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RESEARCH ARTICLE

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Environmental impact of Italian pig herds as affected by farm management factors

Marco Berton, Enrico Sturaro, Alessio Cecchinato, Stefano Schiavon and Luigi Gallo

Dipartimento di Agronomia, Animali, Alimenti, Risorse naturali e Ambiente, University of Padova, Legnaro, Italy

ABSTRACT

This study aimed at evaluating the environmental impact (EI) of herds representative of the Italian heavy pig production system to investigate the EI variation associated with farm management (FM), diet formulation (DF) and animal response (AR) variables. Data originated from 8 breeding farms, which included the sows and preweaning piglets (Site1) and the post-weaned piglets (7.5–30 kg body weight – BW, Site2) and 10 growing–fattening farms, dealing with 30–170 kg BW pigs (Site3). A cradle-to-farm gate Life Cycle Assessment was used, with 1 kg BW gain (BWG) as functional unit. Impact categories were global warming (GWP), acidification (AP) and eutrophication (EP) potentials and land occupation (LO). Whole-production cycle EI (Site123, 0–170 kg BW) was obtained summing up EIs of 0–30 and 30–170 kg BW animals. Impacts were analysed with one- or two-way PERMANOVA to test the effect of FM, DF and AR variables. The Site123-related EI averaged nearly 3.1 kg CO_2-eq (GWP), 50 g SO_2-eq (AP), 22 g PO_4-eq (EP) and 4.9 m^2/y (LO) per kg BWG. Site3 contributed nearly 80% of the whole impact. Regarding Site1, GWP resulted mitigated by increasing sow productivity. Site2 EI resulted mitigated by decreasing feed conversion ratio and increasing average daily gain, whereas Site3 EI by increasing feed self-sufficiency and decreasing dietary crude protein and mortality. In perspective, given the relevance of Site3 on the whole-pig system EI, a deeper integration between the farm agronomical management and the growing–finishing pigs' diets formulation would support the environmental sustainability of heavy pig operations.

HIGHLIGHTS

1. Cradle-to-farm gate environmental impact (EI) of Italian heavy pigs was assessed;
2. Farm and diet management, and animal response were evaluated for mitigation aim;
3. Integration between crop management and diet formulation should be explored for pig EI mitigation;

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Life cycle assessment; heavy pig; environmental impact; feed self-sufficiency

Introduction

Pig production is a main contributor of the Italian livestock production system, with more than 1.3 million tons of carcase weight produced in 2022 and averaging nearly 20% of the economic value of Italian livestock production (ISMEA 2023). The Italian pig system is unique worldwide because of its specialisation in the production of an industrial 'heavy and mature' type of pig, slaughtered at 170 kg body weight (BW) and 9 months of age, aimed at providing Protected Designation of Origin (PDO) dry-cured hams (Bosi and Russo 2004; ISMEA 2023). As a consequence of this specialisation, herd management goals, such as growth targets and feeding plans, and herd management indicators, such as feed conversion, are quite different than those typical of conventional pig chains based on pigs slaughtered at 90–120 kg BW (Gallo et al. 2014; Schiavon et al. 2015).

Similar to other livestock sectors, the Italian pig chain has to face various challenges to maintain its competitiveness, a major one being the increasing importance of environmental sustainability in European policies such as the Farm-to-Fork initiative (European Commission 2020), as well as consumer attitudes (European Commission 2017). Indeed, livestock systems have been estimated to generate nearly one-sixth of anthropogenic greenhouse gas (GHG) emissions (Xu et al. 2021), as well as being a notable driver

CONTACT Marco Berton marco.berton.1@unipd.it

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of acidification, eutrophication and land occupation (Steinfeld et al. 2006).

In recent years, the environmental impact (EI) associated with the pig production system has been investigated in different studies, mainly using the Life Cycle Assessment (LCA) methodology (McAuliffe et al. 2016), a quantitative method that evaluates the impact of one unit of product throughout its life cycle (ISO 2006). However, most of the studies have focused on systems that produce pigs with a final BW in the range of 90–120 kg (González-García et al. 2015; Ruckli et al. 2021; Van Mierlo et al. 2021), whereas studies dealing with the peculiar Italian heavy pig systems are still very limited. Pirlo et al. (2016) and Bava et al. (2017) mainly focused on the description of the EI associated with heavy pig production, whereas Conti et al. (2021) focused on the evaluation of the effects produced by wet acid scrubber technology on the EI of heavy pig production systems. However, although the reporting of some considerations regarding possible determinants suitable as targets for mitigation strategies exists, a specific analysis of these determinants is still lacking. Therefore, this study aimed at investigating the EI of herds representative of the Italian heavy pig production system, considering both the breeding and the fattening phases, and at investigating the relevance of some farm determinants possibly related to the environmental impact of these herds.

Materials and methods

This study involved 18 pig farms located in the Po valley, northern Italy, of which 8 were breeding farms, which rear sows and sell piglets to fattening farms, and 10 were growing–finishing farms, which purchase piglets from breeding farms and fatten them to nearly 170 kg BW. The farms included in this study had structures and management typical of the production systems considered, and they can be assumed as representative of the pig production system of northern Italy. All the farms were characterised by partial or full slatted floor with vacuum system and manure managed as a slurry in open storages. During the data collection, some farms were planning a covering of the slurry storages with floating expanded clay particles, but it was not considered in this study.

Breeding and fattening farms were evaluated with separate LCA models (BREED_LCA and FATTEN_LCA, respectively, see Figure 1) to consider their specific processes and outputs, both constructed to be compliant with FAO LEAP recommendations (FAO 2020). To obtain the EI value of whole-cycle pig production (from birth to the sale of the heavy pig at 170 kg BW), the results of the BREED_LCA and FATTEN_LCA models were merged. The BREED_LCA and FATTEN_LCA are described separately. The common characteristics of the two LCA models are the temporal scale (one year, 2020), the functional unit to which the impact is referred (1 kg BW gain, BWG) and the impact categories analysed: global warming (GWP, kg CO_2-eq), acidification (AP, g SO_2-eq) and eutrophication (EP, g PO_4-eq) potentials and land occupation (LO, m^2/y).

Pig breeding LCA model (BREED_LCA)

The BREED_LCA was set in order to include in the system boundaries the impacts related to animal management, the storage of manure, the production of on-farm feedstuffs, the purchase, transport and use of external feedstuffs, farm materials (electricity, fossil fuels) and the purchase of replacement gilts. The pig breeding farm was divided into two subsystems: Site 1, which included the management of sows and preweaning piglets up to a BW of 7.5 kg, as well as of boars and gilts, and Site 2, which included the rearing of the postweaned piglets in the BW range from 7.5 kg to 30 kg, i.e. from weaning to sale. This subdivision was useful to manage the multifunctionality typical of the pig breeding farm, which has a production based on piglets for fattening as the main product and culled sows as the co-product. The partition of the whole impact associated with Site 1 between weaned piglets and culled sows was based on an economic allocation method, with prices derived from ISMEA (2020) (Supplementary Table S1). The impact associated with the piglets sold to the fattening farm was obtained by summing up the impact associated with Site 1 and allocated to the piglets and that associated with Site 2.

Each farm was visited at least once by the same operator, with the cooperation of the technicians of the farmers' association with which all of the farms were associated. Data collection was based on official documentation (communication for the Integrated Pollution Prevention and Control – IPPC – and Nitrates EU directives) and a questionnaire about farm processes and resources, which was prepared and checked with the technicians of the farmers' association. The farm questionnaire was completed together with the farmer during the farm visit, collecting information about the sow reproductive management, the purchase and management of gilts, the agronomical inputs for the on-farm feedstuff production and the farm materials (electricity and fossil fuels) consumed on the farm. All data collected were checked with farmers and technicians for their temporal stability.

Regarding Site 1 (Table 1), data on the mean number of sows and boars, as well as data on the duration of the reproductive cycle (numbers of days of gestation, lactation and the weaning-to-conception period (WTC), calculated as the average over a one-year period), were collected for each farm. The number of litters per sow was calculated as 365 d divided by the duration of a reproductive cycle (one gestation + one lactation + one WTC). The animal flow into Site 1 consisted of piglets born during the year and gilts purchased to replace culled sows, whereas the animal flow out of Site 1 consisted of piglets destined for Site 2, culled sows (both productive output) and dead animals (non-productive output). Data collected about the animal inflow were the mean number of piglets born alive per sow and of piglets weaned per sow, the mean BW of piglets at weaning, as well as the number of gilts purchased, their age and BW at arrival at the farm and the age at first service. The total number of piglets born and weaned was computed as the number of piglets (born or weaned) per sow per year multiplied by the number of sows. The BW of the gilts at the first service was computed considering an average daily gain (ADG) of 0.6 kg/d. Concerning the animals exiting Site 1, we collected the number of piglets moved to Site 2, with relative mean age and BW per piglet, the number of culled sows (with relative BW per sow at sale) and the number of dead sows.

Data on feed intake and diet composition were derived from both the official documentation and from the farm questionnaire. In the case that the farm used only off-farm feeds, the annual quantity consumed of each type of feed was available in the monitoring report for the IPPC directive, as well as the specific pig category (lactating sows, gestating and WTC sows, boars, pre-weaning piglets, weaning-to-sale piglets, gilts) consuming those feeds. In the case of farms that used single feeds to prepare the ration fed to animals, the consumption of each feed by each pig category was computed based on the animal presence (number of animals multiplied by the days of the presence of each category), the relative inclusion of that feed in the diet of each pig category (retrieved from the farm questionnaire) and the annual consumption of that feed, reported in the monitoring report (Table 2 and Supplementary Table S2). The chemical composition of the rations was derived from the commercial label (purchased compound feeds) and from Sauvant et al. (2004) for the other feedstuffs, weighted by their relative presence in the ration. Nitrogen (N) and phosphorus (P) input–output flows were calculated according to Ketelaars and Van der Meer (1999). Nitrogen and P intakes were calculated as feed intake (kg as-fed basis) multiplied by the N and P contents of the diet (%). Nitrogen retention was computed considering a retention factor of 2.5% BWG for sows and 2.4% BWG for pre-weaning piglets and gilts, whereas the P retention factor was equal to 0.7% BWG (Poulsen and Kristensen 1998). Nutrient excretion was obtained as intake minus retention.

With regard to Site 2 (Table 3), data on the animal places, the duration of the production cycle (days from weaning to sale to the fattening farm), the BW at the beginning and end of the production cycle and

Table 1. Descriptive statistics of farm management and animal performance for sows and piglets < 7.5 kg body weight (Site1, 8 farms).

Variable	Unit	Mean	SD
Farm management			
Sows	*n*	1052	576
Boars	*n*	5	2
Feed self-sufficiency rate	%	6.5	10.6
Sow and piglets performance			
Litters	*n*/sow/y	2.41	0.04
Lactation period, per litter	D	27	2
Gestation period, per litter	D	115	0
Weaning-to conception period, per litter	D	9	3
Piglets, born alive	*n*/sow/y	34.0	5.3
Piglets, weaned	*n*/sow/y	30.1	3.8
Body weight, at weaning	kg/piglet	7.3	0.6
Mortality, pre-weaning	%	10.9	4.1
Replacement rate	%	36	8
Gilts			
Age, at purchase	D	126	56
Body weight, at purchase	kg/head	70	31
Duration from purchase to conception	D	130	52
Age, at first litter	D	370	22

Table 2. Descriptive statistics of feed consumption (as fed) and diet characteristics (% as fed) for sows and piglets < 7.5 kg body weight (Site1, 8 farms).

Variable	Unit	Mean	SD
Sows and piglets			
Feed consumption	kg/head/y	1235	86
Feed consumption, sow, lactation period	kg/head/y	367	28
dietary crude protein (CP) content	%	16.30	1.10
dietary phosphorous (P) content	%	0.64	0.09
dietary metabolisable energy (ME) content	MJ/kg	13.10	0.70
Feed intake, sow, gestation period	kg/head/y	692	66
dietary CP content	%	13.30	0.40
dietary P content	%	0.65	0.13
dietary ME content	MJ/kg	12.30	0.30
Feed consumption, piglets	kg/sow/y	88	16
dietary CP content	%	17.40	0.80
dietary P content	%	0.54	0.09
dietary ME content	MJ/kg	13.50	0.50
Gilts			
Feed consumption	kg/head/d	1.98	0.19
Dietary CP content	%	14.60	0.90
Dietary P content	%	0.54	0.06
Dietary ME content	MJ/kg	12.50	0.70
Dietary NE content	MJ/kg	9.20	0.50
Feed conversion ratio		3.30	0.32

Table 3. Descriptive statistics of farm, diet management, and performance for post-weaning piglets (7.5–30 kg body weight) (Site2, 8 farms).

Variable	Unit	Mean	SD
Farm management			
Animal places	*n*	4658	2807
Feed consumption and dietary nutrient contents			
Feed consumption	kg/d/head	0.87	0.05
Crude protein	%	16.80	0.90
Phosphorus	%	0.59	0.05
Metabolisable energy	MJ/kg	14.10	0.80
Animal performance			
Duration of production cycle	d	53	5
Body weight, initial	kg/head	7.30	0.60
Body weight, at sale	kg/head	31.60	2.40
Mortality, post-weaning	%	3.10	1.30
Average daily gain	kg/head/d	0.46	0.06
Feed conversation ratio		1.90	0.24

Table 4. Descriptive statistics of farm and diet management and of animal performance for fattening pigs (Site3, 10 farms).

Variable	Unit	Mean	SD
Farm management			
Animal places	*n*	3255	1996
Heavy pigs sold, per year	*n*	6249	3480
Feed self-sufficiency rate	%	17.80	25.20
Feed consumption and dietary nutrient contents			
Feed consumption	kg/head/d	2.76	0.10
Crude protein	%	14.20	1.10
Phosphorus	%	0.41	0.04
Metabolisable energy	MJ/kg	12.50	1.70
Animal performance			
Duration of production cycle	*d*	174	13
Body weight, at purchase	kg/head	31	3
Body weight, at sale	kg/head	170	8
Mortality	%	3.10	1.60
Average daily gain	kg/head/d	0.80	0.05
Feed conversion ratio		3.46	0.19

the mortality rate were collected for each farm. The ADG per farm was calculated as the ratio between the mean BWG per head and the mean duration of the production cycle. Regarding the feed consumption and dietary chemical composition, the data collection and editing were equal to those described for Site 1. The feed conversion ratio (FCR) was calculated as the amount of feedstuffs consumed divided by BWG. Nitrogen and P input–output balance was computed similarly to Site 1, based on feed consumption and body retention (retention factor of 2.6% BWG for N and 0.7% BWG for P; Poulsen and Kristensen 1998).

Furthermore, with respect to the breeding farm (Site 1 and Site 2), data on agronomical inputs for the on-farm feedstuff production (farm area, types and amounts of fertilisers and pesticides and mean yields) were collected to calculate the impact related to 1 kg of each feed. Feed self-sufficiency (SELF) per site was calculated as the share of feed intake produced on-farm, computed as dry matter. Additionally, the consumption of energy resources (electricity, fuel, LPG) was collected for each farm through the monitoring report (Supplementary Tables S3a-b).

Fattening farms model (FATT_LCA)

The growing–finishing farm was considered the third site of the whole pig production cycle (Site 3). The system boundaries for the LCA model applied to the fattening farms were similar to those set in the BREED_LCA, consisting of the impacts derived from the animal management, manure storage, on-farm feedstuff production, the purchased feedstuffs and materials, and relative transport. The LCA model was gate-to-gate, from the arrival of the piglets at the fattening farm to their sale to the slaughterhouse. In addition, the sources of the collected data, the construction of the farm questionnaire and the farm visit and the related interview with the farmer were equal to those described for the pig breeding farms. Data collection per farm included the number of piglets purchased and the number of heavy pigs sold in one year, with a relative mean BW per head, the mean duration of the production cycle, the annual amount of the different feedstuffs consumed and the diet formulations, with a relative temporal use, used along the production cycle (Table 4). The ADG and FCR were similar to those for Site 2. The mortality rate was calculated as the difference between the sold and purchased animals, divided by the purchased animals. The annual consumption of each feedstuff was retrieved form the IPPC monitoring report and was checked considering the ingredient composition of the diets and the daily presence (number) of pigs during the year (Supplementary Table S4). Nitrogen and P input–output flows were computed *via* the same procedure used in the BREED_LCA, from feed consumption and body retentions, assuming retention factors of 2.4% and 0.7% BWG for N and P retention, respectively (Poulsen and Kristensen 1998; Gallo et al. 2014). Consumption of energy resources was computed similarly to the BREED_LCA (Supplementary Tables S5a-b). The descriptive statistics of the farm and diet management as well as of the animal response for Site 3 are reported in Table 4.

Cradle-to-farm-gate model

The results obtained from the BREED_LCA and FATT_LCA models were summed up in order to compute the environmental impact of the whole production cycle of the heavy-pig production system, from birth to sale at nearly 170 kg BW, according to the following procedures. The impact category values associated with the piglets sold from the breeding to the fattening farms were obtained by averaging the values of the eight breeding farms, as no information on the origin of the piglets purchased by the fattening farms was available. The background impact associated with one piglet at the beginning of the fattening cycle was computed as the average impact per kg BWG of the piglet multiplied by the mean BW of the piglets entering the fattening farm. Consequently, the cradle-to-farm-gate impact associated with 1 kg BWG of a finished heavy pig was calculated as the impact embedded in the piglet plus the impact caused during the fattening period, divided by the final BW of the heavy pig.

Emissions computation

Emissions of methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) were included in the GWP category. The emissions of enteric CH_4 and of CH_4 and N_2O from manure storage were computed according to the IPCC (2019). In particular, enteric CH_4 was assumed constant and equal to 1.5 kg CH_4/head/year (Tier 1 level), whereas the emission of CH_4 from manure storage was calculated on the basis of the solid volatile rate and the gross and digestible energy intake (Tier 2), considering that the manure was managed as slurry. Emissions of N_2O from manure storage were calculated using the Tier 2 method, on the basis of N excreted by animals and a direct N-N_2O emission rate of 0.1% and an indirect (from N-NH_3 volatilisation) rate of 1% (IPCC 2019). After the storage phase, farms were distinguished according to whether they used on-farm feeds as part of the animal diets or purchased all of the feedstuffs consumed. In the former case, the manure used for agronomic use was retained and the N_2O emission related to manure spreading was considered, as well as the emission due to the other agricultural inputs used to produce the on-farm feedstuffs (chemical fertilisers, pesticides). The remaining manure not used within the pig farm crossed the system boundaries, and relative field emissions were excluded from the inventory. In the latter case, all of the manure crossed the system boundaries, excluding the relative field emissions. It was assumed that the provision of manure to an external farm would substitute an equivalent amount of chemical fertilisers (based on N and P contents), and the avoided emissions related to the production of the chemical fertilisers were considered a credit of the pig farm. In addition, the CO_2 emission related to the land use change (LUC) was not considered.

The flows of nutrients (N and P) within the system boundaries were the basis for the computation of the AP and EP categories. The procedure derived from the European Environmental Agency (EEA 2019) was used to calculate the ammoniacal N emission from manure storage and fertiliser spreading (Tier 2). On the other hand, EP computation included the emissions related to the deposition on the soil of the N volatilised from manure storage and fertiliser spreading, N leaching into the soil as nitrate (NO_3, loss based on the IPCC (2019)) and P loss in the feedstuff production stage (Nemecek and Kägi 2007). For all purchased inputs and relative transport (off-farm feedstuffs, energy resources), background emissions were computed according to the impact factors published in Ecoinvent v3.7 (Wernet et al. 2016) and Agri-footprint v5.0 (Blonk Consultants 2020) databases provided in Simapro v9.3 software. The conversion of the different emissions to the common unit of the impact categories, with respect to GWP, AP and EP, was performed based on Myhre et al. (2013) for GWP and CML (2016) for AP and EP. All impact computation equations and factors are reported in Supplementary Tables S6–S8.

Statistical analysis

The contribution of the different production phases to each impact category was analysed through a hotspot analysis (European Commission 2010). In addition, impact category values were analysed with different one-or two-way permutational multivariate analysis of variance models (PERMANOVA; PROC MULTTEST, SAS 2013) in order to test the effects of farm variables related to different aspects of pig production. The use of PERMANOVA allowed the analysis of the variance in the case of a low number of samples (Anderson 2005). The statistical analysis was performed separately for Site 1, Site 2 and Site 3, since the aims and inner processes of these pig sub-systems were different, as well as the possible farm determinants. The farm variables tested referred to the farm management, animal feeding and the animal response, according to Berton et al. (2023) (Table 5).

Each farm variable was classified into two classes (class low: $<$ mean value; class high $>$ mean value), except for SELF at Site 1 (classification based on whether all feeds consumed were purchased). Differences between the least squares means (LSMs) of the impact category values were contrasted using a Bonferroni correction and were declared significant at $p < .05$ and with a trend towards significance at $p > .05$ but $\leq .10$.

Results

On average the Site 1 (Tables 1 and 2) consisted of nearly 1050 sows (coefficient of variation, CV: 55%); these sows had 2.41 litters per year, and nearly 30 piglets were weaned per year on average (CV: 13%), with a mortality rate of nearly 11% (CV: 38%). Nearly 36% of the sows were replaced each year (CV: 22%). On average, gilts were purchased at an average age of 130 d and had their first litter at 370 d. The post-weaning piglet productive cycle (Site 2, Table 3) lasted 53 days, with almost 29 piglets sold per sow/year at 31 kg BW on average. Site 3 (Table 4) consisted of an average of nearly 3250 places, with nearly 18% of the feed produced on-farm, but a huge variation between farms (CV: 142%). On average, pigs started and finished the production cycle at 31 and 170 kg BW, respectively, with an ADG close to 0.80 kg/d, and an average FCR of 3.46. Variation between farms was limited in terms of animal performance, and the coefficient of variation for these traits did not exceed 10%.

Table 5. Farm variables used as fixed effects in the permanova analysis of the impact category values associated with pig breeding farms (sows plus piglets <7.5 kg body weight – Site1, post-weaning piglets (7.5–30 kg body weight) – Site2) and fattening pig farms (Site3).

	Site1	Site2	Site3
Farm management			
Farm size (places)	X	X	X
Feed self-sufficiency (%)	X	.	X
Dietary nutrient contents %			
Crude protein (CP)		X	X
CP, lactation	X	.	.
CP, gestation	X	.	.
Phosphorous (P)		X	X
P, lactation	X	.	.
P, gestation	X	.	.
Animal response			
Sow productivity (piglets weaned/sow/y)	X	.	.
Replacement rate (%)	X	.	.
Mortality rate (%)	X	X	X
Average daily gain (kg/d)	.	X	X
Feed conversion ratio	.	X	X
Final body weight (kg)	.	.	X

The environmental impact (mean ± standard deviation) and the hotspot analysis associated with 1 kg BWG obtained from piglets sold to fattening farms and with 1 kg BWG obtained from heavy pigs sold to the slaughterhouse are reported in Figures 2 and 3, respectively. Emissions associated with the breeding farms averaged almost 3.4 kg CO_2-eq (GWP), 58 g SO_2-eq (AP) and 23 g PO_4-eq (EP) per kg BWG, whereas the mean LO was nearly 4.7 m^2/y, with a low variation (CV: 6–7%). Regarding the single sources, feedstuff production emerged as the main driver of the GWP, EP and LO categories, contributing from 49% (GWP) to 99% (LO) of the whole impact. Among feed production sources, emissions were much more strongly associated with the purchased than with the home-grown feedstuffs (83–93% vs. 7–17%, respectively). Conversely, the primary driver of AP emissions was the storage of the pig manure (50%), although feedstuff production was again a major contributor (46%, with a purchased vs.

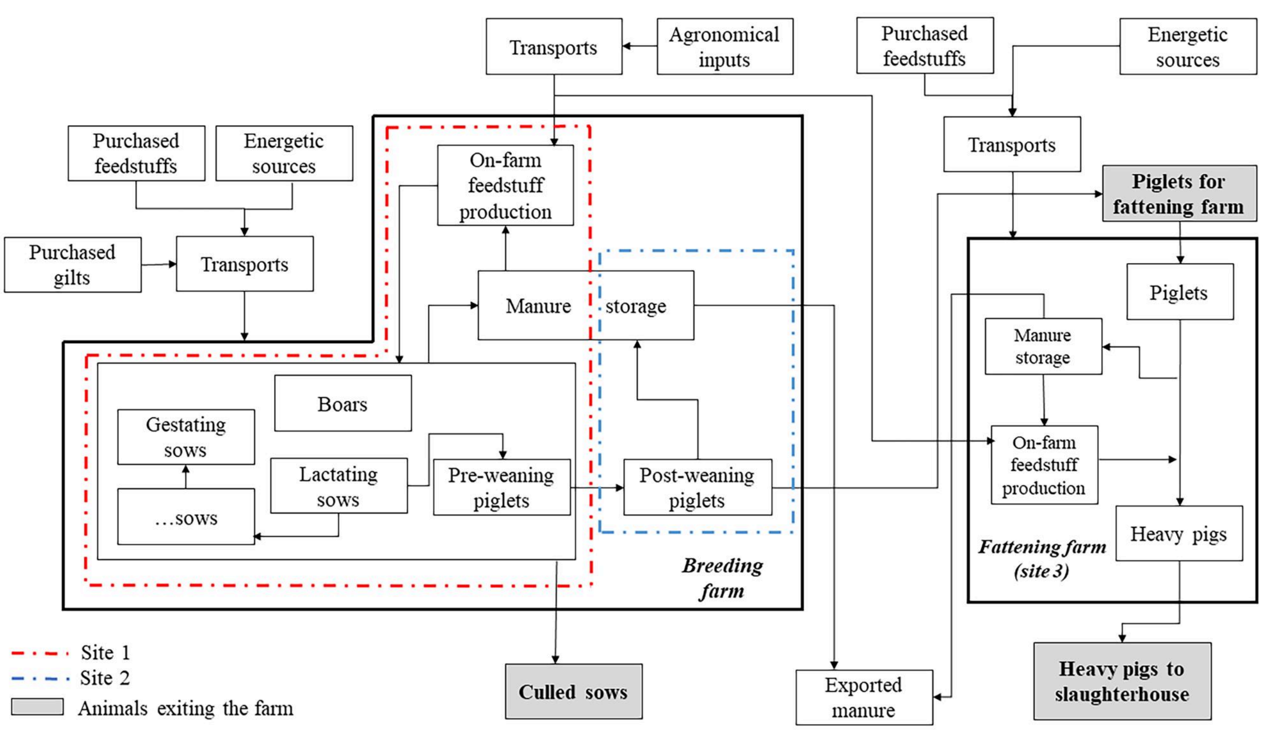

Figure 1. System boundaries for the pig whole production cycle (breeding plus fattening phases).

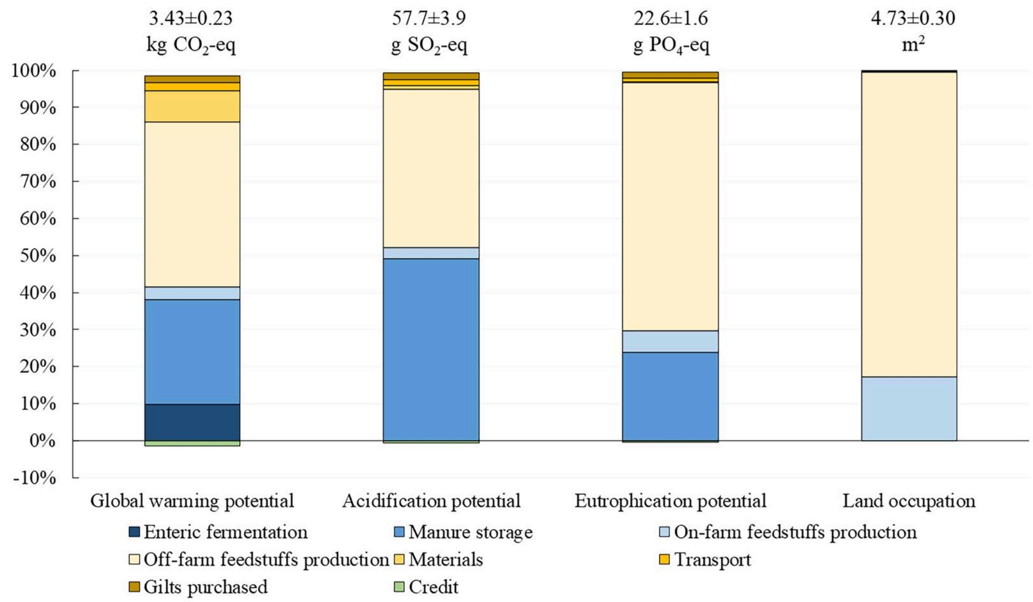

Figure 2. Raw means, standard deviations and hotspot analysis (%) of impact categories, per 1 kg body weight gain, associated with piglets sold by the breeding farms (site 1 + site 2, $n = 8$).

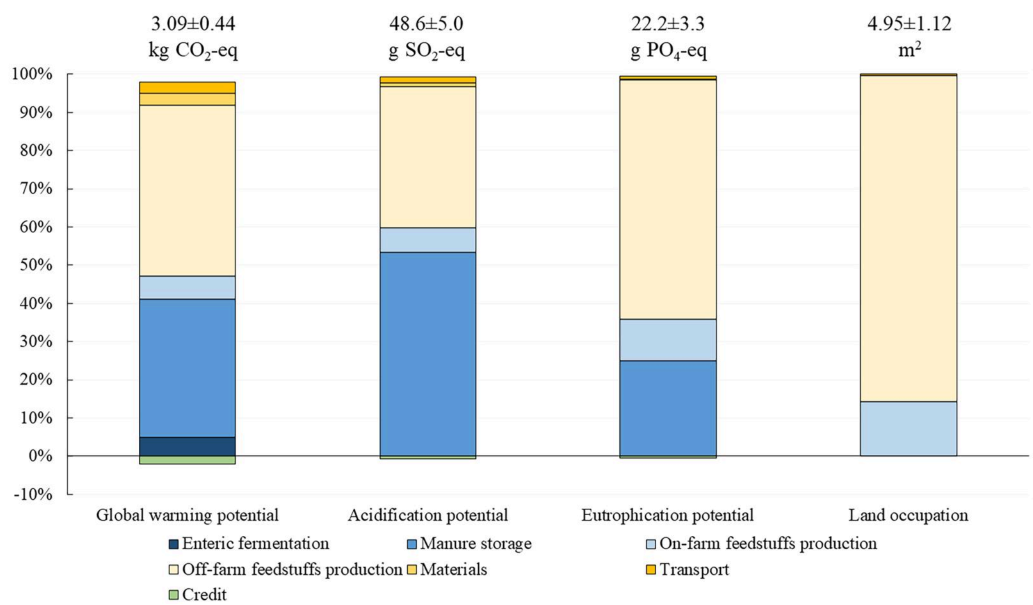

Figure 3. Raw means, standard deviations and hotspot analysis (%) of impact categories, per 1 kg body weight gain, associated with heavy pigs production (during the growing-fattening period) (site 3, $n = 10$).

home-grown feedstuff contribution pattern similar to that observed for GWP, EP and LO). Furthermore, the manure storage had a notable contribution to the EP (24%) and GWP (10%) categories, the latter one having an equal contribution to that of CH_4 originating from enteric fermentations. The other sources (materials, transport, purchased gilts) ranged from 1% to 2%, except for materials with respect to GWP (9%).

Regarding the fattening farm (Figure 3), impact values averaged nearly 3.1 kg CO_2-eq (GWP), 49 g SO_2-eq (AP), 22 g PO_4-eq and 5.0 m^2 (LO), with a variation slightly greater than that observed for the 30 kg BW piglets (CV: 11–23%). The contribution due to the different on- and off-farm processes was similar to that observed for the breeding phase. In particular, feedstuff production dominated the LO category (99% of the total impact) and had a leading contribution to EP (73%) and GWP (53%), although the average share due to home-grown feedstuffs was greater than that observed for the pig breeding farms (14–15% of the impact related to feedstuff production). In addition, manure storage was the main source of emissions

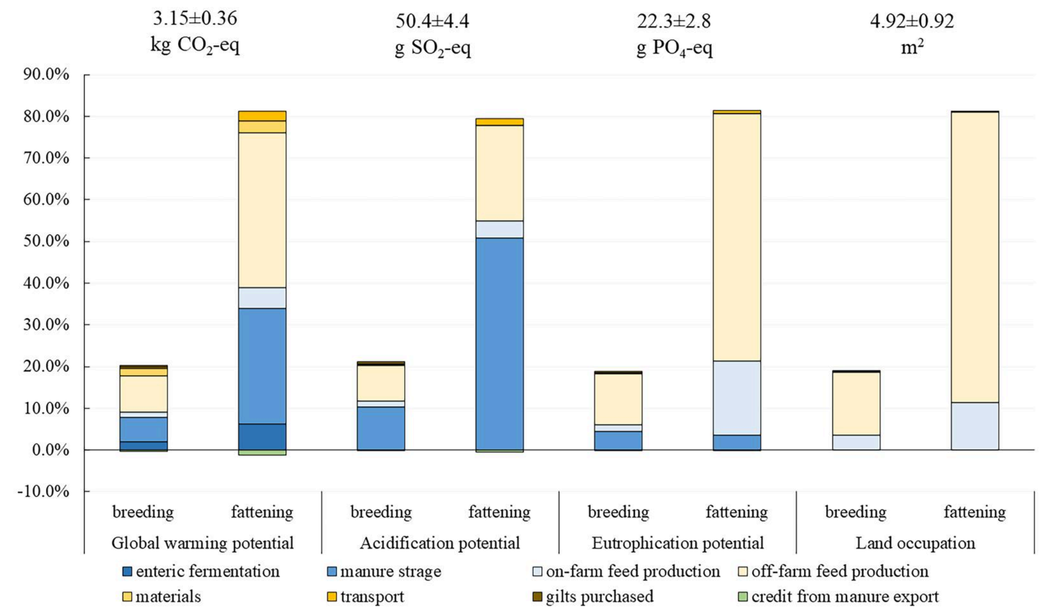

Figure 4. Raw means, standard deviations and hotspot analysis (%) of impact categories, per 1 kg body weight gain (BWG), associated with the heavy pig production in 18 farms (whole life cycle, from birth to sale at 170 kg BW).

with respect to the AP category (53%) and had notable contributions to the GWP (37%) and EP (25%) categories.

When considering the entire production cycle, from the birth to the sale of the heavy pig to the slaughterhouse (Figure 4), 1 kg BWG was associated with the emission of 3.15 kg CO_2-eq (41% CH_4, 23% N_2O and 36% CO_2), 50.4 g SO_2-eq and 22.3 g PO_4-eq, respectively for GWP, AP and EP, and the occupation of 4.9 m^2 of land surface (LO). The fattening phase (from 30 to 170 kg BW on average) was by far the main driver of the whole-cycle environmental impact, accounting for nearly 80% of the total impact, as most of the BWG is completed in this phase.

The results (F and P values) of the statistical analysis are reported in Tables 6–8, with respect to Site 1, Site 2 and Site 3, respectively, whereas the descriptive statistics of the impact category values per subsystem are reported in Supplementary Table S9. Regarding Site 1 (sows plus piglets until weaning), none of the effects tested within farm management, sow diet management and animal response variables appeared to be associated with the impact category considered, with the only exception of the sow productivity (weaned piglets/sow per year) for GWP ($p = .07$). In particular, sow productivity exerted a 10% mitigating effect on GWP (Figure 5).

As for Site 2, farm size and animal response variables (ADG, FCR and mortality rate), but not feeding management, contributed to explaining the variation of the impact values. In particular (Figure 5), the low class of farm size showed significantly lower values of the AP, EP and LO categories (ranging from −19 to −22%) and slightly lower GWP (-16%) with respect to the high class, and all of the impact categories were mitigated by increasing ADG values and decreasing FCR values (from −15 to −18% and from −18 to −20%, respectively, for ADG and FCR). Regarding Site 3, the impact values were statistically affected by farm and diet management but not by the animal response variables, with the partial exception of the mortality rate. In particular, GWP and LO were mitigated by decreasing farm size (−15 and −25%, respectively, Figure 6), whereas increasing SELF decreased the AP and EP emissions (−13 and −16%, respectively, Figure 6). Furthermore, the decrease in the dietary crude protein content was associated with the decrease in the AP and EP impact values. Moreover, the mortality rate slightly affected all of the impact categories, with decreasing impact values when the mortality rate decreased.

Discussion

Mitigating the environmental impact of the operations has increasingly become a key issue for animal production systems. The specific characteristics of the Italian pig sector, based on heavy pigs destined for PDO dry-cured ham production managed under detailed requirements in terms of age, weight, feeding programs and genetic group allowed, pose some constraints on the feasible mitigation options. For this reason, a detailed analysis of the farm determinants of the environmental impact associated with Italian pig

Table 6. Results of PERMANOVA (F-value, *p*-value and root square mean error – RMSE) for the impact category values, referred to 1 kg body weight gain, associated with the pig breeding farms (site 1: sow and gilt management plus piglets from birth to weaning).

	Mean class value		Global warming potential			Acidification potential			Eutrophication potential			Land occupation		
Variable	Low	High	*F*	*p*	RMSE	*F*	*P*	RMSE	*F*	*p*	RMSE	*F*	*p*	RMSE
Farm management														
Farm size (places)	631 ± 283	1472 ± 472	1.61	n.s.	0.34	1.82	n.s.	7.90	1.35	n.s.	3.10	0.93	n.s.	0.52
Feed self-sufficiency (%)	0.00 ± 0.00	17.20 ± 10.70	0.03	n.s.	0.38	0.17	n.s.	8.90	0.23	n.s.	3.30	0.23	n.s.	0.54
Sow diet characteristics														
Dietary crude protein content: – lactation (%)	15.30 ± 0.40	17.00 ± 0.70	1.00	n.s.	0.37	0.64	n.s.	9.10	1.01	n.s.	3.3	3.55	n.s.	0.46
- gestation (%)	12.90 ± 0.20	13.60 ± 0.20	1.00	n.s.		0.11	n.s.		0.21	n.s.		0.22	n.s.	
Dietary phosphorus content: - lactation (%)	0.57 ± 0.05	0.72 ± 0.04	1.08	n.s.	0.36	1.10	n.s.	8.9	1.31	n.s.	3.2	4.26	.09	0.44
- gestation (%)	0.51 ± 0.01	0.70 ± 0.10	1.24	n.s.		1.26	n.s.		0.70	n.s.		0.72	n.s.	
Animal response														
Productivity (piglets weaned/sow/y)	27.10 ± 1.70	33.10 ± 2.40	4.94	.070	0.29	1.81	n.s.	7.90	1.58	n.s.	3.10	1.76	n.s	0.48
Replacement rate (%)	31.00 ± 5.10	44.80 ± 0.50	0.08	n.s.	0.38	0.22	n.s.	8.80	0.46	n.s.	3.20	0.18	n.s.	0.54
Mortality rate, piglets (%)	7.20 ± 3.20	13.20 ± 2.70	1.27	n.s.	0.35	0.67	n.s.	8.60	0.26	n.s.	3.30	1.12	n.s.	0.51

Table 7. Results of PERMANOVA (F-value, *p*-value and root square mean error – RMSE) for the impact category values, referred to 1 kg body weight gain, associated with the pig breeding farms (site 2: piglets from weaning to sale).

	Mean class value		Global warming potential			Acidification potential			Eutrophication potential			Land occupation		
Variable	Low	High	F	*p*	RMSE	F	*p*	RMSE	F	*P*	RMSE	F	*p*	RMSE
Farm management														
Farm size (places)	2085 ± 905	6202 ± 2331	5.48	.06	0.24	13.89	.01	3.20	17.55	.006	1.00	13.81	.01	0.21
Diet characteristics														
Dietary crude protein content (%)	16.90 ± 0.40	17.9 ± 0.4	0.15	n.s.	0.32	0.14	n.s.	5.70	0.34	n.s.	1.90	0.01	n.s.	0.37
Dietary phosphorous content (%)	0.52 ± 0.04	0.61 ± 0.03	1.00	n.s.	0.31	3.32	n.s.	4.70	2.29	n.s.	1.70	2.28	n.s.	0.32
Animal response														
Average daily gain (kg/d)	0.41 ± 0.03	0.50 ± 0.05	15.62	.008	0.18	5.37	.06	4.40	5.79	.05	1.40	12.32	.01	0.21
Feed conversion ratio	1.70 ± 0.16	2.09 ± 0.09	26.83	.002	0.15	12.6	.01	3.60	23.03	.003	0.90	35.98	.001	0.14
Mortality rate (%)	2.20 ± 0.60	4.00 ± 1.10	0.27	n.s.	0.32	1.30	n.s.	5.30	4.58	.08	1.50	1.53	n.s.	0.32

Table 8. Results of PERMANOVA (*F*-value, *p*-value and root square mean error – RMSE) for the impact category values, referred to 1 kg body weight gain, associated with the pig fattening farms (site 3).

Variable	Mean class value		Global warming potential			Acidification potential			Eutrophication potential			Land occupation		
	Low	High	F	*p*	RMSE	F	*p*	RMSE	F	*p*	RMSE	F	*p*	RMSE
Farm management														
Size (places)	1905 ± 650	4156 ± 2117	3.81	.09	0.38	0.33	n.s.	6.30	0.79	n.s.	3.30	5.22	.05	0.78
Feed self-sufficiency (%)	2.20 ± 3.40	42.20 ± 18.30	0.44	n.s.	0.45	6.88	.03	4.70	4.67	.06	2.70	0.33	n.s.	0.99
Diet characteristics														
Dietary crude protein content (%)	13.20 ± 0.80	14.80 ± 0.60	0.44	n.s.	0.45	6.88	.03	4.70	4.67	.06	2.70	0.33	n.s.	0.99
Dietary phosphorous content (%)	0.38 ± 0.02	0.45 ± 0.02	1.13	n.s.	0.44	0.12	n.s.	6.40	0.37	n.s.	3.40	3.45	n.s.	0.84
Animal response														
Average daily gain, (kg/d)	0.76 ± 0.04	0.84 ± 0.03	1.13	n.s.	0.44	0.11	n.s.	6.40	0.14	n.s.	3.40	0.02	n.s.	0.99
Feed conversion ratio	3.27 ± 0.08	3.58 ± 0.12	0.46	n.s.	0.45	0.14	n.s.	6.30	0.09	n.s..	3.40	0.86	n.s.	0.97
Final body weight (kg)	163 ± 5	175 ± 2	1.09	n.s.	0.44	2.56	n.s.	5.60	1.83	n.s..	3.30	0.78	n.s.	0.97
Mortality rate (%)	1.80 ± 0.80	4.30 ± 1.00	3.99	.09	0.38	3.31	.10	5.40	3.54	.10	2.90	3.40	.10	0.84

production along the whole production cycle, from the birth to the sale of finished pigs, is a pre-requisite to planning effective mitigation strategies.

The mean impact values found in this study were somewhat different from those found in previous studies dealing with the Italian pig system considering the whole production cycle, from Site 1 to Site 3 (Pirlo et al. 2016; Bava et al. 2017). In particular, we obtained slightly lower GWP (−5% on average) and lower EP (−21%) values with respect to Pirlo et al. (2016) and Bava et al. (2017), whereas we found a mean AP value similar to and greater than those found by Pirlo et al. (2016) and Bava et al. (2017), respectively. Regarding the LO category, the mean value found in this study was nearly −40% relative to that found by Bava et al. (2017). These differences could probably be related to two different aspects. First, the animal response values found in this study were generally greater than those found in Pirlo et al. (2016) and Bava et al. (2017), for example, in terms of piglet weaned/sow per year (+29 to 49%) or ADG values at Site 2 and Site 3 (+37% and +8%, respectively, compared to Pirlo et al. (2016)). Second, various differences in impact computation methodology could be found with respect to Pirlo et al. (2016), who mainly used tier 1-based emission factors, and to Bava et al. (2017), who used a different version of the IPCC and EEA protocols. Moreover, differences in impact results could be also determined by the use of different statistical methodologies and software (with related impact factor databases). By contrast, the results of the hotspot analysis were similar to those found in previous Italian (Pirlo et al. 2016; Bava et al. 2017) and European (Ruckli et al. 2021; Van Mierlo et al. 2021; Zira et al. 2021) studies, which highlighted the major role of the feed production in all of the impact categories and of the manure storage in AP.

The results of this study provide evidence that the impacts of the sites of which the whole pig production cycle is composed were affected by variables related to the farm management, the feeding practices and the animal response in a complex and differentiated way. The EI associated with Site 1 was not affected by the tested farms' traits (see Table 5), with the only exception of GWP, which appeared to be slightly affected by sow productivity. The mitigating effect associated with the increasing sow productivity could be attributed to the greater BWG per sow/year, with BWG being the denominator of the impact intensity value. An increase in BWG per sow/year was also suggested by Bava et al. (2017) to mitigate GWP and by Ruckli et al. (2021) to mitigate AP, although

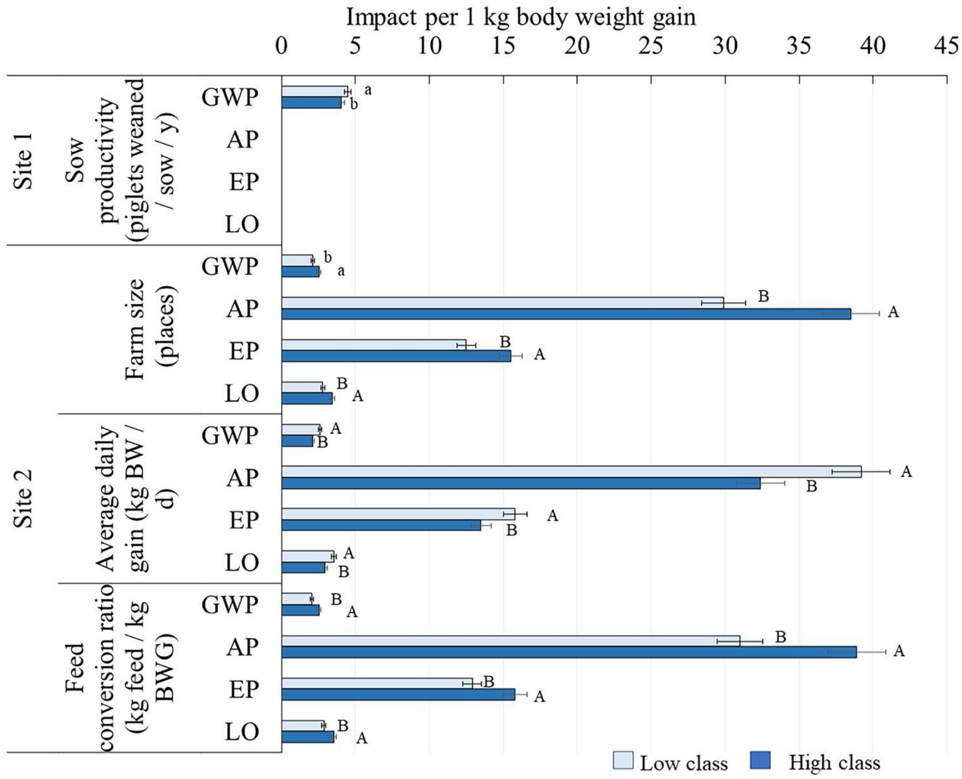

Figure 5. Least square means (LSmeans) of the impact categories (GWP: global warming potential, kg CO_2-eq, AP: acidification potential, g SO_2-eq, EP: eutrophication potential, g PO_4-eq, LO: land occupation, m^2), referred to 1 kg body weight (BW) gain, for the farm traits affecting the impact categories with $p < .1$ in Site1 (sows plus piglet <7.5 kg BW) and Site2 (piglets 7.5–30 kg BW). The farms were classified in two classes on the basis of the average value of each variable of farm management, feeding practice or animal response. LSmeans for low- and high-class farms with different superscripts within row differ significantly (a,b: $p < .10$; A, B: $p < .05$).

considering Site 1 and Site 2 together, and at a general level by Dorca-Preda et al. (2021) with respect to Site 1 only.

Conversely, the other farm traits considered did not significantly affect the impact values, probably due to the high level of standardisation in the management of the sow herds. Although some farm variables evidenced a notable variation, such as farm size (CV: 55%), the variation associated with this dimensional trait was much lower than that found in studies reporting an effect related to farm size (e.g. the interquartile range—the difference between the third and first quartiles—of the farm size was 1.7 in this study, with respect to 2.9 in Bava et al. (2017) and 3.3 in Ruckli et al. (2021)). Furthermore, although SELF showed a nominal high variation among breeding herds in this study (CV: 142%), it was probably too low in absolute value (mean close to 6%) to exert those observable effects on the impact values found, for instance, for Site 3 in this study or in other production systems, such as the Italian dairy cow system (Battini et al. 2016; Berton et al. 2023). Finally, the reduction in the mortality rate of piglets has been associated with a reduction in the impacts of pig breeding farms by Pirlo et al. (2016).

Site 2 focused on growing weaned piglets to around 30 kg BW. The results found in this study provide evidence that both the farm management and the animal response variables were effective in mitigating the EI associated with this production stage. In particular, the lower impact values found for the low class of farm size compared to the high class could be related to the possibility to better monitor animals on smaller farms; in fact, farms with a low size class obtained better ADG and FCR than the high class farms ($p < .05$) and showed a slightly lower mortality rate (1.8% vs. 4.3% for low and high class farms, respectively; $p = .09$), which, in turn, had a mild mitigating effect on EP (Supplementary Table S10). In fact, ADG and FCR emerged as drivers of the impact values for Site 2, the former reducing the period during which animals stayed on the farm before achieving the target BW, and the latter reducing the feedstuff and the impact associated with its production needed

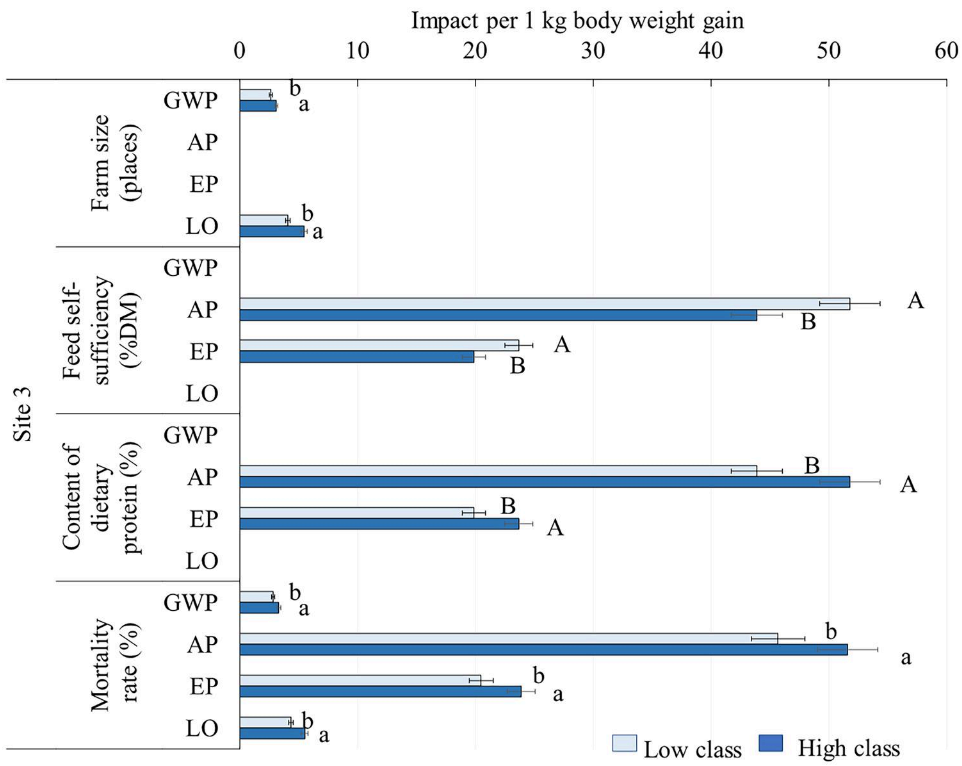

Figure 6. Least square means (LSmeans) of the impact categories (GWP: global warming potential, kg CO_2-eq, AP: acidification potential, g SO_2-eq, EP: eutrophication potential, g PO_4-eq, LO: land occupation, m^2), referred to 1 kg body weight (BW) gain, for the farm traits affecting the impact categories with $p < .1$, in the Site3 (fattening pigs 30–170 kg BW). The farms were classified in two classes on the basis of the average value of each variable of farm management, feeding practice or animal response. LSmeans for low- and high-class farms. LSmeans for low- and high-class farms with different superscripts within row differ significantly (a,b: $p < .10$; A, B: $p < .05$).

to obtain the same BWG. Improving production efficiency is a well-established measure to mitigate the environmental impact of animal production (McAuliffe et al. 2016; Gallo et al. 2017), and farms with a lower efficiency level had notable room for improvement, as the differences between the mean ADG and FCR values for farms of class low vs. those of class high were close to 20%. Furthermore, in agreement with previous work (Schiavon et al. 2019, 2022), the dietary level of CP and P did not affect the ADG and FCR levels (data not shown in tables), thus allowing a reduction in N and P supplementation, with the associated advantage of a reduction in the nutrient loss to the environment.

The role of farm traits as targets for mitigation strategies for Site 3 farms emerged as a priority issue in this study, as the fattening stage was truly predominant (about 80%) with respect to the whole-production impacts (Figure 4). The relevance of the growing–fattening stage in the emissions of the whole pig chain is further emphasised considering that growing–finishing pigs outnumber the reproductive ones in the Italian pig sector, with approximately 0.5 million sows versus nearly 5 million fattening heads (ISTAT 2023). Therefore, a reduction in the EI of the fattening phase could exert a notable effect on the environmental sustainability of the whole supply chain.

Among animal response traits, those related to the efficiency of production, such as ADG and FCR, were not associated with herd emissions. This was probably related to the low variation observed in these traits (CV: 5–6%, Table 4) due to the standardisation of the growth rate and the adoption of restricted plans of nutrition imposed by the rules governing PDO dry-cured ham production (Gallo et al. 2015; Malgwi et al. 2021). On the other hand, the mortality rate emerged as an animal response variable that can be addressed as a mitigating trait, with a mild reduction in all of the impact category values from nearly 4 to nearly 2%.

Regarding farm management, as at Site 2, we observed at Site 3 a mild reduction in the GWP and EP categories in farms with a smaller size, which posed a warning point to maintain high animal monitoring capacity while increasing the farm size. Moreover, impact values associated with Site 3 were affected by SELF, in particular AP and EP, and it was the only production site whose emissions were also affected by the dietary content of CP. Therefore, the diet formulation criteria and the origin of feedstuffs could be effective areas of intervention to address the EI of pig production, as the contribution of the diet was a primary factor in all of the impact categories (see Figures 2–4 and McAuliffe et al. (2016) for a review), and the diet formulation is under the farmers' control. The results found in this study evidence that Site 3 farms with a high level of SELF were also those that fed fattening pigs diets characterised by a lower dietary CP content. On these farms, the observed mitigating effect could be related to the major use of maize grain silage in the diet. In fact, this feedstuff is produced on-farm, thus sustaining SELF, and has a low CP content (8.5–9.3% DM, INRA-CIRAD-AFZ 2021; NASEM 2021) and may effectively contribute to lowering the impact values of the ration per 1 kg DM (from −18 to −31% on high-class vs low-class farms, depending on the impact category). Furthermore, a reduction in the dietary CP content can reduce the animal excretion in terms of N and P nutrients, thus reducing the potential pollutant pools (Berton et al. 2018; Esteves et al. 2021). These results are in agreement with the findings of Gallo et al. (2014) and Schiavon et al. (2015), who did not report any detrimental effect of a reduction of nearly 20% CP content with respect to conventional diets on the performance of finishing heavy pig farms; in addition, the chemical–physical profile of dry-cured hams obtained from these animals was not impaired (Carcò et al. 2019). At the same time, this reduction could help farmers curb feed costs related to high-protein feeds such as soybean meal, which is also frequently associated with increased LUC and therefore possibly with additional CO_2 emissions (Caro et al. 2018). In this regard, the use of traditionally less exploited feeds, such as peas and faba beans, could be of interest to sustain SELF (at the farm or regional level) while yielding similar animal performances (Prandini et al. 2011; Mordenti et al. 2012).

Conclusions

Complex relationships between the environmental impact of the different production sites of pig herds and the variables related to the farm management (farm size, feed self-sufficiency), the diet formulation (dietary CP content) and the animal response (productivity, FCR, mortality rate) have been revealed in this study, highlighting the importance of considering the various aspects of the farm in the effort to mitigate the environmental impact of animal production. The growing–fattening phase (Site 3) had a dominant contribution to the environmental impact of the whole production cycle, and improvements at this production site can play a major role in the whole supply chain. In particular, the increase in feed self-sufficiency and the reduction in the dietary CP content showed interesting room for connecting the agronomical and animal management aspects, and the feasibility of strengthen the integration between the design of crop rotations and the formulation of the pig diets should be deeper investigated. Moreover, in order to improve the feasibility of regular monitoring of farm emissions, further studies should evaluate the opportunities offered by portable gas analysers, and comparing their outcomes with emissions modelled by LCA approaches.

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Ethical approval

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.

Disclosure statement

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

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ORCID

Marco Berton http://orcid.org/0000-0002-2351-3090
Enrico Sturaro http://orcid.org/0000-0001-9508-5622
Alessio Cecchinato http://orcid.org/0000-0003-3518-720X
Stefano Schiavon http://orcid.org/0000-0002-5539-8947
Luigi Gallo http://orcid.org/0000-0002-8908-5105

Data availability statement

The data presented in this study are available on request from the corresponding author upon reasonable request.

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