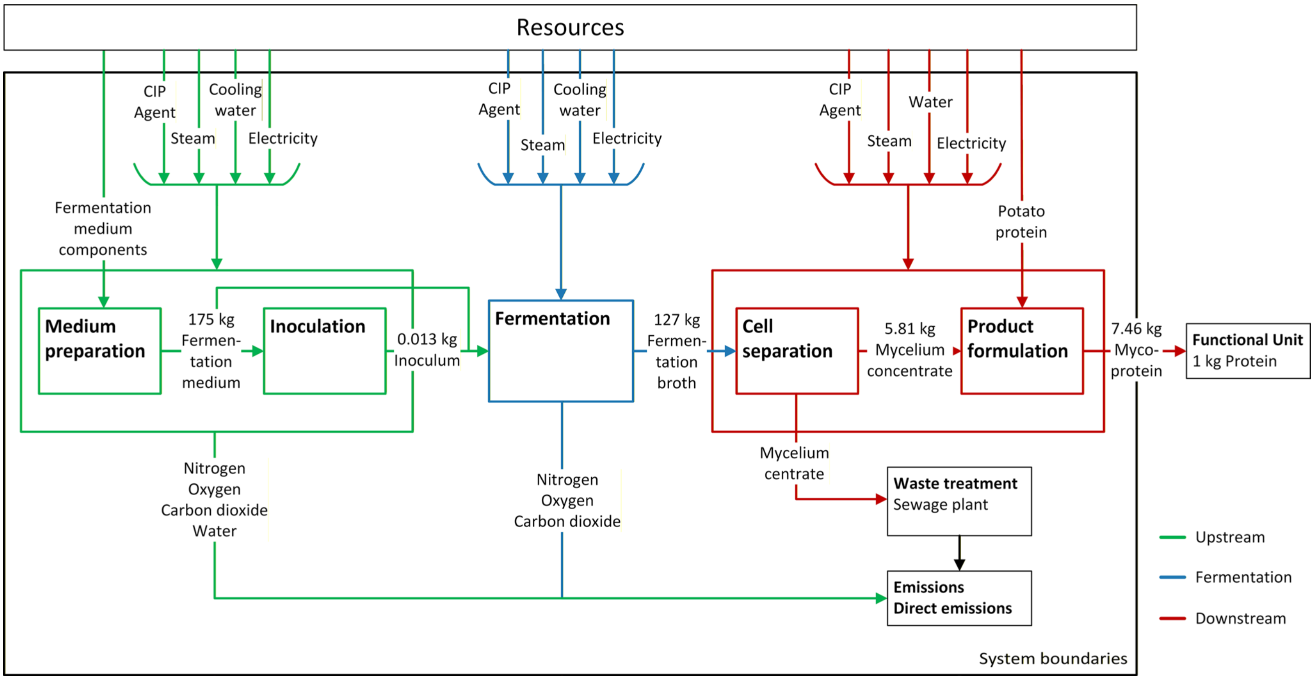


Fig. 2 System boundaries for the modeled mycoprotein production and the distinct production steps based on literature data. Reference flows for production correspond to the total input mass required to obtain this FU. The colors indicate the affiliation of the process in- and outputs to the different 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

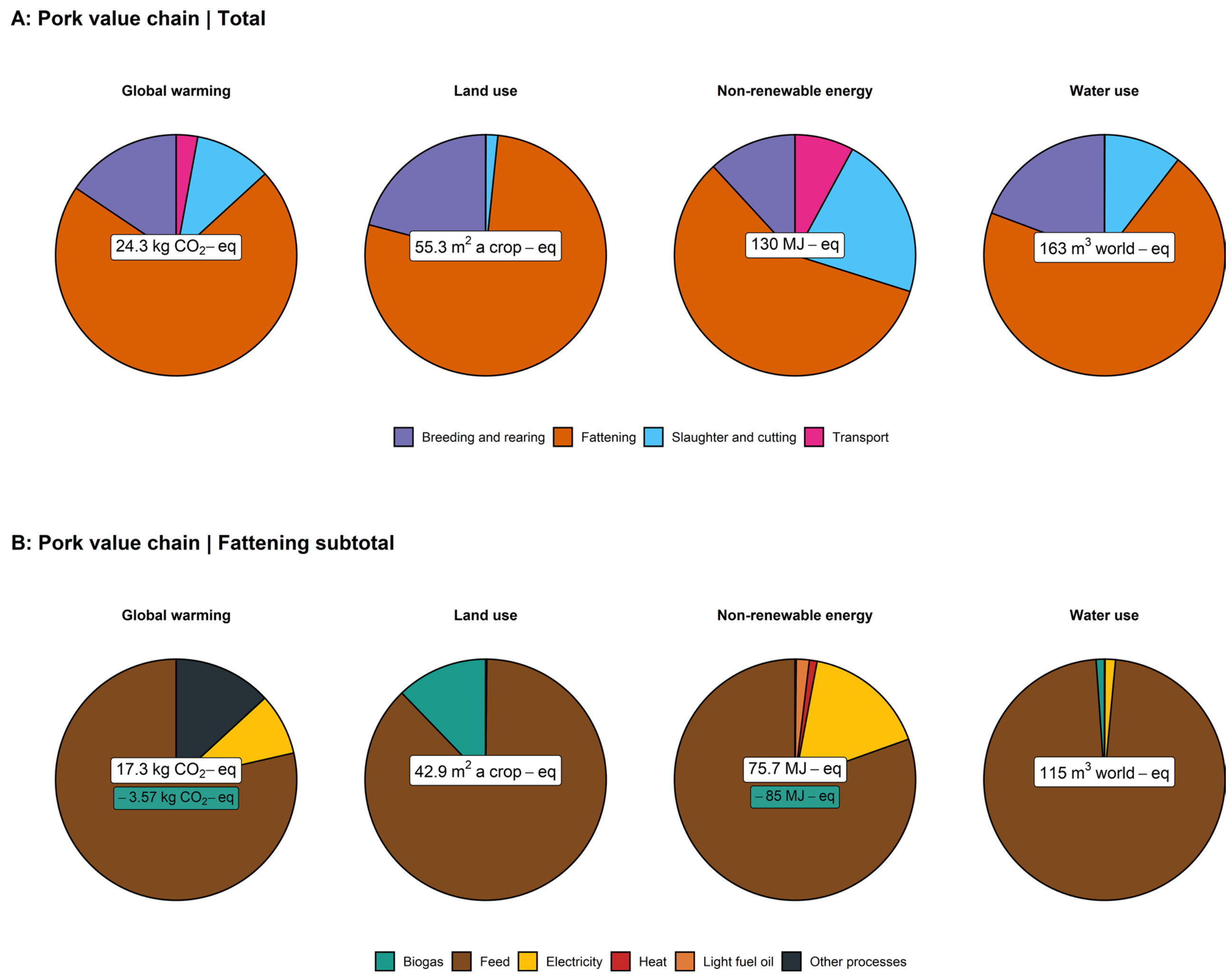


Fig. 3 Environmental impact assessment of pork meat production. (**A**) shows percentages of impact allocations per process with the sum as an absolute value label tag in the center of each pie chart. (**B**) disaggregates the most impactful process "fattening" into its sub-processes with negative values 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

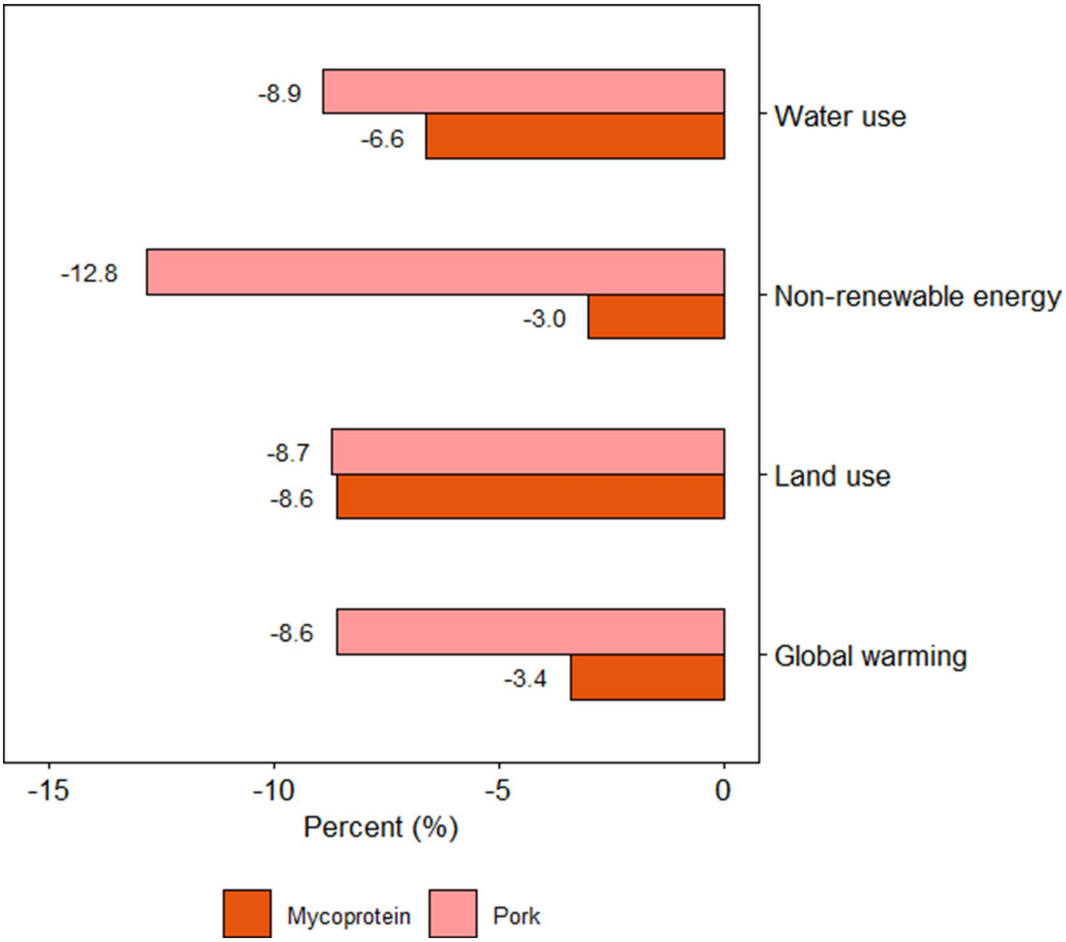


Fig. 5 Sensitivity analysis results of the four impact categories representing calculations with 10% reduced feed and glucose input for the pork and mycoprotein case, respectively

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

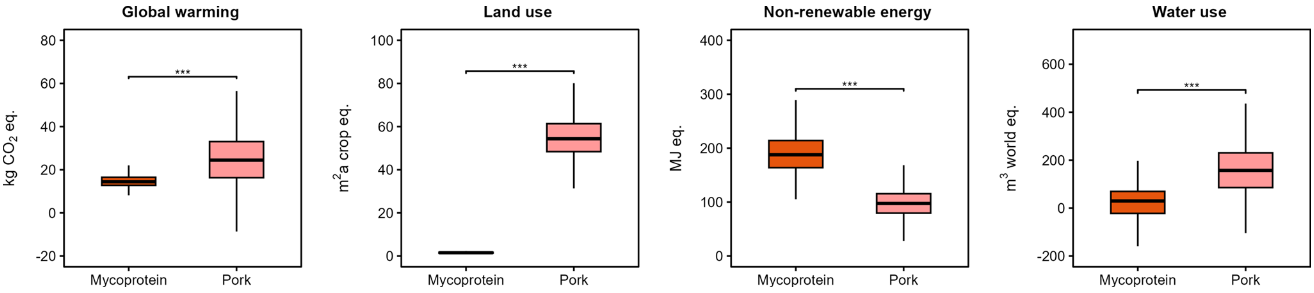


Fig. 6 Uncertainty analysis based on Monte-Carlo simulations for pork and mycoprotein. The upper and lower hinges of the boxplots span the interquartile range (IQR), with the whiskers extended to a maximum of 1.5 times the IQR in both directions. The median is displayed. Outliers are not plotted. ***,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

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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.

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