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Environmental performance of Italian heavy pig production systems using farm-level regulatory data

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ABSTRACT

Italian heavy pig production plays a major economic role within the national livestock sector but faces increasing environmental pressure due to greenhouse gas emissions and nutrient losses. This study assessed the environmental performance of Italian heavy pig production systems using technical and environmental data routinely collected for compliance with the Industrial Emissions Directive and the Nitrates Directive. A life cycle assessment (LCA) approach was applied to 21 commercial pig farms located in Northern Italy, representative of the main production systems, including breeding-site (BS), finishing-site (FS), and farrow-to-finish (FTF) farms. Environmental impacts were evaluated across multiple functional units, with particular focus on global warming potential (GWP), acidification, and eutrophication. Average GWP values amounted to 5.96 ± 1.93 kg CO_2 eq kg^{-1} body weight (BW), 6.58 ± 1.18 kg CO_2 eq kg^{-1} light pig BW, and 5.51 ± 0.93 kg CO_2 eq kg^{-1} heavy pig BW. Feed production represented the main environmental hotspot across all impact categories, accounting for approximately 68% of total GWP per kg BW. Differences among production systems were primarily associated with structural and management characteristics rather than with manure management technology class. Although the relatively limited sample size reduced the statistical power of some comparisons, the study highlighted that routinely collected regulatory data may support robust, ISO-compliant environmental assessment under commercial farming conditions, providing a scalable framework for the evaluation of Italian heavy pig production systems.

HIGHLIGHTS

- Regulatory farm datasets can support ISO-compliant environmental assessment of Italian heavy pig systems.
- Feed production was the main environmental hotspot, contributing approximately 68% of total global warming potential.
- Environmental impacts were influenced more by production structure and management than by manure treatment technologies.

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Heavy pig production; life cycle assessment; environmental impact; sustainability; regulatory data

Introduction

Pork production is a key component of the European livestock sector playing a significant role in meat supply and agri-food value chains. Across the European Union, pig farming is characterised by a considerable heterogeneity in production systems, farm size and management intensity, reflecting differences in regional specialisation, market orientation, and regulatory frameworks. Although intensive production systems have enabled high productivity and economic efficiency, the geographical concentration of pig farming has raised increasing concern regarding its environmental impacts particularly with regard to nutrient surpluses, greenhouse gas emissions and air pollutants.

These challenges have underscored the need to better understand how feeding strategies, manure management practices, and farm organisation can improve nutrient use efficiency and production performance while reducing environmental impacts at the farm level. Consequently, European research and policy have increasingly promoted pig production systems that reconcile environmental sustainability with

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economic viability and social acceptance, in line with the objectives of the European Green Deal and the Farm to Fork Strategy, with particular emphasis on reducing GHG emissions, nitrogen losses, and ammonia emissions throughout the production chain (European Commission 2019; Mateos et al. 2024).

Within this European context, Italy represents a distinctive case, being one of the leading pork-producing countries in the European Union. Pig farming plays a major economic and cultural role, particularly in northern Italy, where production systems are strongly linked to high-value Protected Designation of Origin (PDO) products (ISMEA 2024a). In 2024, approximately 8 million pigs were raised in Italy, with nearly 48% of the national herd concentrated in Lombardy region (ISTAT 2024a). Italian production is highly specialised in heavy pigs, with slaughter weights averaging approximately 159 kg, substantially exceeding those commonly observed in most European production systems (ISTAT 2024b). This specialisation supports the competitiveness and adds value of the Italian pork chain but may also increase environmental pressures due to longer fattening periods and greater feed, energy, and nutrient requirements.

The environmental sustainability of pig production has attracted increasing attention due to its contribution to greenhouse gas (GHG) emissions and nutrient-related impacts. Unlike ruminant systems, where enteric methane is the main emission source, the environmental profile of pig production is largely determined by feed production and manure management. Feed production is recognised as a major environmental hotspot due to the demand for land and energy requirements, whereas manure management is the principal source of methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3), during housing, treatments and storage, and land application stages. The high nitrogen throughput characteristic of intensive pig systems makes ammonia volatilisation a particularly critical pathway, reducing nutrient use efficiency while contributing to particulate matter formation, acidification, eutrophication, and atmospheric nitrogen deposition (Gerber et al. 2013; Rebolledo et al. 2013; FAO 2023).

In response to the environmental challenges, the European Union has progressively strengthened the regulatory framework governing intensive livestock production systems. Key legislative instruments include the Industrial Emissions Directive (IED) 2010/75/EU and the Nitrates Directive (91/676/EEC), which respectively aim to reduce emissions through the implementation of Best Available Techniques (BATs) and to improve nutrient management by regulating manure storage, application, and nitrogen planning (European Council 1991; European Parliament 2010). In Italy, the IED applies to pig farms with more than 2,000 places for pigs over 30 kg or 750 sow places, encompassing most large-scale intensive production systems (European Parliament 2024). Compliance with these regulations requires farms to routinely collect standardised environmental and technical information on animal production, manure management, and nutrient balances.

Despite the growing number of LCA studies on pig production, most analyses rely on survey farm data. By contrast, the environmental and technical information routinely collected under the Industrial Emissions Directive (IED) and the Nitrates Directive has rarely been exploited for environmental assessment, despite covering a large number of commercial farms and providing standardised information on animal performance, feeding practices, manure management, and nutrient flows. Consequently, the potential of these regulatory datasets to support large-scale environmental benchmarking of intensive pig production systems remains largely unexplored. Against this background, the present study aimed to evaluate the environmental performance of Italian heavy pig production systems using environmental and technical data routinely collected under the Industrial Emissions Directive and the Nitrates Directive. Specifically, the study: (i) quantified the environmental impacts of commercial heavy pig farms through a LCA method, focusing on global warming potential, acidification, and eutrophication; (ii) identified the main emission hotspots across the production system; and (iii) investigated how farm characteristics and manure management strategies influence environmental performance. By demonstrating the potential of regulatory datasets for environmental assessment, this study provides a novel approach for supporting both environmental benchmarking and evidence-based policy implementation.

Material and methods

Farm data

Data were collected exclusively from mandatory environmental and technical documentation prepared by farms for regulatory compliance under the Industrial Emissions Directive (IED) and Integrated Pollution Prevention and Control (IPPC) framework, the Nitrates Directive (91/676/EEC), and the National Animal Identification and Registration Database (BDN) (National Animal Identification and Registration Database 2024) (Figure 1). The study relied solely on

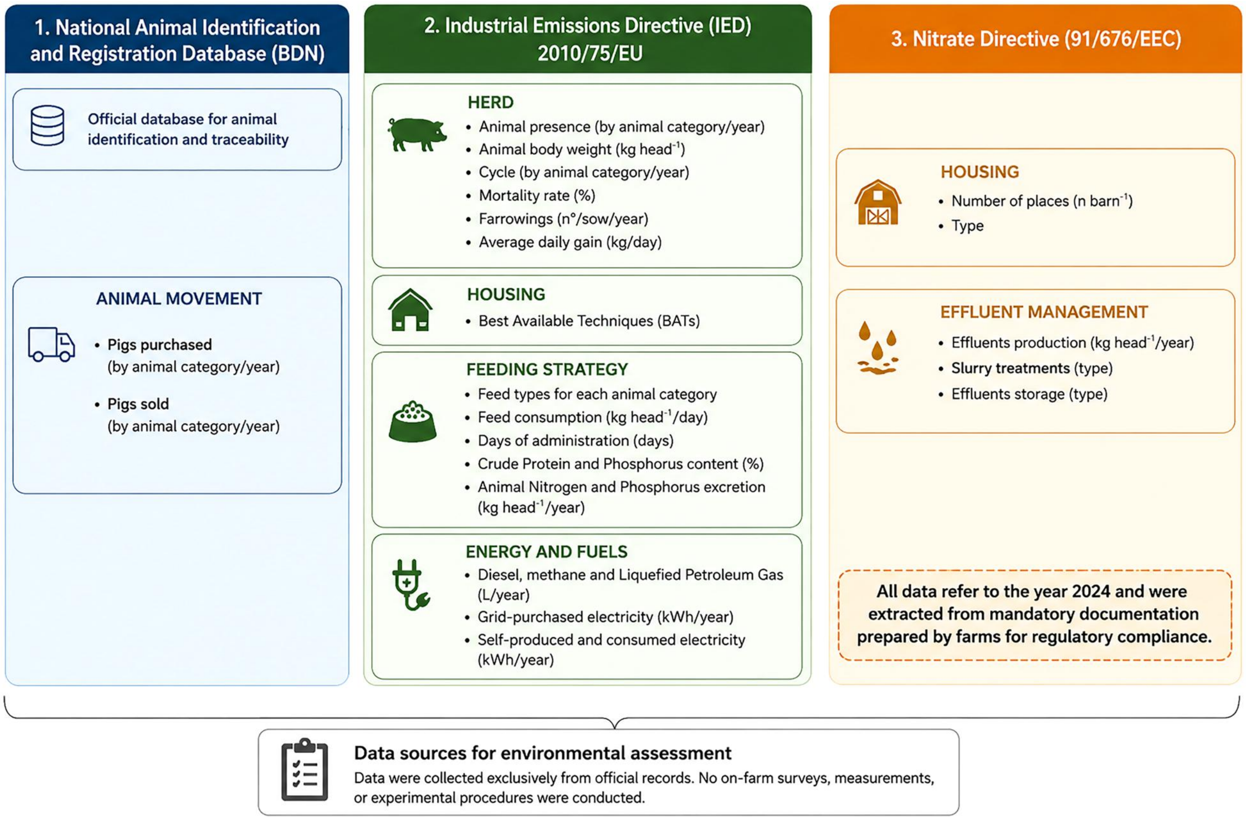

Figure 1. Schematic overview of the data sources and types of information used in the study. Farm-level data were collected from three main regulatory and administrative sources.

existing official records and administrative datasets, without any direct on-farm measurements, animal sampling, experimental procedures, or ad hoc data collection activities. All data referred to the year 2024.

The study was conducted on a sample of commercial pig farms located in the Po Valley (Northern Italy), specifically within the provinces of Brescia, Cremona and Mantova. Farms were randomly selected from the portfolio of commercial pig farms assisted by an independent agronomic consultant responsible for preparing the technical and environmental documentation required under the Industrial Emissions Directive (IED) and the Nitrates Directive. This approach ensured access to complete and standardised datasets while avoiding selection based on farm environmental or productive performance. A total of 21 farms were included, comprising three farrow-to-finish (FTF) farms and 18 farms specialised in a single production phase, namely breeding sites (BS; $n = 7$) and finishing sites (FS; $n = 11$). A subset of FS farms also managed the post-weaning growing phase, covering pigs with body weights ranging from 7 to 30 kg. Farms operating exclusively as dedicated weaning units were excluded from the analysis because this production stage is not covered by the Industrial Emissions Directive (IED) requirements. Although the sample was not designed to be statistically representative of the entire Italian pig sector, it includes commercial farms covering the main intensive heavy pig production systems operating in the Po Valley, which accounts for the majority of Italian pig production.

For each farm, herd structure was characterised for all animal categories by recording the number of animals, duration of each production phase, initial and final body weights, and average daily gain. Herd performance indicators, including mortality rate, number of sow farrowings per year, and number of weaned piglets per sow, were retrieved from technical documentation prepared within the Industrial Emissions Directive (IED) compliance framework. Information on animal movements, including the number and of purchased and sold animals, was retrieved from the National Animal Identification and Registration Database (BDN). The corresponding body weights were derived by cross-referencing the animal category recorded in the BDN with farm-specific feeding-phase records, which provided information on phase duration and the body weight reached by animals at the end of each production phase. These primary data were used to quantify animal inputs and outputs for each farm. Housing systems, floor characteristics, and manure management systems for all animal categories were collected from documentation prepared under both the IED and Nitrates Directive compliance frameworks.

Feeding strategies were characterised at the farm level for each animal category using information extracted from the Integrated Self-Control Application required under Lombardy Regional Council Resolution No. XI/1926. As part of this mandatory documentation, farms are required to report the commercial feed used in each production phase, together with the corresponding feed label specifying its nutritional composition (including crude protein and phosphorus content), and the quantity of feed supplied to each animal category. These records were used to determine feed types, nutrient composition, total feed consumption, and average feed intake per animal. Information regarding feed transport, including annual delivery frequency and distances from feed manufacturing sites, was not available (Lombardy Regional Council 2019). In addition, the same documentation provided information on farm-level electricity consumption, fuel use (diesel, liquefied petroleum gas, and natural gas). When the same information was available from multiple regulatory sources, records were cross-checked at the farm and animal-category levels to identify and resolve inconsistencies before inclusion in the inventory.

Slurry production for each animal category was estimated using the coefficients reported in Annexe A of Lombardy Regional Council Resolution No. XII/3634 (Lombardy Regional Council 2024), taking into account housing systems, floor types, and slurry removal systems. Nitrogen and phosphorus excretion were calculated for each animal category using the BAT-Tool Plus software (CRPA 2024), based on primary farm data related to feeding strategies, feed intake, and crude protein content.

Direct on-farm emissions were estimated for each animal category using available primary farm data and the BAT-Tool Plus software as a supporting calculation tool (CRPA 2024; Valli and Rocchini 2024). Enteric methane emissions were calculated according to the IPCC Tier 1 methodology, adopting an emission factor of 1.5 kg CH_4 head^{-1} year^{-1} for swine in high-productivity systems (IPCC 2019). Methane (CH_4) and nitrous oxide (N_2O) emissions from slurry storage were estimated using the IPCC Tier 2 approach (IPCC 2019) accounting for the specific storage conditions of each farm, including the presence of storage covers and/or manure treatment systems. Ammonia (NH_3) emissions from animal housing, manure treatment, and slurry storage were estimated according to the EMEP/EEA Air Pollutant Emission Inventory Guidebook (EEA 2016). For housing-related NH_3 emissions, the specific flooring system and the frequency of slurry removal from under-floor pits were considered. All emission estimates were calculated separately for each animal category, thereby accounting for category-specific manure production and management conditions.

Farm-level nitrogen use efficiency (F-NUE) was calculated based on total herd N intake. Finally, gaseous N losses occurring during housing, manure treatment, and storage were subtracted from excreted N to estimate the amount of N remaining in manure after these management stages. F-NUE was then expressed as the proportion of total N intake represented by this remaining manure N.

Total N intake was estimated from the amount and crude protein content of feed consumed by all animals contributing to farm production over their entire production cycle. When a production cycle extended across calendar years, feed consumed before the reference year was included to ensure consistency between N inputs and animal outputs. Feed consumed by animals that died during the production cycle was also included; when the exact time of death was unavailable, mortality was assumed to occur at the midpoint, in terms of body weight, of the corresponding production phase. Nitrogen retained by animals was calculated as the difference between total N intake and N excretion.

Life Cycle Assessment

The study was conducted following the Life Cycle Assessment (LCA) methodology in accordance with UNI EN ISO 14040 and UNI EN ISO 14044 standards (ISO 2006a, 2006b).

System boundaries were defined using a cradle-to-farm gate approach and included upstream processes associated with feed and animal purchase, feed production, fuel and electricity consumption (both grid-supplied and self-produced), as well as direct on-farm emissions related to animal housing and manure storage and management (Figure 2). Emissions associated with manure application to agricultural land were excluded from the system boundaries because livestock effluents were not exclusively applied to feed crops associated with the analysed production systems.

Secondary data and emission factors associated with feed production, energy use, and upstream

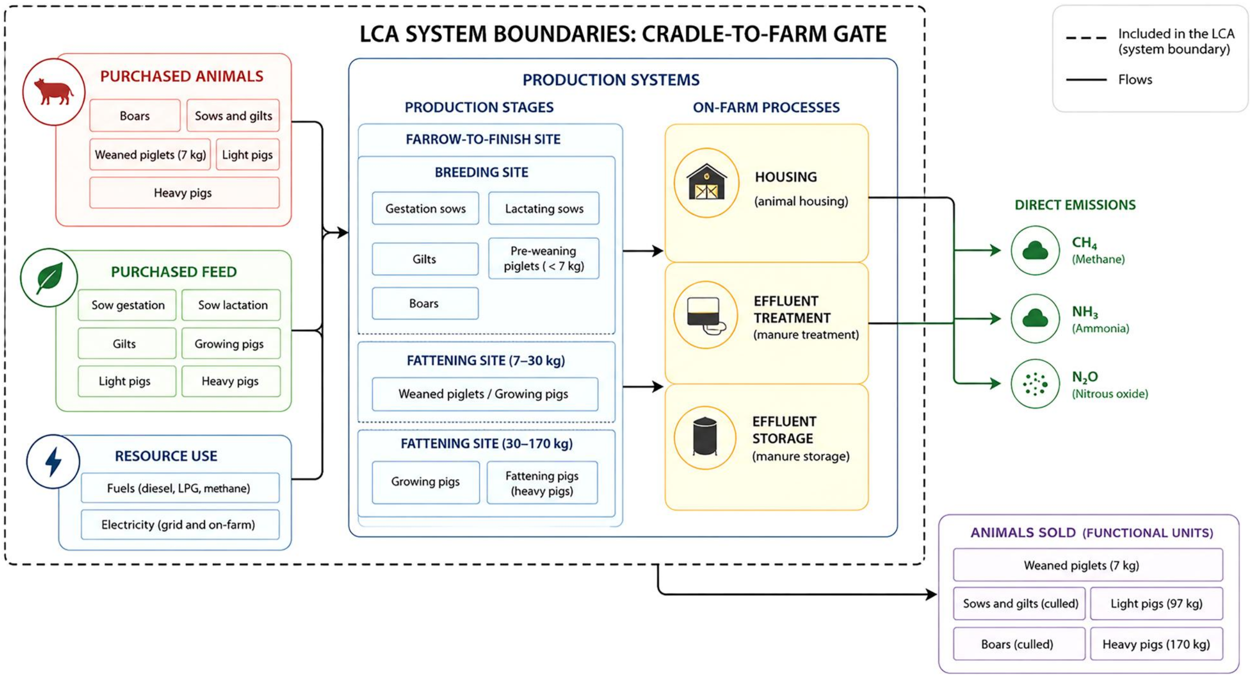

Figure 2. System boundaries and main material, energy, and emission flows considered in the Life Cycle Assessment of Italian heavy pig production systems. The diagram includes purchased inputs (animals, feed, and energy), farm production system (breeding, fattening, and farrow-to-finish systems), housing and manure management practices, manure storage and treatment options, associated gaseous emissions, and production outputs expressed as animals sold.

processes were obtained from the Ecoinvent database (versions 3.8 and 3.9.1) (Wernet et al. 2016) and the Agri-footprint database (version 5) (Durlinger et al. 2014). For feed modelling, background datasets were selected to represent as closely as possible the type and characteristics of the feeds actually used on each farm and for each animal category. Feed labels provided by the farms were used to characterise feed composition and to select the most representative datasets, considering ingredient composition, crude protein content, and the presence of genetically modified ingredients. Farm- and phase-specific feed inventories were then created in SimaPro by combining these background datasets according to the characteristics of the feeds reported by each farm. The geographical origin of individual feed ingredients was not consistently available from farm records; therefore, the geographical assumptions embedded in the selected background datasets were retained (Table S1).

Economic allocation among animal categories sold from the farms was performed in accordance with ISO 14044, using average 2024 market prices for Protected Designation of Origin (PDO) swine production systems reported by ISMEA (ISMEA 2024b) (Table S2). Allocation factors were calculated considering the economic value of the different animal categories marketed by each production system.

Different functional units (FU) were adopted according to the production system analysed. Environmental impacts were expressed as: (i) 1 kg of live body weight (BW) produced at farm gate for the overall farm assessment; (ii) 1 kg of weaned piglet for breeding and farrow-to-finish systems (BS and FTF); (iii) 1 kg of culled sow live weight for breeding and farrow-to-finish systems (BS and FTF); (iv) 1 kg of live weight of light pigs for finishing and farrow-to-finish systems (FS and FTF); and (v) 1 kg of live weight of finished pigs for finishing and farrow-to-finish systems (FS and FTF) (Figure 3).

Life cycle impact assessment (LCIA) was performed using the Environmental Footprint method EF 3.1 (EPLCA 2022) and modelled in SimaPro software (version 9.5.0.0). The environmental impact categories considered included climate change (kg CO_2 eq), acidification (mol H^+ eq), freshwater ecotoxicity (CTUe), particulate matter formation (kg $PM_{2.5}$ eq), marine eutrophication (kg N eq), freshwater eutrophication (kg P eq), terrestrial eutrophication (mol N eq), human toxicity-cancer effects (CTUh), human toxicity-non-cancer effects (CTUh), ionising radiation (kBq U-235 eq), land use (Pt), ozone depletion (kg CFC-11 eq), photochemical ozone formation (kg NMVOC eq), fossil resource use (MJ), mineral and metal resource use (kg Sb eq), and water use (m^3 deprivation).

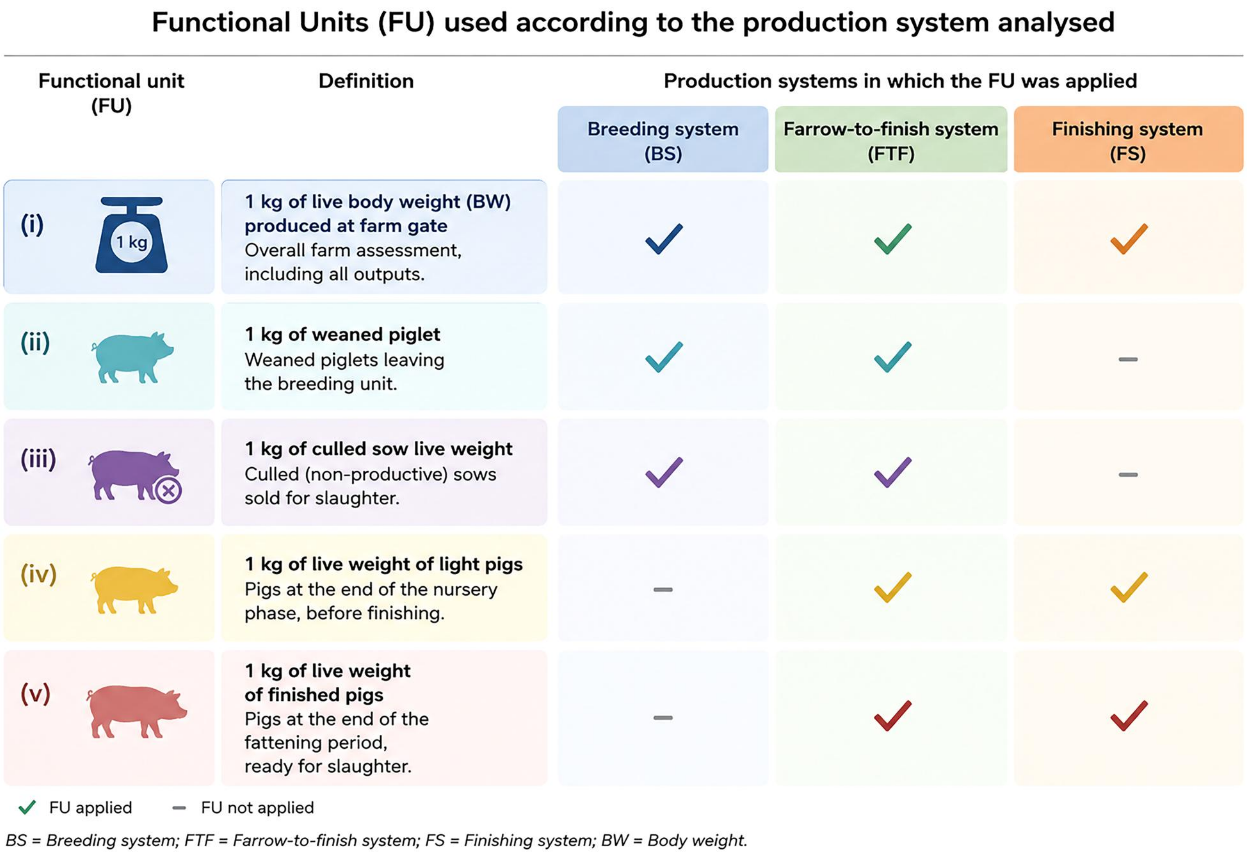

Figure 3. Functional units (FU) adopted for the life cycle assessment according to the pig production system analysed. Environmental impacts were expressed per 1 kg of live body weight (BW) produced at farm gate for the overall farm assessment; per 1 kg of weaned piglet and 1 kg of culled sow live weight for breeding (BS) and farrow-to-finish (FTF) systems; and per 1 kg of live weight of light pigs and finished pigs for finishing (FS) and farrow-to-finish (FTF) systems.

Statistical analysis

Data analysis was performed using R software (version 4.4.3) (R Core Team 2025). Data normality was assessed using Pearson's normality test (package nortest, version 1.0–4). Descriptive statistics were calculated using the psych (version 2.5.6) and rstatix (version 0.7.2) packages.

Analyses were stratified according to production site and manure management technology class. Three manure management technology classes were defined (low, medium, and high) based on the type of effluent treatment applied and the characteristics of slurry storage covers. The low technology class included farms without effluent treatment and with uncovered storage tanks or tanks covered only with straw. The medium class comprised farms adopting at least solid–liquid separation combined with straw or lightweight expanded clay aggregate (LECA) storage covers. The high technology class included farms implementing multiple manure treatment technologies combined with storage covers characterised by higher emission mitigation efficiency. The effects of production site (BS, FS and FTF), manure management technology class, and their interaction on environmental impact indicators were assessed separately for each combination of impact category, contribution cluster (feed-purchase, animal-purchase, energy and fuel consumption, emissions), and functional units using the Scheirer–Ray–Hare test (Dytham 2003), implemented in the rcompanion package (version 2.5.0), resulting in a total of 360 Scheirer-Ray-Hare tests were performed.

For combinations showing a significant effect ($p < 0.05$), multiple pairwise comparisons among the relevant factor levels were performed using Dunn's post hoc test with Bonferroni correction, implemented in the FSA package (version 0.9.6).

Results

Farm description

The analysed sample included commercial pig farms representative of the main Italian heavy pig production systems. Descriptive statistics are reported in Tables 1–3.

Table 1. Descriptive statistics of herd structure and production performance in breeding-sow (BS) farms included in the study.

Variable	Unit	Number observations	Mean	Sd	Min	Max	CV
Herd size-average presence							
Productive sows	n/y	7	1587.43	1052.55	512.00	3618.00	66.31
Lactation sows	n/y	7	436.14	443.26	125.00	1401.00	101.63
Weight	kg/head	7	183.60	0.00	183.60	183.60	0.00
Gestation sows	n/y	7	1151.29	639.46	387.00	2217.00	55.54
Weight	kg/head	7	180.00	0.00	180.00	180.00	0.00
Gilts	n	7	334.43	291.43	102.00	887.00	87.14
Weight	kg/head	7	61.07	9.05	46.50	68.00	14.82
Weaned gilts	n	7	122.43	221.48	0.00	555.00	180.90
Weight	kg/head	2	18.00	1.41	17.00	19.00	7.83
Weaned pigs	n	7	774.43	2048.95	0.00	5421.00	264.58
Weight	kg/head	1	18.50	–	18.50	18.50	–
Boars	n	7	3.86	4.10	0.00	12.00	106.29
Weight	kg/head	5	250.00	0.00	250.00	250.00	0.00
Light pigs	n	7	184.86	489.09	0.00	1294.00	264.58
Weight	kg/head	1	40.00	–	40.00	40.00	–
Total LU[1]	n	7	974.87	613.34	287.80	1985.70	62.92
Performance							
Litters	n/sow/y	7	2.60	0.00	2.60	2.60	0.00
Piglets weaned	n/sow/y	7	28.72	8.01	17.78	38.86	27.89
Growth cycles	n/y	4	5.07	1.62	2.89	6.44	32.03
Gilt cycles	n/y	7	4.47	2.11	1.89	6.50	47.15
Fattening cycles	n/y	1	2.01	–	2.01	2.01	–
ADG[2] fattening pigs	kg/d	1	0.69	–	0.69	0.69	–
Mortality rate gilts	%	7	7.86	5.79	2.00	16.00	73.64
Mortality rate weaned pigs	%	1	7.00	–	7.00	7.00	–
Mortality rate fattening	%	1	7.00	–	7.00	7.00	–
Animal arrivals							
Purchased gilts	n/y	7	1019.57	871.51	0.00	2061.00	85.48
Weight	kg/head	5	24.60	24.11	6.00	51.00	98.01
Purchased boars	n/y	7	2.71	3.30	0.00	8.00	121.66
Weight	kg/head	4	200.00	0.00	200.00	200.00	0.00
Animal movements							
Sows and gilts sold	n/y	7	2723.71	3493.90	138.00	9909.00	128.28
Weight	kg/head	7	164.29	42.76	130.00	210.00	26.03
Weaned pigs sold	n/y	7	38855.71	18514.72	14819.00	67830.00	47.65
Weight	kg/head	7	7.00	0.00	7.00	7.00	0.00
Boars sold	n/y	7	16.00	34.89	0.00	95.00	218.06
Weight	kg/head	6	275.00	61.24	150.00	300.00	22.27
Dead animals	LU[1]/y	5	35.69	14.35	16.14	55.65	40.19

Values are expressed as mean ± standard deviation.
[1]LU: Livestock Units; [2]ADG: average daily gain

Breeding sites (BS) housed on average 436 ± 443 lactating sows and 1,151 ± 639 gestating sows, while farrow-to-finish (FTF) farms included an average of 656 ± 152 productive sows and also covered the growing–finishing phase. Reproductive performance was comparable among systems, with an average productivity of approximately 29 weaned piglets per sow per year.

Finishing sites (FS) showed an average annual presence of 1,880 ± 1,143 light pigs and 3,459 ± 1,780 heavy pigs, corresponding to an average farm size of 1,476 ± 892 livestock units (LU). Farrow-to-finish farms were generally larger, with an average of 2,342 ± 1,616 gilts and light pigs and 5,929 ± 722 heavy pigs. Growth performance was relatively consistent across systems, with average daily gain values ranging from 0.74 to 0.77 kg/day and feed conversion ratios close to 3.0 kg feed/kg live weight. Slaughter weights averaged 97 kg for light pigs and 170 kg for heavy pigs across all production systems.

Feeding strategies varied according to physiological stage and farm management practices, although none of the farms produced feed from their own land (Table S3). Sow feed intake was comparable among systems, while lactation diets generally showed higher crude protein (CP) content than gestation diets. The use of pre-starter feed for suckling piglets was a farm-specific management strategy and was adopted only by a minority of farms. Consequently, the observed high variability in pre-starter feed intake reflects differences in management practices among farms. During the growing–finishing phase (30–170 kg body weight), feed consumption averaged 468.41 ± 36.84 kg/head/cycle in FS farms and 446.72 ± 36.09 kg/head/cycle in FTF farms.

Direct emissions

Methane emissions from manure management were consistently higher than enteric methane emissions across all production systems. Enteric methane emissions averaged 4.19 ± 1.94, 6.86 ± 2.73, and 6.32 ± 0.72 kg LU^{-1} in breeding-site (BS), finishing-site (FS),

Table 2. Descriptive statistics of herd structure and production performance in finishing-site (FS) farms included in the study.

Variable	Unit	Number observations	Mean	Sd	Min	Max	CV
Herd size-average presence							
Weaned pigs	n	11	2932.91	4368.74	0.00	11656.00	148.96
Weight	kg/head	5	18.50	0.00	18.50	18.50	0.00
Light pigs	n	7	1880.14	1142.97	158.00	3657.00	60.79
Weight	kg/head	7	63.52	10.58	54.81	85.00	16.65
Heavy pigs	n	11	3458.73	1780.00	630.00	6856.00	51.46
Weight	kg/head	11	117.14	16.49	97.50	145.00	14.08
Total LU[1]	n	11	1475.74	891.61	236.40	3052.51	60.42
Performance							
Growth cycles	n/y	5	5.20	0.69	4.64	6.18	13.32
Fattening cycles	n/y	11	1.63	0.22	1.33	2.06	13.46
ADG[2] weaned piglets	kg/d	5	0.48	0.07	0.37	0.51	14.58
ADG fattening pigs	kg/d	11	0.74	0.07	0.61	0.86	9.02
FCR[3] fattening pigs	kg/kg	11	3.00	0.40	2.34	3.84	13.33
Mortality rate weaned pigs	%	5	19.80	8.53	11.00	29.00	43.06
Mortality rate fattening	%	11	12.36	9.35	2.00	29.00	75.64
Animal arrivals							
Purchased weaned pigs	n/y	11	15569.00	22205.90	0.00	62866.00	142.63
Weight	kg/head	8	15.63	11.90	7.00	30.00	76.18
Purchased light pigs	n/y	11	3309.36	3589.31	0.00	10610.59	108.46
Weight	kg/head	8	33.25	4.17	31.00	40.00	12.53
Purchased heavy pigs	n/y	11	0.94	3.10	0.00	10.29	331.66
Weight	kg/head	1	90.00	–	90.00	90.00	–
Animal movements							
Light pigs sold	n/y	11	5766.36	9521.82	0.00	29883.00	165.13
Weight	kg/head	9	96.11	17.28	85.00	130.00	17.98
Heavy pigs sold	n/y	11	8693.09	5240.44	2079.00	17601.00	60.28
Weight	kg/head	11	170.00	0.00	170.00	170.00	0.00
Dead animals	LU[1] /y	11	1168.75	1810.65	25.06	5818.46	154.92

Values are expressed as mean ± standard deviation.
[1]LU: Livestock Units; [2]ADG: average daily gain, [3]FCR: feed conversion ratio

and farrow-to-finish (FTF) farms, respectively. In contrast, methane emissions associated with manure management reached 16.96 ± 6.99 kg LU^{-1} in BS systems and increased to 33.86 ± 16.01 kg LU^{-1} in FS systems, while lower values were observed in FTF farms (13.33 ± 12.55 kg LU^{-1}).

Nitrous oxide emissions from manure storage were comparatively low across all production systems, ranging from 0.06 ± 0.06 kg LU^{-1} in BS farms to 0.16 ± 0.10 kg LU^{-1} in FS farms. Emission variability among farms may be related to differences in housing systems and storage configurations, including under-slatted systems, uncovered and covered tanks, and solid-separated manure heaps.

Ammonia emissions mainly originated from animal housing and manure storage. Housing emissions averaged 4.11 ± 1.49, 5.59 ± 2.58, and 7.49 ± 0.80 kg LU^{-1} in BS, FS, and FTF systems, respectively. Additional emissions were associated with manure treatment and storage phases, although their relative contribution varied among production systems (Table S4).

Nitrogen flows

Farm nitrogen use efficiency (F-NUE) differed among production systems and was assessed by accounting for total nitrogen intake, including N intake by animals that died during the production cycle, nitrogen excretion, and gaseous N losses occurring during housing, manure treatment, and storage (Table S5). In BS systems, nitrogen losses from housing accounted for 5.69 ± 2.20% of nitrogen intake, whereas additional losses from manure storage and treatment represented 2.95 ± 0.93% and 0.97 ± 0.87%, respectively. The resulting F-NUE averaged 63.10 ± 8.42% of nitrogen intake, although marked variability was observed among farms.

Finishing systems showed the highest nitrogen retention values. In these farms F-NUE averaged 39.86 ± 14.39% of nitrogen intake. In these farms, housing-related losses averaged 5.49 ± 3.36%, while manure treatment and storage losses accounted for 1.77 ± 1.29% and 2.20 ± 1.07% of nitrogen intake, respectively.

In FTF systems, housing represented the main source of nitrogen losses (9.31 ± 0.64% of nitrogen intake), whereas lower contributions were associated with manure treatment and storage. Overall, F-NUE averaged 52.34 ± 10.17% of nitrogen intake. Considerable between-farm variability was observed across all production systems, particularly in relation to manure management strategies and housing characteristics.

Environmental impacts

All 16 environmental impact categories included in the life cycle impact assessment were analysed. In this

Table 3. Descriptive statistics of herd structure and production performance in farrow-to-finish (FTF) farms included in the study.

Variable	Unit	Number observations	Mean	Sd	Min	Max	CV
Herd size-average presence							
Productive sows	n/y	3	656.00	152.21	490.00	789.00	23.20
Lactation sows	n/y	3	175.00	46.70	126.00	219.00	26.69
Weight	kg/head	3	183.60	0.00	183.60	183.60	0.00
Gestation sows	n/y	3	481.00	148.13	310.00	570.00	30.80
Weight	kg/head	3	180.00	0.00	180.00	180.00	0.00
Boars	n/y	3	5.67	4.93	0.00	9.00	87.05
Weight	kg/head	2	250.00	0.00	250.00	250.00	0.00
Weaned pigs	n	3	3339.33	1185.19	2186.00	4554.00	35.49
Weight	kg/head	3	18.33	0.29	18.00	18.50	1.57
Gilts and light pigs	n	3	2342.00	1616.35	637.00	3852.00	69.02
Weight	kg/head	3	51.88	12.27	41.01	65.18	23.65
Heavy pigs	n	3	5929.67	721.75	5247.00	6685.00	12.17
Weight	kg/head	3	133.33	2.89	130.00	135.00	2.17
Total LU[1]	n	3	2901.36	214.10	2716.46	3135.92	7.38
Performance							
Litters	n/sow/y	3	2.56	0.07	2.48	2.60	2.64
Piglets weaned	n/sow/y	3	29.30	6.84	23.81	36.96	23.34
Growth cycles	n/y	3	4.91	0.86	4.25	5.89	17.60
Fattening cycles	n/y	3	1.68	0.18	1.48	1.85	10.89
ADG[2] weaned piglets	kg/d	3	0.40	0.05	0.36	0.46	12.50
ADG fattening pigs	kg/d	3	0.77	0.03	0.74	0.80	3.98
FCR[3] fattening pigs	kg/kg	3	2.90	0.35	2.51	3.21	12.07
Mortality rate weaned pigs	%	3	12.67	8.08	8.00	22.00	63.81
Mortality rate fattening	%	3	12.67	8.08	8.00	22.00	63.81
Animal arrivals							
Purchased gilts	n/y	3	96.33	166.85	0.00	289.00	173.21
Weight	kg/head	1	6.00	–	6.00	6.00	–
Animal movements							
Sows and gilts sold	n/y	3	266.67	19.14	251.00	288.00	7.18
Weight	kg/head	3	210.00	0.00	210.00	210.00	0.00
Weaned pigs sold	n/y	3	1596.33	780.69	734.00	2255.00	48.90
Weight	kg/head	3	7.00	0.00	7.00	7.00	0.00
Boars sold	n/y	3	7.00	11.27	0.00	20.00	160.99
Weight	kg/head	2	300.00	0.00	300.00	300.00	0.00
Light pigs sold	n/y	3	1163.67	570.44	505.00	1497.00	49.02
Weight	kg/head	3	96.67	5.77	90.00	100.00	5.97
Heavy pigs sold	n/y	3	13704.67	2156.96	11388.00	15655.00	15.74
Weight	kg/head	3	170.00	0.00	170.00	170.00	0.00
Dead animals	LU[1]/y	3	240.51	265.95	74.29	547.24	110.58

Values are expressed as mean ± standard deviation.
[1]LU: Livestock Units; [2]ADG: average daily gain, [3]FCR: feed conversion ratio

section, only the impact categories considered most representative for pig production are reported, namely global warming potential (GWP), acidification (AC), and eutrophication (EP). Results for the remaining impact categories are reported in Table 4.

Environmental impacts differed among functional units. Average GWP values ranged from 1.16 ± 0.66 kg CO_2 eq kg^{-1} sow BW to 12.50 ± 7.66 kg CO_2 eq kg^{-1} weaned piglet BW, while impacts associated with light and heavy pig production averaged 6.58 ± 1.18 and 5.51 ± 0.93 kg CO_2 eq kg^{-1} BW, respectively. Across all production systems, feed purchase represented the main contributor to GWP, accounting approximately 68% of total GWP per kg BW, followed by direct on-farm emissions (16%), energy and fuel consumption (9%), and animal purchase (7%).

Similar contribution patterns were observed for acidification and eutrophication categories. Feed purchase was the dominant contributor to acidification potential, representing approximately 51% of total impacts, whereas direct emissions accounted for 43% of total acidification burden. Marine, freshwater, and terrestrial eutrophication averaged 0.028 ± 0.010 kg N eq kg^{-1} BW, 0.0010 ± 0.0004 kg P eq kg^{-1} BW, and 0.326 ± 0.108 mol N eq kg^{-1} BW, respectively. Feed purchase contributed most strongly to eutrophication impacts, accounting for 88%, 77%, and 49% of marine, freshwater, and terrestrial eutrophication, respectively.

Statistical analyses showed no significant interaction between production site and manure management technology class across the evaluated impact categories and functional units. Conversely, significant differences were mainly associated with production site, whereas manure management technology class showed a limited influence on environmental impacts (Table 5). In particular, finishing-site (FS) farms generally showed higher impacts associated with feed purchase, especially when impacts were expressed per kg light pig BW.

When impacts were disaggregated by contribution cluster, the effect of production site differed according

Table 4. Environmental impact results for Italian heavy pig production systems across selected functional units, including global warming potential (GWP), acidification (AC), and eutrophication (EP).

Impact category	Unit	emissions/kg BW[1]	emissions/ kg WP[2] BW	emissions/ kg S[3] BW	emissions/ kg LP[4] BW	emissions/ kg HP[5] BW
Climate change	kg $CO_{2\ eq}$	5.96E + 00 ± 1.93E + 00	1.25E + 01 ± 7.66E + 00	1.16E + 00 ± 6.64E-01	6.58E + 00 ± 1.18E + 00	5.51E + 00 ± 9.29E-01
Acidification	mol $H^{+}_{\ eq}$	7.48E-02 ± 2.48E-02	1.70E-01 ± 1.21E-01	1.63E-02 ± 1.11E-02	8.37E-02 ± 1.54E-02	7.00E-02 ± 1.29E-02
Ecotoxicity freshwater	CTUe	3.80E + 02 ± 1.75E + 02	7.73E + 02 ± 3.85E + 02	6.97E + 01 ± 2.98E + 01	3.90E + 02 ± 1.12E + 02	3.26E + 02 ± 8.85E + 01
Particulate matter	disease inc.	6.49E-07 ± 2.25E-07	1.40E-06 ± 9.28E-07	1.32E-07 ± 8.32E-08	7.21E-07 ± 1.45E-07	6.08E-07 ± 1.23E-07
Eutrophication marine	kg $N_{\ eq}$	2.76E-02 ± 1.01E-02	5.51E-02 ± 3.13E-02	5.33E-03 ± 3.21E-03	3.06E-02 ± 6.93E-03	2.56E-02 ± 5.54E-03
Eutrophication freshwater	kg $P_{\ eq}$	9.75E-04 ± 3.66E-04	1.91E-03 ± 1.16E-03	1.77E-04 ± 1.00E-04	1.08E-03 ± 2.59E-04	9.17E-04 ± 1.95E-04
Eutrophication terrestrial	mol $N_{\ eq}$	3.26E-01 ± 1.08E-01	7.20E-01 ± 5.09E-01	6.94E-02 ± 4.70E-02	3.69E-01 ± 7.08E-02	3.09E-01 ± 5.92E-02
Human toxicity cancer	CTUh	1.73E-09 ± 6.53E-10	3.77E-09 ± 2.31E-09	3.50E-10 ± 2.00E-10	1.83E-09 ± 2.88E-10	1.56E-09 ± 2.16E-10
Human toxicity non cancer	CTUh	9.47E-08 ± 3.66E-08	1.81E-07 ± 1.00E-07	1.75E-08 ± 1.04E-08	1.04E-07 ± 2.54E-08	8.84E-08 ± 1.97E-08
Ionising radiation	kBq U-235 $_{eq}$	1.34E-01 ± 5.86E-02	2.89E-01 ± 1.44E-01	2.57E-02 ± 1.08E-02	1.35E-01 ± 2.94E-02	1.13E-01 ± 2.31E-02
Land use	Pt	3.23E + 02 ± 1.31E + 02	5.99E + 02 ± 3.17E + 02	5.75E + 01 ± 3.26E + 01	3.58E + 02 ± 1.09E + 02	3.01E + 02 ± 8.49E + 01
Ozone depletion	kg CFC11 $_{eq}$	8.83E-08 ± 5.45E-08	1.91E-07 ± 9.84E-08	1.68E-08 ± 7.09E-09	8.12E-08 ± 2.15E-08	6.88E-08 ± 1.66E-08
Photochemical ozone formation	kg NMVOC $_{eq}$	1.46E-02 ± 5.78E-03	3.22E-02 ± 1.90E-02	2.98E-03 ± 1.65E-03	1.51E-02 ± 2.18E-03	1.28E-02 ± 1.85E-03
Resource use fossils	MJ	3.85E + 01 ± 1.75E + 01	8.99E + 01 ± 4.59E + 01	8.22E + 00 ± 3.92E + 00	3.75E + 01 ± 5.63E + 00	3.14E + 01 ± 5.33E + 00
Resource use minerals and metals	kg Sb $_{eq}$	1.23E-05 ± 4.39E-06	2.61E-05 ± 1.88E-05	2.45E-06 ± 1.64E-06	1.37E-05 ± 2.62E-06	1.17E-05 ± 2.02E-06
Water use	m^3 depriv.	1.07E + 01 ± 3.56E + 00	2.21E + 01 ± 1.56E + 01	2.21E + 00 ± 1.63E + 00	1.22E + 01 ± 1.01E + 00	1.03E + 01 ± 7.56E-01

Results are expressed as mean ± standard deviation.
[1]BW: body weight; [2]WP: weaned piglet, [3]S: sow; [4]LP: light pigs; [5]HP: heavy pig.

to both the functional unit and the impact category considered. Within the feed-purchase cluster, significant site effects were detected exclusively for impacts expressed per kg light pig BW, including global warming potential, acidification, particulate matter formation, ozone depletion, and fossil resource use ($p < 0.05$). In these cases, FS farms showed higher impacts than FTF farms. In the animal-purchase cluster, all impact categories differed significantly among production sites across all functional units ($p < 0.04$). The highest impacts were generally observed in FS farms, followed by BS and FTF farms.

Significant site effects were also detected within the energy and fuel consumption cluster. For impacts expressed per kg BW, all impact categories were significantly affected by production site ($p < 0.02$), except for water use. In contrast, for impacts expressed per kg light pig BW, significant differences among sites were observed only for ionising radiation ($p = 0.049$). Within this contribution cluster, BS farms generally showed the highest impacts, followed by FTF and FS farms.

Within the emissions cluster, site-related differences were more limited and mainly involved global warming potential and human toxicity (non-cancer effects) expressed per kg sow BW ($p < 0.03$). Emission-related impacts per kg of light pig and heavy pig body weight tended to be higher in FS farms compared with FTF farms, although GWP did not differ significantly between the two production systems. Conversely, under the limited conditions analysed in this case study, manure management technology class showed a limited influence on environmental impacts and significantly affected only water use associated with the energy and fuel consumption cluster for the functional unit of 1 kg heavy pig BW ($p = 0.044$).

Discussion

This study provides a comprehensive environmental assessment of a sample of Italian heavy pig production systems based on technical data routinely collected by farms for compliance with existing regulatory frameworks. The findings highlight the potential of these datasets to support farm-level life cycle assessment under commercial conditions, while reducing the need for additional primary data collection.

The limited number of studies specifically assessing the environmental performance of Italian heavy pig production highlights the need for additional evidence for this production sector. Despite methodological

Table 5. Results of the Scheirer–Ray–Hare test assessing the effects of production site, manure management technology class, and their interaction on environmental impact categories across functional units.

Impact category	Item	Total					Animal purchased					Feed purchased					Consumption					Emissions				
		kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW	kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW	kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW	kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW	kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW
Climate change	TC[6]	0.49	0.21	0.31	0.61	0.94	0.84	0.21	0.18	0.98	0.90	0.60	0.45	0.45	0.28	0.65	0.60	0.26	0.25	0.17	0.83	0.46	0.52	0.39	0.53	0.45
	Site	0.10	1.00	0.14	0.03	0.05	0.01	0.02	0.03	0.04	0.03	0.26	0.79	0.11	0.04	0.06	0.00	0.28	0.89	0.11	0.14	0.47	0.89	0.02	0.95	0.92
	TC: Site	0.49	0.45	0.94	0.79	0.58	0.37	0.82	0.76	0.79	0.80	0.96	0.35	0.91	0.79	0.49	0.68	0.39	0.39	0.98	0.61	0.80	0.31	0.83	0.30	0.35
Acidification	TC	0.42	0.61	0.61	0.18	0.58	0.84	0.21	0.18	0.98	0.90	0.38	0.37	0.45	0.68	0.87	0.54	0.54	0.80	0.12	0.56	0.65	0.61	0.61	0.50	0.63
	Site	0.70	0.69	0.08	0.30	0.55	0.01	0.02	0.03	0.04	0.03	0.06	1.00	0.11	0.04	0.05	0.01	0.42	0.59	0.43	0.33	0.15	0.69	0.08	0.17	0.10
	TC: Site	0.92	0.32	0.88	0.49	0.29	0.37	0.82	0.76	0.79	0.80	0.68	0.34	0.91	0.68	0.54	0.85	0.31	0.31	0.88	0.57	0.69	0.32	0.88	0.67	0.66
Ecotoxicity freshwater	TC	0.66	0.12	0.21	0.84	0.85	0.84	0.21	0.18	0.98	0.90	0.64	0.25	0.45	0.64	0.90	0.58	0.21	0.39	0.11	0.60	0.67	0.61	0.61	0.50	0.63
	Site	0.07	0.59	0.18	0.02	0.03	0.01	0.02	0.03	0.04	0.03	0.10	0.89	0.11	0.14	0.18	0.01	0.18	0.69	0.45	0.51	0.12	0.69	0.08	0.17	0.10
	TC: Site	0.61	0.48	0.98	0.82	0.67	0.37	0.82	0.76	0.79	0.80	0.69	0.39	0.91	0.47	0.35	0.98	0.45	0.41	0.84	0.42	0.69	0.32	0.88	0.67	0.66
Particulate matter	TC	0.41	0.45	0.45	0.29	0.63	0.84	0.21	0.18	0.98	0.90	0.48	0.37	0.45	0.68	0.87	0.51	0.47	0.61	0.07	0.58	0.65	0.61	0.61	0.50	0.63
	Site	0.33	0.79	0.11	0.08	0.14	0.01	0.02	0.03	0.04	0.03	0.08	1.00	0.11	0.04	0.05	0.02	0.50	0.69	0.90	0.64	0.15	0.69	0.08	0.17	0.10
	TC: Site	0.87	0.35	0.91	0.58	0.38	0.37	0.82	0.76	0.79	0.80	0.71	0.34	0.91	0.68	0.54	0.95	0.30	0.32	0.79	0.39	0.69	0.32	0.88	0.67	0.66
Eutrophication marine	TC	0.66	0.31	0.45	0.57	0.88	0.84	0.21	0.18	0.98	0.90	0.75	0.31	0.45	0.52	0.97	0.62	0.26	0.45	0.08	0.55	0.65	0.61	0.61	0.50	0.63
	Site	0.22	0.89	0.11	0.03	0.10	0.01	0.02	0.03	0.04	0.03	0.28	0.89	0.11	0.07	0.17	0.01	0.28	0.79	0.74	0.64	0.15	0.69	0.08	0.17	0.10
	TC: Site	0.63	0.39	0.91	0.72	0.43	0.37	0.82	0.76	0.79	0.80	0.65	0.39	0.91	0.58	0.38	0.98	0.39	0.35	0.80	0.40	0.69	0.32	0.88	0.67	0.66
Eutrophication freshwater	TC	0.45	0.21	0.21	0.96	0.98	0.84	0.21	0.18	0.98	0.90	0.31	0.45	0.45	0.19	0.23	0.39	0.18	0.14	0.17	0.45	–	–	–	–	–
	Site	0.06	1.00	0.18	0.03	0.04	0.01	0.02	0.03	0.04	0.03	0.49	0.79	0.11	0.15	0.28	0.00	0.42	0.79	0.11	0.11	–	–	–	–	–
	TC: Site	0.31	0.45	0.98	0.69	0.71	0.37	0.82	0.76	0.79	0.80	0.66	0.35	0.91	0.54	0.46	0.81	0.41	0.63	0.98	0.85	–	–	–	–	–
Eutrophication terrestrial	TC	0.39	0.61	0.61	0.19	0.39	0.84	0.21	0.18	0.98	0.90	0.48	0.25	0.45	0.70	0.91	0.40	0.26	0.31	0.08	0.50	0.65	0.61	0.61	0.50	0.63
	Site	0.55	0.69	0.08	0.15	0.30	0.01	0.02	0.03	0.04	0.03	0.08	0.89	0.11	0.07	0.08	0.02	0.28	0.89	0.74	0.57	0.15	0.69	0.08	0.17	0.10
	TC: Site	1.00	0.32	0.88	0.54	0.36	0.37	0.82	0.76	0.79	0.80	0.68	0.39	0.91	0.59	0.48	0.91	0.39	0.39	0.80	0.45	0.69	0.32	0.88	0.67	0.66
Human toxicity cancer	TC	0.54	0.21	0.21	0.66	0.89	0.84	0.21	0.18	0.98	0.90	0.37	0.61	0.45	0.51	0.58	0.65	0.17	0.17	0.19	0.88	–	–	–	–	–
	Site	0.18	1.00	0.18	0.10	0.10	0.01	0.02	0.03	0.04	0.03	0.83	0.69	0.11	0.88	0.96	0.00	0.22	0.89	0.07	0.10	–	–	–	–	–
	TC: Site	0.61	0.45	0.98	0.41	0.43	0.37	0.82	0.76	0.79	0.80	0.68	0.32	0.91	0.31	0.31	0.68	0.45	0.53	0.99	0.66	–	–	–	–	–

Impact category	Item	Total					Animal purchased					Feed purchased					Consumption					Emissions				
		kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW	kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW	kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW	kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW	kg BW[1]	kg WP[2] BW	kg S[3] BW	kg LP[4] BW	kg HP[5] BW
Human toxicity non cancer	TC	0.81	0.31	0.31	0.90	0.98	0.84	0.21	0.18	0.98	0.90	0.53	0.31	0.45	0.50	0.77	0.58	0.30	0.35	0.19	0.80	0.50	0.41	0.39	0.53	0.45
	Site	0.15	0.89	0.14	0.08	0.07	0.01	0.02	0.03	0.04	0.03	0.67	0.89	0.11	0.53	0.66	0.00	0.79	0.35	0.07	0.06	0.48	0.59	0.02	0.95	0.92
	TC: Site	0.35	0.39	0.94	0.53	0.58	0.37	0.82	0.76	0.79	0.80	0.97	0.39	0.91	0.30	0.26	0.65	0.35	0.64	0.99	0.82	0.80	0.31	0.83	0.30	0.35
Ionising radiation	TC	0.36	0.16	0.21	0.62	0.65	0.49	0.21	0.18	0.98	0.95	0.32	0.45	0.45	0.06	0.14	0.83	0.26	0.37	0.96	0.67	–	–	–	–	–
	Site	0.06	0.79	0.18	0.02	0.02	0.01	0.02	0.03	0.02	0.02	0.42	0.79	0.11	0.13	0.33	0.01	0.28	1.00	0.05	0.07	–	–	–	–	–
	TC: Site	0.53	0.46	0.98	0.79	0.72	0.48	0.82	0.76	0.79	0.79	0.60	0.35	0.91	0.76	0.53	0.54	0.39	0.34	0.69	0.65	–	–	–	–	–
Land use	TC	0.83	0.31	0.31	0.94	0.88	0.84	0.21	0.18	0.98	0.90	0.65	0.31	0.45	0.49	0.97	0.64	0.26	0.26	0.22	0.78	–	–	–	–	–
	Site	0.15	0.89	0.14	0.06	0.09	0.01	0.02	0.03	0.04	0.03	0.20	0.89	0.11	0.14	0.17	0.00	0.28	0.79	0.14	0.19	–	–	–	–	–
	TC: Site	0.40	0.39	0.94	0.61	0.54	0.37	0.82	0.76	0.79	0.80	0.70	0.39	0.91	0.52	0.38	0.74	0.39	0.46	0.90	0.56	–	–	–	–	–
Ozone depletion	TC	0.87	0.15	0.25	0.52	0.88	0.76	0.21	0.18	0.98	0.90	0.64	0.37	0.45	0.44	0.43	0.41	0.39	0.45	0.05	0.29	–	–	–	–	–
	Site	0.19	0.50	0.22	0.15	0.12	0.01	0.02	0.03	0.04	0.03	0.12	1.00	0.11	0.03	0.19	0.00	0.35	0.79	0.10	0.09	–	–	–	–	–
	TC: Site	0.76	0.44	0.89	0.58	0.54	0.43	0.82	0.76	0.79	0.80	0.93	0.34	0.91	0.78	0.52	0.93	0.34	0.35	1.00	0.81	–	–	–	–	–
Photochemical ozone formation	TC	0.22	0.31	0.45	0.14	0.39	0.76	0.21	0.18	0.98	0.90	0.23	0.45	0.45	0.09	0.15	0.58	0.21	0.45	0.11	0.60	0.52	0.52	0.41	0.58	0.45
	Site	0.12	0.89	0.11	0.03	0.03	0.01	0.02	0.03	0.04	0.03	0.60	0.79	0.11	0.12	0.30	0.01	0.18	0.79	0.45	0.51	0.44	0.89	0.06	0.88	0.92
	TC: Site	0.94	0.39	0.91	0.79	0.59	0.43	0.82	0.76	0.79	0.80	0.50	0.35	0.91	0.70	0.53	0.98	0.45	0.35	0.84	0.42	0.86	0.31	0.61	0.30	0.35
Resource use fossils	TC	0.29	0.21	0.21	0.09	0.53	0.71	0.21	0.18	1.00	0.94	0.43	0.45	0.45	0.10	0.30	0.77	0.33	0.31	0.12	0.87	–	–	–	–	–
	Site	0.12	1.00	0.18	0.08	0.12	0.01	0.02	0.03	0.03	0.03	0.31	0.79	0.11	0.02	0.07	0.00	0.42	0.89	0.12	0.14	–	–	–	–	–
	TC: Site	0.75	0.45	0.98	0.83	0.41	0.40	0.82	0.76	0.78	0.79	0.86	0.35	0.91	0.91	0.51	0.86	0.34	0.39	0.97	0.54	–	–	–	–	–
Resource use minerals and metals	TC	0.39	0.21	0.21	0.69	0.77	0.84	0.21	0.18	0.98	0.90	0.41	0.61	0.45	0.58	0.30	0.40	0.19	0.15	0.16	0.48	–	–	–	–	–
	Site	0.44	1.00	0.18	0.19	0.21	0.01	0.02	0.03	0.04	0.03	0.92	0.69	0.11	0.81	0.50	0.00	0.69	0.50	0.06	0.06	–	–	–	–	–
	TC: Site	0.58	0.45	0.98	0.32	0.35	0.37	0.82	0.76	0.79	0.80	0.75	0.32	0.91	0.30	0.48	0.74	0.41	0.78	1.00	0.89	–	–	–	–	–
Water use	TC	0.18	0.45	0.31	0.11	0.45	0.84	0.21	0.18	0.98	0.90	0.13	0.61	0.45	0.15	0.20	0.14	0.69	0.72	0.17	0.04	–	–	–	–	–
	Site	0.40	0.79	0.14	0.02	0.14	0.01	0.02	0.03	0.04	0.03	0.90	0.69	0.11	0.88	0.62	0.33	0.28	0.50	0.98	0.77	–	–	–	–	–
	TC: Site	0.83	0.35	0.94	0.84	0.41	0.37	0.82	0.76	0.79	0.80	0.61	0.32	0.91	0.67	0.63	0.79	0.35	0.29	0.51	0.78	–	–	–	–	–

[1]BW: body weight; [2]WP: weaned piglet, [3]S: sow; [4]LP: light pigs; [5]HP: heavy pig; [6]TC: Technology class

differences, the environmental impacts estimated in the present study are generally consistent with those reported in the literature. In particular, the global warming potential (GWP) ranged within the values previously reported for Italian heavy pig systems (3.1–5.08 kg CO_2-eq kg^{-1} live weight or body weight gain (Pirlo et al. 2016; Bava et al. 2017; Conti et al. 2021; Berton et al. 2024). GWP values expressed per kilogram of live weight were generally higher than those reported for conventional pigs slaughtered at lower body weights (de Vries and de Boer 2010; Dourmad et al. 2014). The higher GWP values generally reported for heavy pig production systems are likely related to their structural characteristics, including higher slaughter weights, longer production cycles, and greater cumulative feed intake per animal (Dekkers 2025). Nevertheless, direct comparisons with previous studies should be interpreted with caution due to differences in methodological assumptions, system boundaries, functional units, and life cycle inventory modelling. This is reflected in the wide range of climate change impacts reported in the international literature. For example, Gislason et al. (2023) reported climate change impacts ranging from −0.02 to 11.2 kg CO_2-eq kg^{-1} live weight, while showing that the inclusion of direct land-use change alone could increase GWP estimates by up to 470%.

Part of the environmental variability observed in the present study may be associated with differences in production stage and farm management. The higher GWP values observed in breeding-sow (BS) systems may reflect the specific requirements of the reproductive phase. Compared with growing-finishing systems, breeding farms generally require greater energy inputs for climate control in farrowing and nursery facilities and rely on diets with higher nutrient density and crude protein content for gestating and lactating sows and pre-weaning piglets (Sossidou et al. 2025). These characteristics may result in greater nitrogen inputs and potentially higher nitrogen excretion per unit of production. Differences between finishing-site (FS) and farrow-to-finish (FTF) systems should be considered in light of their different production structures and associated modelling assumptions. FS farms purchase weaned piglets from external suppliers and focus on the growing-finishing phase, whereas FTF farms manage the entire production cycle within the same production unit. As dedicated weaning units are not subject to the Industrial Emissions Directive, they were not represented in the available dataset. Purchased piglets in FS systems were therefore modelled using farm-specific data on their number and average live weight, while upstream environmental burdens were derived from certified LCA background databases. Consequently, the numerically lower GWP per kilogram of live weight observed in FTF compared with FS farms may partly reflect differences in system configuration and the modelling of purchased piglets rather than farm management alone.

While global warming potential represents a key indicator, it alone does not fully capture the environmental profile of heavy pig production systems. Acidification and eutrophication are particularly relevant in high-density livestock areas and provide complementary information on nitrogen-related environmental pressures (McAuliffe et al. 2016; McClelland et al. 2018). Comparisons among studies for these impact categories should account for differences in characterisation methods and unit of measure (Reckmann et al. 2013). In the present study acidification potential was lower than García-Gudiño et al. (2020) but higher than Conti et al. (2021). These differences may reflect variations in production systems, feeding strategies, nitrogen excretion, manure management practices, and methodological choices among studies. Within the present dataset, nitrogen excretion varied among production systems, which is consistent with the observed variability in acidification and eutrophication potentials (Rigolot et al. 2010; Esteves et al. 2021).

The environmental performance of pig production systems is known to be influenced by both animal performance and farm management practices. Previous studies have identified feed conversion ratio (FCR) as one of the main drivers of environmental performance (Reckmann et al. 2016; Berton et al. 2024). However, the limited variability observed among farms in the present dataset, likely reflecting the standardised production requirements of the PDO production system, did not allow its influence to be evaluated in detail. Nevertheless, feed production emerged as the dominant contributor to all impact categories, in agreement with previous European LCA studies that consistently identify feed as the main environmental hotspot in pig production (Basset-Mens and van der Werf 2005; Basset-Mens et al. 2007; Nguyen et al. 2011; Reckmann et al. 2013; Gallo et al. 2015; Malgwi et al. 2021).

The importance of feed production is particularly evident in heavy pig systems, where the extended finishing period results in greater cumulative feed consumption per animal. In addition, diet composition, especially the inclusion of protein-rich ingredients such as soybean meal, contributes substantially to land-use impacts and, where relevant, land-use change (Caro et al. 2018). Feed-related impacts were modelled using Ecoinvent and Agri-footprint, which are established background databases widely used in LCA studies. The datasets were selected to represent as closely as possible the characteristics of the feeds used on the investigated farms, particularly with regard to crude protein content and the use of genetically modified (GM) feed ingredients. However, to our knowledge, specific LCA datasets for compound and complementary feeds formulated for pigs within Italian PDO production chains are currently unavailable. Therefore, the development of supply-chain-specific inventory data could further improve the representativeness of feed-related impact estimates for Italian heavy pig production. Given the dominant contribution of feed production, several mitigation strategies have been proposed in the literature, including reducing dietary crude protein while balancing essential amino acids (Portejoie et al. 2004; Pomar and Remus 2019), partially replacing soybean meal with locally produced protein sources or agro-industrial by-products (Reckmann et al. 2016; Bava et al. 2017), and implementing precision feeding systems. These approaches may improve nutrient use efficiency and reduce emission intensity, particularly in heavy pig production systems characterised by long finishing periods (Pomar and Remus 2019). Accordingly, the land-use values estimated in the present study are consistent with those reported for Italian pig systems (Bava et al. 2017) while manure storage remained one of the main contributors to acidification potential, in agreement with previous hotspot analyses (Pirlo et al. 2016; Bava et al. 2017; Ruckli et al. 2021; Van Mierlo et al. 2021; Zira et al. 2021; Hietala et al. 2024).

Animal health and mortality have also been identified as important determinants of environmental performance (Berton et al. 2024). Although mortality was accounted for in the life cycle inventory, the available data were insufficient to isolate its specific contribution to environmental impacts or to distinguish among its underlying causes. Consequently, mortality could not be evaluated as a specific driver of the environmental variability observed among farms. This limitation is particularly relevant because diseases such as porcine reproductive and respiratory syndrome (PRRS) have been shown to increase the environmental impacts of pig production through adverse effects on mortality and reproductive performance (Thoma et al. 2025).

No consistent differences in environmental impacts were detected among manure management technology classes. The only significant difference was observed for water use associated with the energy and fuel consumption cluster per 1 kg of heavy pig BW ($p = 0.044$). However, given the limited sample size and the unbalanced distribution of farms across categories, the absence of significant differences should not be interpreted as evidence of a limited effect of manure management technologies on environmental performance. Previous studies have consistently identified manure management as an important mitigation strategy for reducing gaseous emissions from livestock systems (McAuliffe et al. 2016; Ferreira et al. 2024), and further investigations based on larger and more balanced datasets are needed to better quantify its contribution under specific Italian heavy pig production conditions.

The findings of this study should be considered within the context of the available sample and regulatory data. While the number and distribution of farms support a primarily descriptive interpretation of the observed patterns, the use of routinely collected regulatory information enabled the environmental performance of commercial Italian heavy pig farms to be assessed under real production conditions. Further development of this approach could benefit from larger and more balanced farm samples and from the integration of additional farm-specific information, particularly on productive and reproductive performances. Linking regulatory datasets with digital farm-monitoring systems could further improve data completeness and farm specificity. Overall, the results support the potential of regulatory datasets as a practical basis for farm-level environmental assessment and benchmarking, while providing a framework that can be further refined to identify mitigation strategies for Italian heavy pig production.

Conclusions

This study provides an environmental assessment of Italian heavy pig production systems using technical data routinely collected within existing regulatory frameworks. The results confirm feed production as a major contributor to environmental impacts and highlight the relevance of production structure and farm-specific management conditions in explaining the observed variability. No clear differences associated with manure-management technologies could be identified within the investigated sample; however, this result should be interpreted cautiously because of the limited sample size and the unbalanced representation of management categories. The study also indicates that regulatory datasets can provide a useful basis for farm-level environmental assessment, potentially reducing the resources required for primary data collection. However, the applicability and scalability of this approach should be further evaluated using larger and more representative datasets and considering the methodological uncertainties associated with the use of secondary background data. Integration with digital farm-monitoring systems could further improve data completeness and farm-specificity. Future research should therefore expand the number and diversity of farms investigated and integrate more detailed information on feed origin and supply chains, including inventory data specifically representative of feeds used in Italian PDO pig production. Such developments would improve the robustness of environmental assessments and support the identification of effective mitigation strategies for the Italian heavy pig sector.

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Ethical statement

All research reported in this research has been conducted in an ethical and responsible manner, and is in full compliance with all relevant codes of experimentation and legislation.

Author contributions

CRediT: **Giulia Ferronato**: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing; **Noemi Tobanelli**: Data curation, Formal analysis, Writing – original draft, Writing – review & editing; **Anna Simonetto**: Conceptualization, Formal analysis, Writing – review & editing; **Gianni Gilioli**: Conceptualization, Supervision, Visualization, Writing – review & editing.

Generative artificial intelligence (AI)

The graphical illustration included in this manuscript was generated with the assistance of ChatGPT (GPT-5.5, OpenAI; https://chatgpt.com) based on author-provided instructions and subsequently reviewed and edited by the authors. The authors take full responsibility for the content and accuracy of the final figure.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, [GF], upon reasonable request.

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