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# 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*

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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).

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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

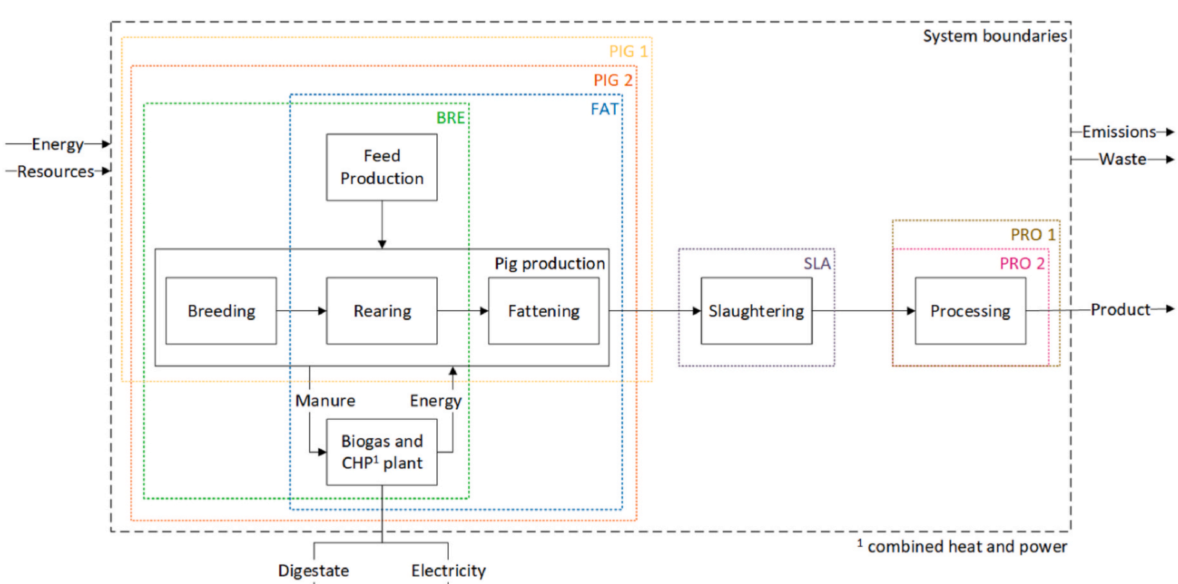


**Fig. 1.** System boundaries for the considered case studies aligned with the supply chain.

**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

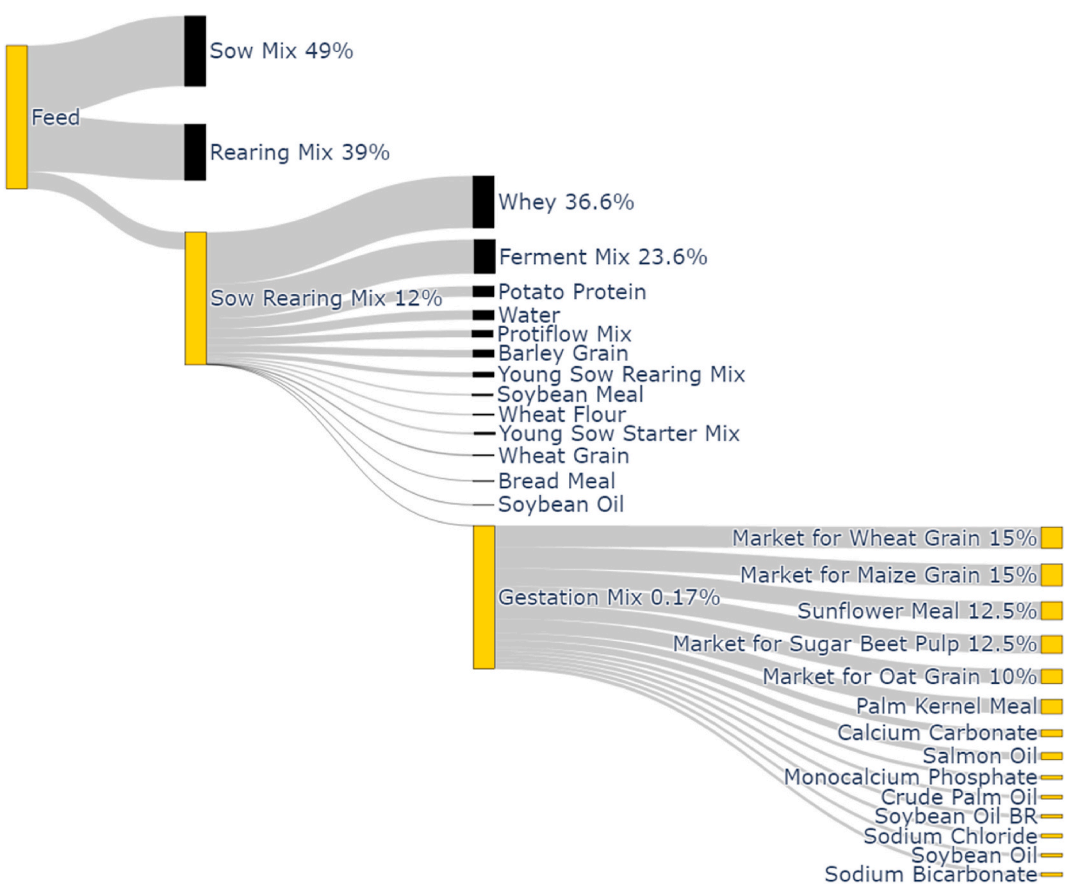


**Fig. 2.** The Sankey diagram quantitatively visualises the disaggregation of the feed composition of the BRE case study, broken down from mixtures and components to ingredients for the specific feed mix *Gestation Mix*.

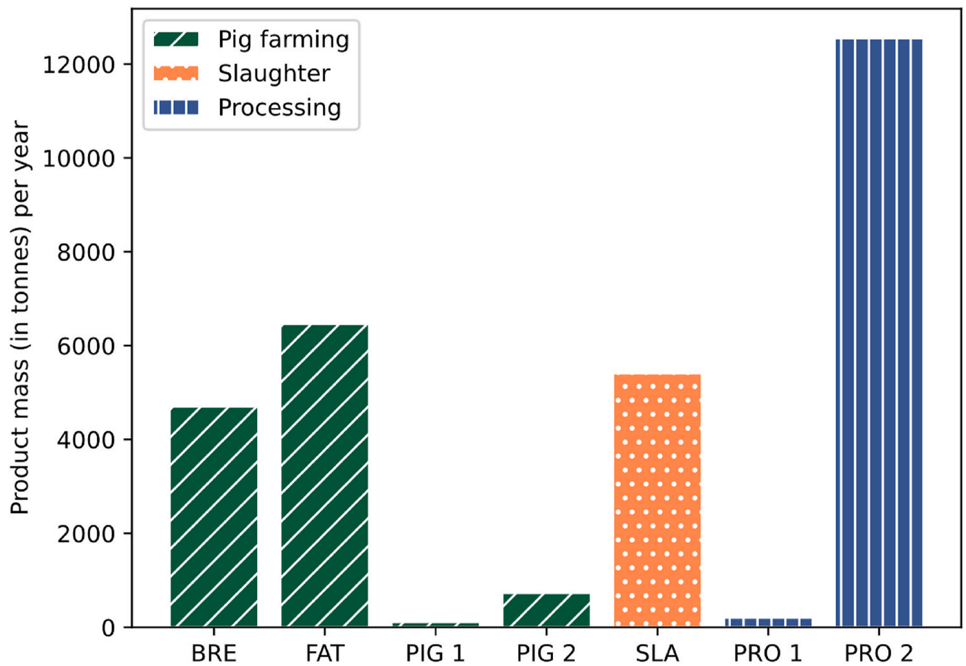


**Fig. 3.** Product masses in tonnes per year and case study.

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.

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 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 |

**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.

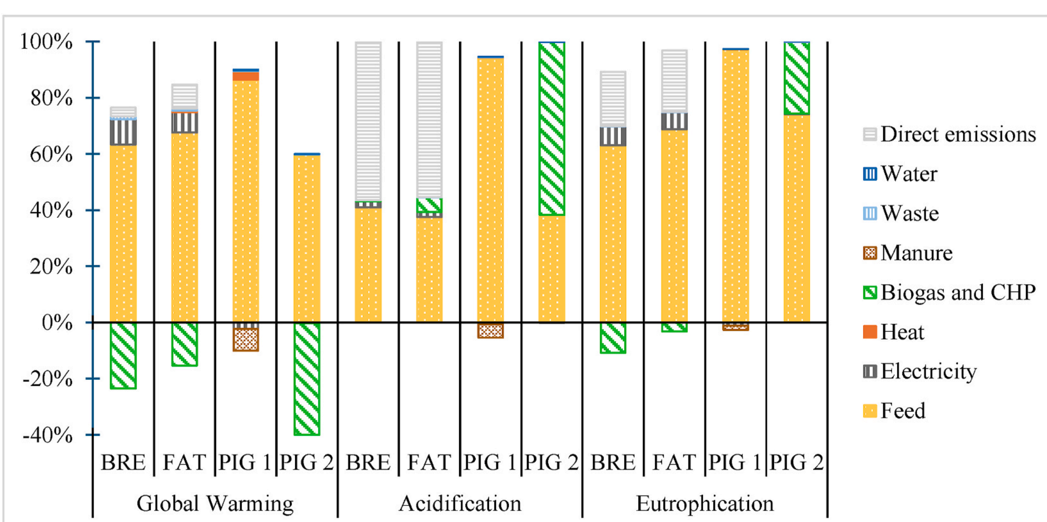


**Fig. 4.** Environmental impacts per process for the four pig production case studies expressed as relative percentages per impact category.

**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.

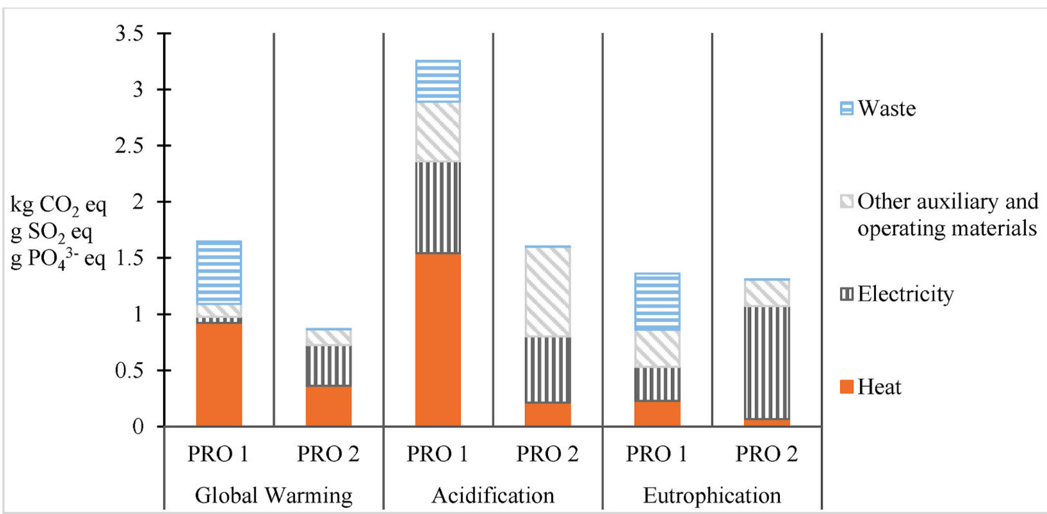


**Fig. 5.** Environmental impacts per processing case study parted by impact categories and processes.

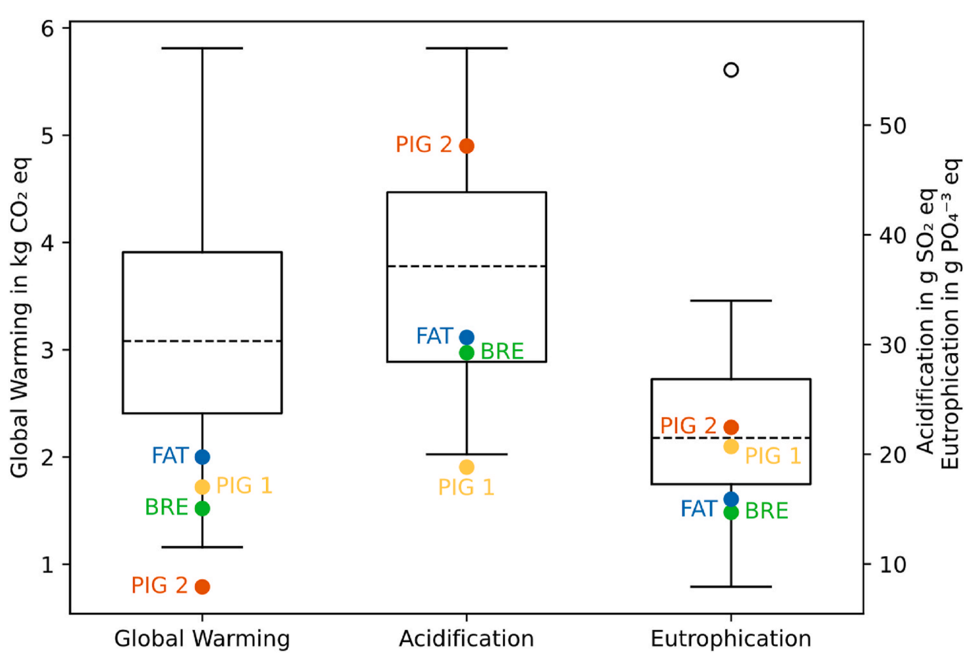


**Fig. 6.** Results of the presented case studies (coloured dots) in comparison with those of 22 scenarios from nine comparable studies, displayed in a boxplot with dotted lines indicating the medians for each category.

### 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

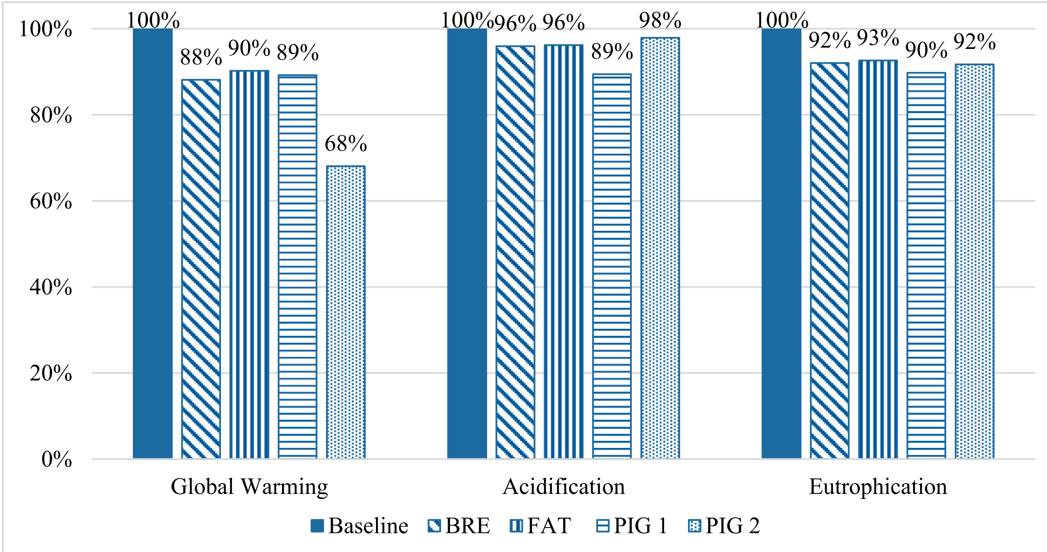


**Fig. 7.** Comparative environmental results considering −10 % less feed consumption for every case study.

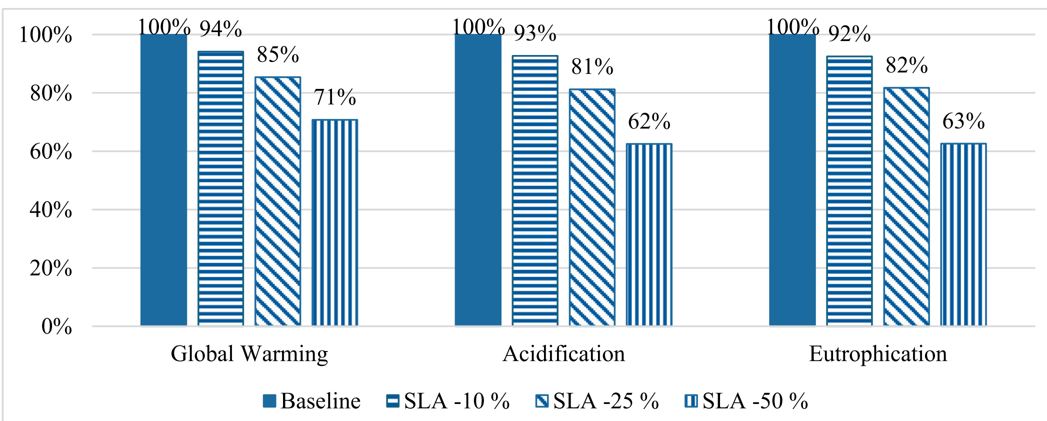


**Fig. 8.** Comparative environmental results considering −10 % to −50 % less slaughterhouse waste for SLA.

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.

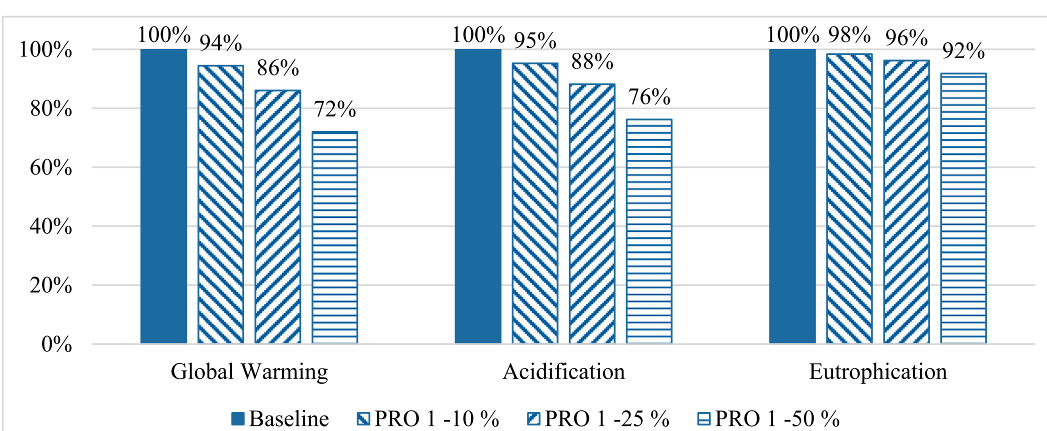


**Fig. 9.** Comparative environmental results considering −10 % to −50 % less heat heating for PRO 1.

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

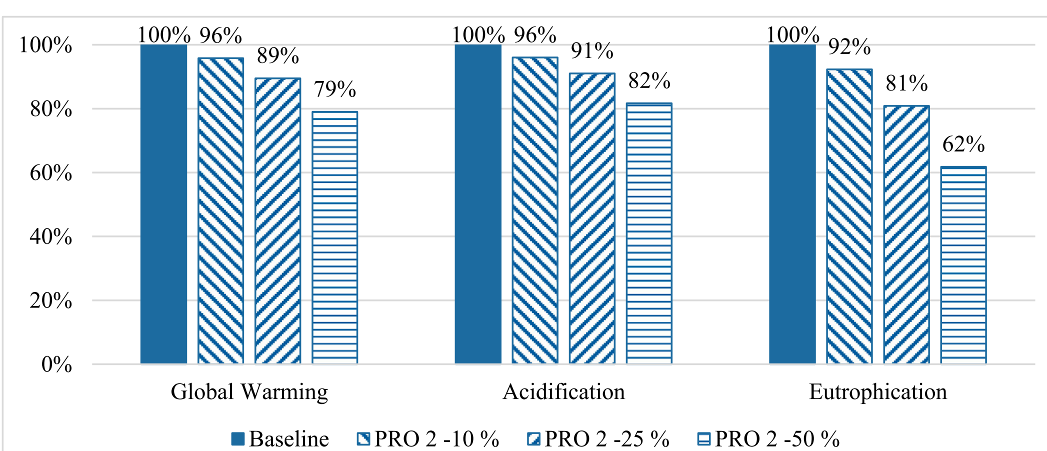


**Fig. 10.** Comparative environmental results considering −10 % to −50 % less electricity consumption for PRO 2.

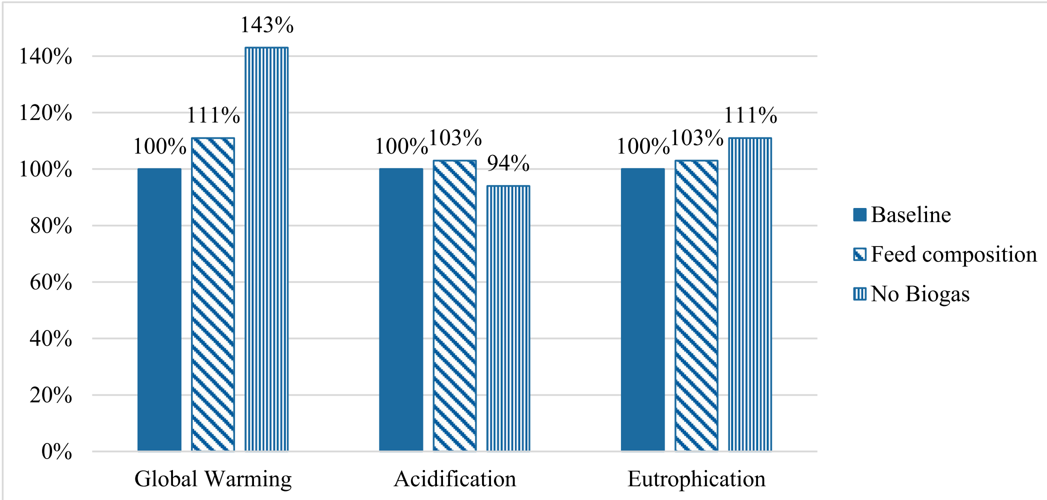


**Fig. 11.** Relative deviations in environmental impacts for the feed composition and no biogas scenarios compared to the baseline scenario for case study BRE.

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

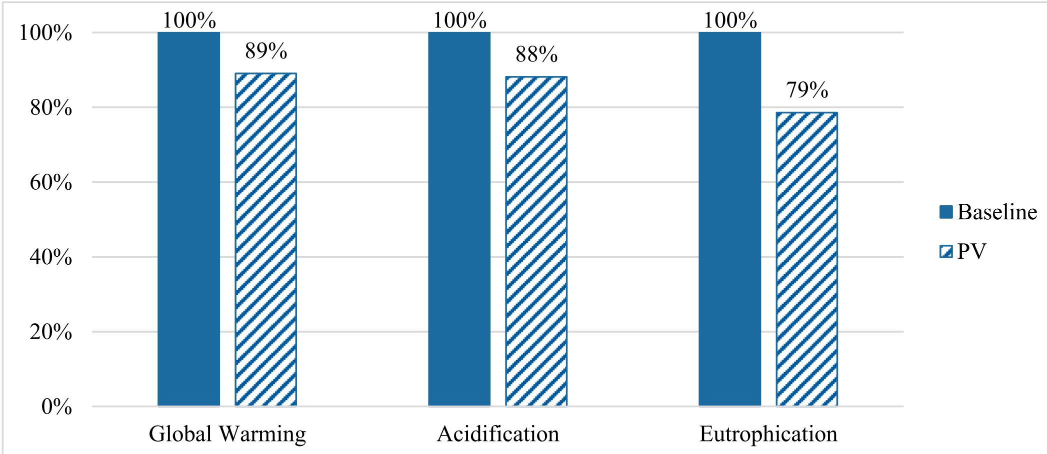


**Fig. 12.** Comparative environmental results considering the baseline scenario and PV scenario that covers electricity production by photovoltaic and crediting the overlap fed to grid for case study SLA.

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.

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## 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.

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