Science of the Total Environment 922 (2024) 171197

Contents lists available at ScienceDirect

Science of the Total Environment

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

Air treatment technologies in pig farms. Life cycle assessment of dry and wet scrubbers in Northern Italy and Northeastern Spain

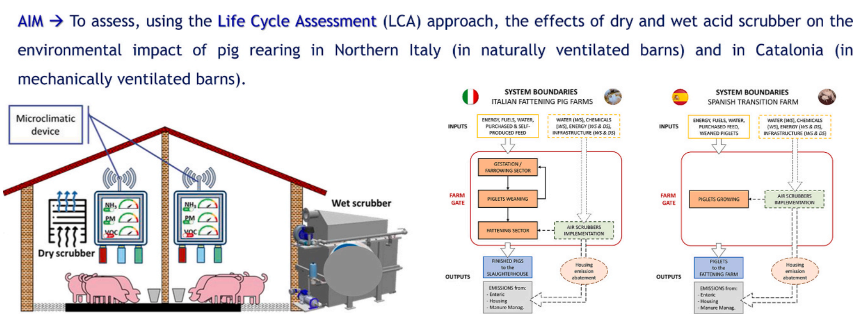
Marta Ruiz-Colmenero [a], Michele Costantini [b], Ariadna Bàllega [a], Michele Zoli [b], Miquel Andón [a], Miriam Cerrillo [a], Emma Fàbrega [a], August Bonmatí [a], Marcella Guarino [b], Jacopo Bacenetti [b],*

[a] Institute of Agrofood Research and Technology (IRTA), Torre Marimon, 08140 Caldes de Montbui, Barcelona, Spain
[b] Department of Environmental Science and Policy, Università degli Studi di Milano, Via Giovanni Celoria 2, Milan 20133, Italy

HIGHLIGHTS

- Dry and wet acid scrubbers were tested in pig barns in Italy and Spain.
- Environmental performances of scrubber were evaluated by Life Cycle Assessment.
- Scrubbers use involves trade-offs among the different environmental effects.
- Impact categories related to ammonia (e.g., PM formation) are reduced.
- Energy and acid consumptions are the main environmental contributor for wet scrubber.

GRAPHICAL ABSTRACT



AIM → To assess, using the **Life Cycle Assessment** (LCA) approach, the effects of dry and wet acid scrubber on the environmental impact of pig rearing in Northern Italy (in naturally ventilated barns) and in Catalonia (in mechanically ventilated barns).

ARTICLE INFO

Editor: Damià Barceló

Keywords:
Ammonia emission
Particulate matter
Livestock
Environmental impact
Impact mitigation

ABSTRACT

Over the years, different solutions were developed and tested to reduce the emissions of ammonia and particulate matter from the livestock facilities. The environmental performances of these solutions were not always evaluated in detail.

This study examines the environmental footprint of pig production at farm gate, with a focus on emissions from housing. Using Life Cycle Assessment, the environmental impact of pig production in a transition farm in Spain and in two finishing farms in Italy was evaluated considering three scenarios (one baseline and two of them involving an air treatment technology: wet scrubber or dry scrubber).

The study goal was to quantify the environmental footprint of pig production in different scenarios, identify key environmental hotspots, and to assess impact reduction efficiency due to the two assessed technologies, analyze the environmental trade-offs that come with the use of these technologies, and identify potential for improvements.

Both wet and dry scrubbers showed potential for reducing emissions in pig housing, affecting environmental impact categories related to air pollutants such as particulate matter, acidification and eutrophication. However, there were trade-offs between emissions reduction and categories related to energy and resource use. The infrastructure and consumables required to operate the scrubber added to the impacts compared to the baseline.

The dry scrubber showed a more favorable balance between emission reduction and trade-offs. In this regard, results were similar for the Spanish and Italian farms, although there were slight variations. Scrubbers had a

---

* Corresponding author.
E-mail address: jacopo.bacenetti@unimi.it (J. Bacenetti).

https://doi.org/10.1016/j.scitotenv.2024.171197
Received 30 November 2023; Received in revised form 10 February 2024; Accepted 21 February 2024
Available online 24 February 2024

greater effect in the Italian farms due to their use along longer periods of the pig fattening (closed cycle farms) compared to the Spanish farm (transition farm).

Scrubbers are environmentally promising, especially where acidification, eutrophication and particulate matter are local problems. However, they alone cannot fully address the complex environmental impacts of pig production, which require comprehensive interventions across the supply chain.

1. Introduction

The livestock sector is responsible of a considerable environmental impact, and, over the years, the awareness regarding this impact has increased. Ammonia (NH_3), volatile organic compounds (VOCs), particulate matter (PM) and greenhouse gases (GHG) like methane and dinitrogen monoxide stand as the primary pollutants related to this livestock activity. Ammonia is responsible of different environmental concerns. This pollutant not only contributes to nitrous oxide (N_2O) indirect emissions (contributing to climate change), but it is one of the main responsible (together with NO_2 and SO_X) for soil acidification and terrestrial eutrophication. Moreover, it also contributes to marine eutrophication as well as freshwater ecotoxicity. Besides this, NH_3 is one of the causes in the formation of particulate aerosols in the atmosphere. Secondary aerosols, measuring less than 10 μm (PM10) and 2.5 μm (PM2.5), result from chemical reactions involving NH_3, nitrogen oxides (NOx), and sulfur dioxide (SO_2) (Behera et al., 2013; Hristov et al., 2013). This issue is worrisome because fine PM can deeply penetrate the alveolar region, entering the bloodstream, elevating the risk of cardiovascular and respiratory illnesses, thereby adversely impacting human health (Dominici et al., 2006). Among the different livestock activities, pig rearing is one of those for which the environmental concerns described above are most pressing mainly because of its high concentration in specific areas (e.g., Catalonia, North Italy, Denmark) with large farms, small or no agricultural area that mainly rely on purchased feeds. In these areas, the high concentration of pig farming coupled with other livestock and agricultural activities affects the air quality, the neighborhood, the health of all three citizens, pigs, and workers, as well as pig welfare.

In this context, many mitigation solutions can be adopted to limit ammonia and PM emissions as well as the odor nuisance (Ndegwa et al., 2008; Yan et al., 2024). These solutions can be applied to the different subsystems of the pig farming process: field cultivation, animal rearing and manure management. Among the solutions applicable to animal rearing the air treatment technologies (such as biofilter, bioscrubber, biotrickling filter, dry filter, water trap, water scrubber, and wet acid scrubber) are one of the most effective (Van der Heyden et al., 2015). In Northern European pig farms, the most used air treatment technique involves the wet acid scrubber use (Costantini et al., 2020). The wet acid scrubber is tailored as an end-of-pipe technique designed specifically for forced ventilation systems in animal housing facilities to remove pollutants from the air before it is released. Air from the pig barns undergoes filtration by passing through inert packing material sprayed with an acid solution, typically made by water and sulfuric acid, before being reintroduced into the barns. The extensive contact between the air and the acid solution facilitates the conversion of soluble pollutants from gaseous to liquid form. As a result, the acid solution absorbs NH_3, leading to the formation of ammonium salt. Most of the applications of wet acid scrubber are in pig barns with mechanical ventilation where the airflow is determined by air moving fans driven while the use in natural ventilated facilities where natural forces (wind and thermal convection) are responsible for the airflow is less experienced (Bovo et al., 2022). Besides the wet acid scrubbers, also dry scrubbers (also called dry filter) can be used. This latter is a technology already used for the air treatment of industrial environments. In dry scrubbers, the air is conveyed by a ventilation system through a series of filters that retain dust of different particle sizes. The operating principle of the dry filter is based on the interposition of serial filtering panels between the dusty zone and the clean zone.

Despite the effectiveness of scrubbers was proved in Northern Europe, they do not represent a consolidated method to reduce emissions and related impacts in southern European regions (Conti et al., 2021). Nevertheless, to adhere to both present and forthcoming regulations, the utilization of air scrubbers is anticipated to increase in intensive livestock production zones throughout Europe.

However, the use of emission reduction technologies to the standard farm production structure requires additional infrastructure and consumables. Therefore, a holistic scientific approach is needed to assess the environmental performance of these technologies. Life Cycle Assessment (LCA) has become increasingly employed in recent years in the agricultural sector since it provides a useful and valuable tool for agricultural systems environmental evaluations and comparisons. LCA has been widely used to assess environmental impact of livestock activities (Hietala et al., 2021; Singaravadivelan et al., 2023) and also pig production specifically (Dourmad et al., 2014; Poore and Nemecek, 2018). This tool was selected due to its standardized quantitative approach to estimating environmental impacts from a global perspective, including multi criteria environmental indicators. LCA is an internationally recognized methodology, regulated by ISO standards (ISO, 2006a; ISO, 2006b), that aims to analyze products, processes, or activities from an environmental perspective throughout their entire life cycle, or even part of it. This methodology considers all the inputs (resources, materials, and energy consumed) used, and outputs (emissions and wastes) generated (Tsangas et al., 2023).

The aim of this study was to perform an environmental assessment of the use of two emission reduction technologies, wet and dry scrubber to test their effectiveness to reduce emissions in the pig housing in a Mediterranean context as well as assessing the trade-offs that these technologies could involve. Both technologies were tested during the project LIFE MEGA[1] in two different geographical contexts, in Northern Italy, in fattening pig farms characterized by natural ventilation and in Catalonia in transition farms with mechanical ventilation. In the wet scrubber, the acid solution is made using citric acid, this one, even if it is a less strong acid compared to the sulfuric one, involves less risks for workers and animals and can be also managed by unspecialized workers.

2. Methods

According to the ISO standards (ISO, 2006a) LCA involves 4 different steps: (i), "Goal & scope" includes outlining the functional unit (FU), setting system boundaries, and target audience; (ii) the Life Cycle Inventory where all the data regarding the energy and material flows characterizing, as inputs and outputs, the analyzed system are collected; (iii) the Life Cycle Impact Assessment involving the conversion of the inventory data in potential environmental impact and, (iv) the life cycle interpretation phase ensures the analysis and discussion of LCI and LCIA results.

2.1. Goal and scope and definition of scenarios

The goal of this LCA was to quantify the environmental footprint of

---

[1] "Smart computing system to monitor and abate the indoor concentrations of NH 3, CH 4 and PM in pig farms (LIFE-MEGA)" LIFE18 ENV/IT/000200) funded from the LIFE programme of the European Union.

pig production system at farm gate, with a focus on technologies to reduce emissions from housing and considering two of the most important European livestock areas regarding pig rearing: Northern Italy and Catalonia. In Italy, in 2022 about 8.740 million of pigs and 693.000 sows were reared, about 50 % of the heads are raised in Lombardy (Associazione Nazionale Allevatori Suini (ANAS), 2023). Spain holds first place in pig farm census with the 27 % of the European Union in 2021, and Catalonia is the Spanish region with the largest amount of meat production contributing with 40.16 % of the total amount produced in Spain (DACC, 2021).

The assessment was conducted using an attributional approach, comparing the baseline scenario (no emissions reduction technologies) with two alternative scenarios using wet and dry scrubber technologies respectively. The study considered three pig farms: a transition farm in Catalonia, Spain, and two fattening farms (referred to as Farm A and Farm B) in Italy. In this study, the 16 indicators recommended by the European Commission (CE) through the Product Environmental Footprint (Zampori and Pant, 2019) initiative, were used to quantify potential impact to climate change, acidification, and eutrophication, among others. The analysis was carried out following the guidelines on the Environmental Performance of Pig Supply Chains published by the Food and Agriculture Organization of the United Nations (FAO, 2018).

The analysis was carried out with a cradle-to-farm gate approach, the functional unit adopted was 1 kg of live weight (LW) produced per year, in accordance with the FAO guidelines (FAO, 2018) and previously carried out LCA studies focused on pig livestock (McAuliffe et al., 2016; Andretta et al., 2021). The system boundaries were cradle-to-farm gate (Fig. 1).

No impact allocation procedure was carried out because the only outputs having an economic value of the system are represented by the animals leaving the farm for fattening (in Spain) or slaughter (in Italy).

2.2. *Inventory analysis: general approach and baseline scenario*

As for Italy, the farms analyzed are in Lombardy, Northern Italy. They are two intensive closed cycle (or farrow-to-finish) farms, meaning that they produce piglets and grow them to market weight. Specifically, they produce heavy pigs for Protected Designation of Origin (PDO) dry-cured ham consortia. Mixed livestock farms are widespread in northern Italy, which means that it is common for these farms to have some arable land, usually used to grow energy-intensive crops (most commonly maize). As a result, the animals are partially fed with home-grown crops, supplemented with purchased commercial feeds and supplements.

The animals are housed in an indoor system with different specific conditions depending on their life stage. During lactation, sows are housed in farrowing crates where they are confined between bars to reduce the risk of the sow crushing her newborn piglets. After 3 weeks, the piglets are weaned and placed in a nursery while the sow is returned to the gestation crate. Here, all females are artificially inseminated and remain in the gestation barn for the gestation period. When the piglets reach approximately 25–35 kg, they are moved to a finishing barn where they remain until they reach 160 kg, which is approximately 9 months (minimum live weight and age required by the PDO regulation). Boars are used to collect semen for artificial insemination.

The categories of pigs reared are housed in barns, more specifically farrowing pigs in closed, mechanically ventilated buildings, while fattening pigs are housed in closed, naturally ventilated buildings. Electricity is consumed in both the farrowing and fattening sections for lighting, feeding, and manure management, which is handled as slurry. The feeding process also requires diesel fuel consumption for grinding, mixing and distribution operations.

As for Spain, the farm analyzed is in Santa Eulalia de Riuprimer, Catalonia. The farm in Spain includes the transition stage (pre-starter and starter), i.e. pigs from post-weaning (5 kg, 21 days of life) until they move to a new stage (a fattening farm) with 15 kg (up to 56 days of life). The farm assessed is an intensive conventional farm. The animals are housed in an indoor system. Pigs are fed with commercially purchased compound feed. Feed in the pre-starter phase was mainly composed by whey, maize, wheat, and barley. In the starter phase, main ingredients were maize, wheat, soybean meal and barley. Regarding heating, in

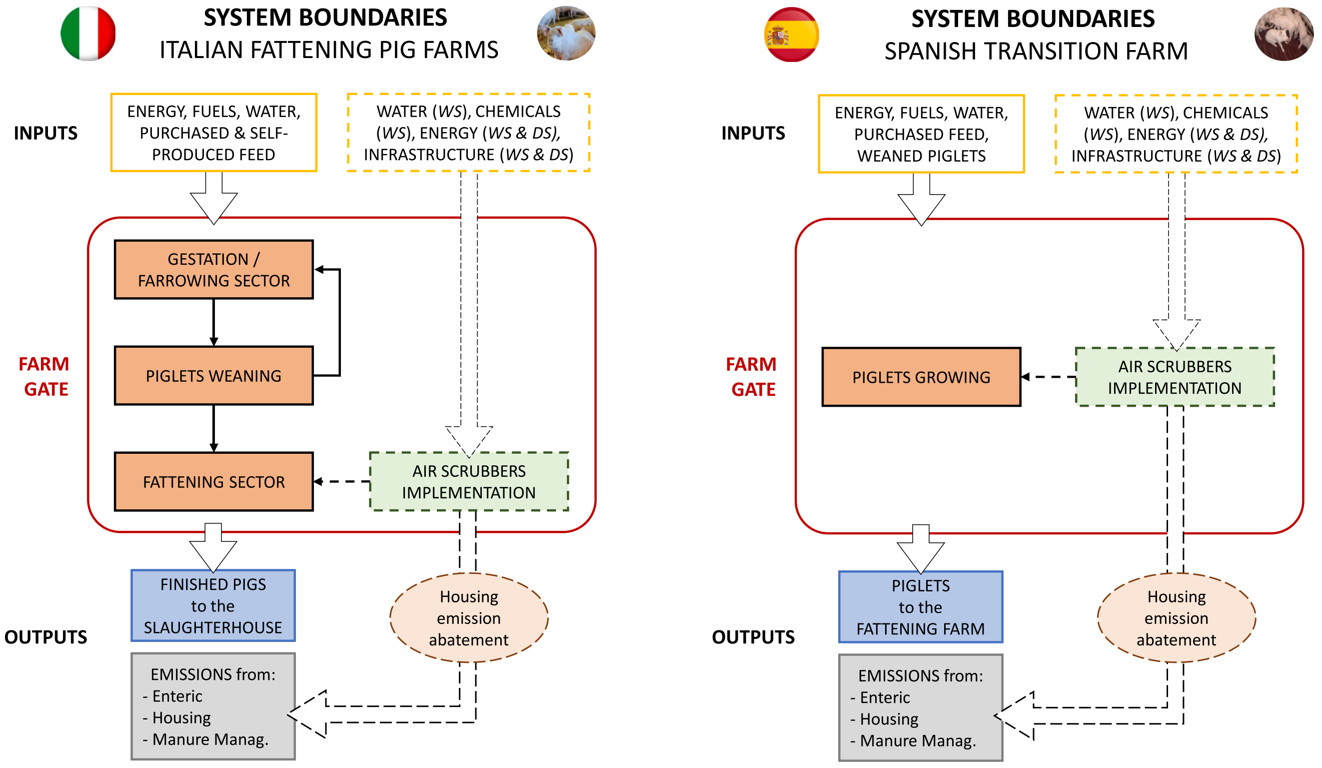


Fig. 1. System boundaries from the study.

Catalonia (temperate Mediterranean climate), for transition farms, some heating is used in winter. In this case, the thermal energy to heat the buildings is produced by a diesel boiler.

Primary data concerning farming activities were collected by means of questionnaires provided to farmers regarding inputs and outputs of production processes. Particular attention was given to: average annual pig population and mortality, divided into different sub-categories (e.g. piglets, lactating sows, gestating sows, fattening pigs for the Italian farms; piglets for the Spanish farm); annual animal purchase (i.e.: weaned piglets for transition in Spain); sales of animal heads (piglets for fattening in Spain and pigs for slaughter in Italy) considering their average LW; composition and consumption of feeds; possible on farm production of feed components; slurry management (necessary for the subsequent estimation of greenhouse gases (GHG), NH_3 and other pollutant emissions); energy and water consumption.

Primary data were supplemented with secondary data regarding air pollutant emissions which were estimated using different established models available in the literature. In detail, methane emissions due to enteric fermentation and methane and dinitrogen monoxide emissions due to manure management were considered following the Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC (Intergovernmental Panel on Climate Change), 2019). Since animal feeds did not change across scenarios, we applied TIER I emission factors. For the Spanish farm, enteric emission factors were adapted to national specific conditions for transition pigs, as the emission factor by IPCC was for higher pig live weights (72 kg for high productivity systems, while piglets in the Spanish farm were between 5 and 15 kg; IPCC (Intergovernmental Panel on Climate Change), 2019). While for manure managed as slurry as in these cases, the temperature and the retention time of the storage unit greatly affect the amount of methane produced. Default values were used depending on type of animal, manure management and climate conditions. Values for the potential IPCC climate zones of both countries, Italy, and Spain, were extracted. Regarding ammonia emissions at the manure management stage, Tier II was used according to the European Environment Agency (EEA) guidelines. This estimation method is based on information such as the number of animals, total nitrogen excretion rates (calculated according to IPCC guidelines); proportion of nitrogen excreted in buildings; proportion of nitrogen excreted as total ammoniacal nitrogen (TAN) and proportion of excretion site; amount of manure handled as liquid or solid manure; use of animal bedding; slurry storage system.

The farm's infrastructure (stables) was excluded from the impact assessment (Bacenetti and Fusi, 2015; Notarnicola et al., 2012). Their impact on the pork supply chain was assumed negligible due to their life span (tens of years), as widely reported in the literature for livestock. On the other hand, the infrastructure of the technologies used has been included. In fact, these have much shorter life spans (about 10 years) and therefore it cannot be taken for granted that the contribution to the impacts is low.

Secondary data regarding raw materials and some feed ingredients were retrieved from the established Ecoinvent database v3.8, Cut-Off system model (Wernet et al., 2016). Where available, datasets with specific geographic representativeness were used (e.g.: crops where geographical origin was known like wheat grain used in the Spanish farm, coming mainly from Spain "ES"), or datasets were adapted to local conditions when possible for better geographical representation (e.g., taking into account the electricity sources used in the electricity mix at a national level for Italy and Spain), or otherwise European ("Europe without Switzerland" dataset) or world ("GLO" datasets) average ones. In some cases, especially for feed ingredients, average datasets were modified considering local conditions to better represent the reference Italian and Spanish production context.

The inventory data for the three different farms is reported in the *Supplementary Material.*

2.3. Inventory analysis: alternative scenarios

Two alternative scenarios were assessed in each farm which were compared with the baseline scenario (i.e., no air treatment technologies): i) a wet scrubber scenario, ii) a dry scrubber scenario. This section describes the methodological framework of each air treatment technology for pig housing in the production cycle, detailing the corresponding inventory data.

2.3.1. Wet scrubber

The wet scrubber (Fig. 2) is made by two stainless steel tanks, the first one contains water while the second one a solution of water and citric acid. The device treats the polluted indoor air, which is drawn in by a vacuum created by a blower and recirculates the purified air into the barns. It consumes a citric acid solution, water and energy for the blower. In this scenario, the energy, water, and acid consumption data for the scrubber, as well as the raw materials and energy required to build the machinery, were included in the system boundaries.

A single wet scrubber prototype unit weighs 2000 kg and it is also equipped with 30 m of corrugated polyethylene ducting for air intake and exhaust. A depreciation rate of 10 years (based on De Vries and Melse, 2017) was considered to model the infrastructure inventory by year, as shown in Table 1. The same amount unit^{-1} year^{-1} was inventoried as waste (scrap steel and waste polyethylene). For polyethylene pipes it was considered the conversion 1 m (corrugated polyethylene pipe - DN75) = 0.347 kg.

Consumables for scrubber operation, namely citric acid, water, and electricity, were modelled in order to express them in relation to 1 kg of ammonia removed by the scrubber. Water and citric acid consumption values used as inventory data correspond to the medians of the measurements made during the field trials. Expressed per kilogram of removed NH_3, water consumption was 279.42 dm^3 while citric acid consumption was 13.81 kg.

As regards electricity consumption, the average hourly consumption of 0.48 kWh per scrubber unit was used, measured during field trials thanks to an energy meter, and considered in the alternative scenario assuming 100 % annual operation of the device.

Table 2 shows the abatement efficiencies considered for the wet scrubber for the various air pollutants, resulting from the field trials.

All the pig farms where the scrubbers were tested are characterized by different barns. One wet scrubber and one dry scrubber were installed per farm; therefore, the scrubbers were not operating in all the barns. The results achieved during the monitoring of the scrubbers were scaled up to assess their impact in the whole farm. For the scaling up, the following parameters so were taken into account:

- the ventilation capacity → 6700 m^3 h^{-1}
- an ammonia concentration inside pig barns → 10 mg m^{-3}
- ammonia emission factor from housing, per pig place → 2.5 kg year^{-1} (reference value for fattening pig farms in Europe, source EEA)
- 100 % of working time during the year.

The total inlet ammonia, the amount of ammonia contained in the volume of air that is treated by the scrubber per year, is equal to 586.9 kg of NH_3 while the number of heads for which a wet scrubber of this size would be suitable is about 230. This latter can be estimated as the ratio between the total inlet ammonia/ammonia emission and the ammonia emission factor from housing, per pig place. In the Spanish farm, as pigs were smaller, the number of heads for which a wet scrubber of this size would be suitable is greater, 1402 piglets. Thus, the ammonia emission factor per pig obtained was about 0.4185 kg $^{-1}$ year^{-1} (calculated value based on the total obtained ammonia emissions calculated following the methodology from the EEA divided by the 7573 pig average occupied places in the farm along the year).

In the modelled Spanish farms 5.4 scrubber units were calculated

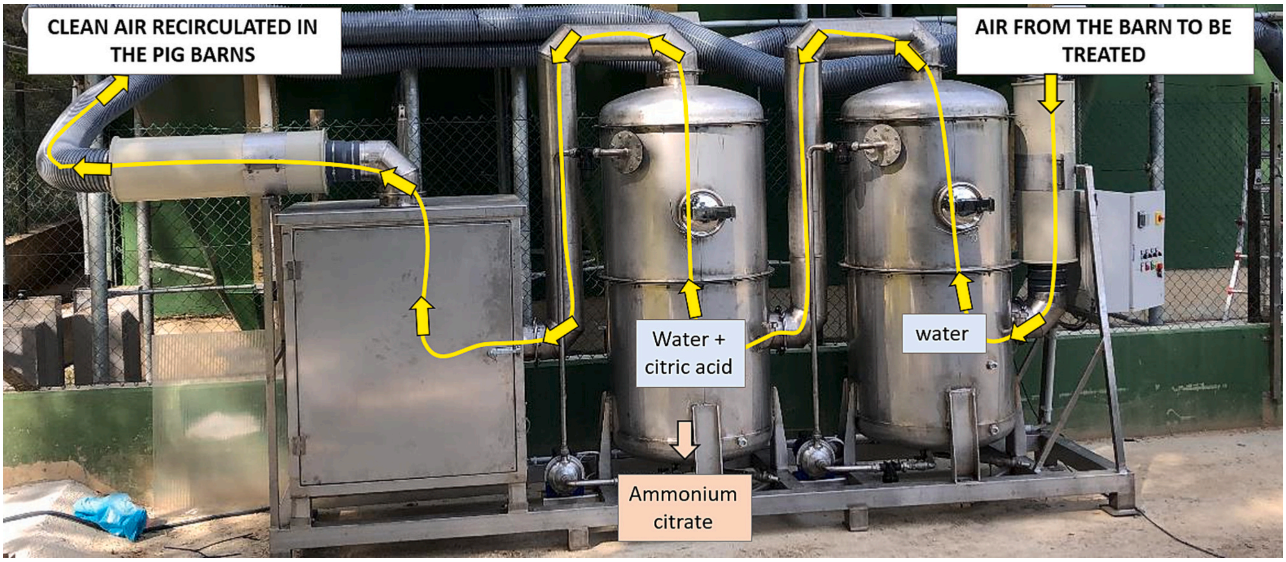


Fig. 2. The wet acid scrubber installed in the farm in Catalonia. The yellow line represents the path of the air inside the device.

Table 1
Wet scrubber infrastructure inventory.

Material	Amount	Life Span
Chromium steel	2000 kg	10 years
Polyethylene	30 m	10 years

Table 2
Pollutants abatement efficiency obtained during the field trials in Italy and Spain regarding the *wet scrubber*, used to model the alternative scenario.

Air pollutant	Spain	Italy
Ammonia	−79 %	−59 %
PM10	−100 %	−27 %

necessary to treat the whole assessed farm while, for Italy, the installation of 12 and 16 scrubber units was considered in the Farm A and B, respectively.

As regards the modelling of alternative scenarios in the Italian farms, the technologies were considered as if they were implemented only in the fattening phase facilities (pigs weighing from 50 to 80 kg onwards) and not in the sow reproduction and piglet growth phases where the experimental tests were not carried out.

2.3.2. *Dry scrubber*

The dry scrubber is produced by the Tecnosida company (https://www.tecnosida.com/), it has a fan inside a box mounted inside the pig housing facilities which blows air towards polyester fiber panels (about half a square meter of the total surface per scrubber unit). The flow rate can vary between 3000 and 6000 m^3 h^{-1}. The same lifetime of the wet scrubber (10 years) was considered for the analysis and the same principle of sizing and scaling, these having been used in field trials on rooms of similar size.

As for the infrastructure, the Ecoinvent process "*Blower and heat exchange unit, central, 600-1200 m^{3}h^{-1} {GLO}| market for | Cut-off, U*" was used as a proxy. Considering that the flow of dry scrubber is higher than the one of dataset (3000–6000 m^3 h^{-1} vs 600–1200 m^3 h^{-1}), the dataset was scaled up.

Considering that, the polyester fiber has a very low weight and that, according to the manufacturer, the panels, under correct periodic maintenance, can also be replaced every 3–5 years, the filtering material was considered negligible for the purposes of the life cycle analysis and excluded. Consequently, the only consumable included for the dry scrubber scenario was electricity (average hourly consumption 0.55 kWh).

Table 3 shows the abatement efficiencies considered for the dry scrubber for the various air pollutants, resulting from the field trials of this project.

2.4. *Impact assessment*

Life Cycle Impact Assessment (LCIA) can be defined as the phase of the LCA that aims to assess the magnitude of the potential environmental impacts of a production system, in this case the production of pigs at farm gate. In LCIA, impact models are used to calculate characterization factors (CF) that relate elementary flows (resource consumption, emissions) to the corresponding environmental impacts in different indicators (impact categories).

While climate change and other impact categories such as eutrophication, acidification or land use are commonly assessed in LCA studies from pig production (Gislason et al., 2023), there are other impact categories which are often not addressed despite their potential importance for human and ecosystems health, such as particulate matter. The method used, EF, intends to include all aspects relevant for human health and ecosystem quality and resources depletion, giving a global view of the studied product environmental performance. Not considering those aspects can lead to unwanted externalizations of the impact. In this study. In this study all 16 indicators recommended by the European Commission (EC) through the Product Environmental Footprint initiative (Zampori and Pant, 2019) were assessed:

- Climate change (CC - kg CO_2 eq);
- Ozone depletion (OD - kg CFC11 eq);
- Ionising radiation (IR - kBq U-235 eq);
- Photochemical ozone formation (POF - kg NMVOC eq);
- Particulate matter (PM - disease inc.);
- Human toxicity, non-cancer (HT-noc - CTUh);

Table 3
Pollutants abatement efficiency obtained during the field trials in Italy and Spain regarding the *dry scrubber*, used to model the alternative scenario.

Air pollutant	Spain	Italy
Ammonia	−48 %	−62 %
PM10	−100 %	−45 %

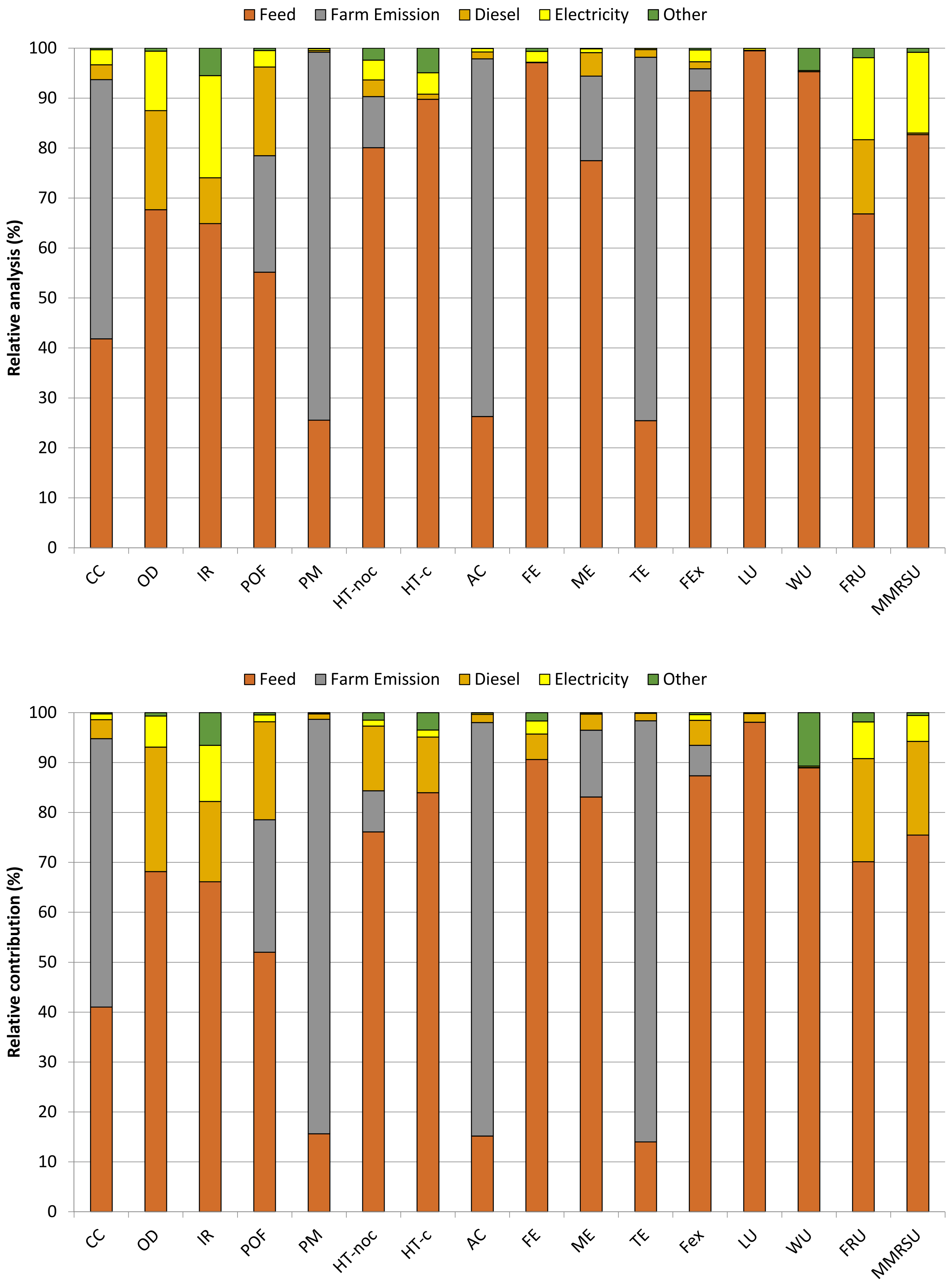


Fig. 3. Contribution analysis from the three farms assessed. Italy farm A (fattening farm) on the top, Italy farm B (fattening farm) in the middle, Spain (transition farm where piglets were purchased) on the bottom.

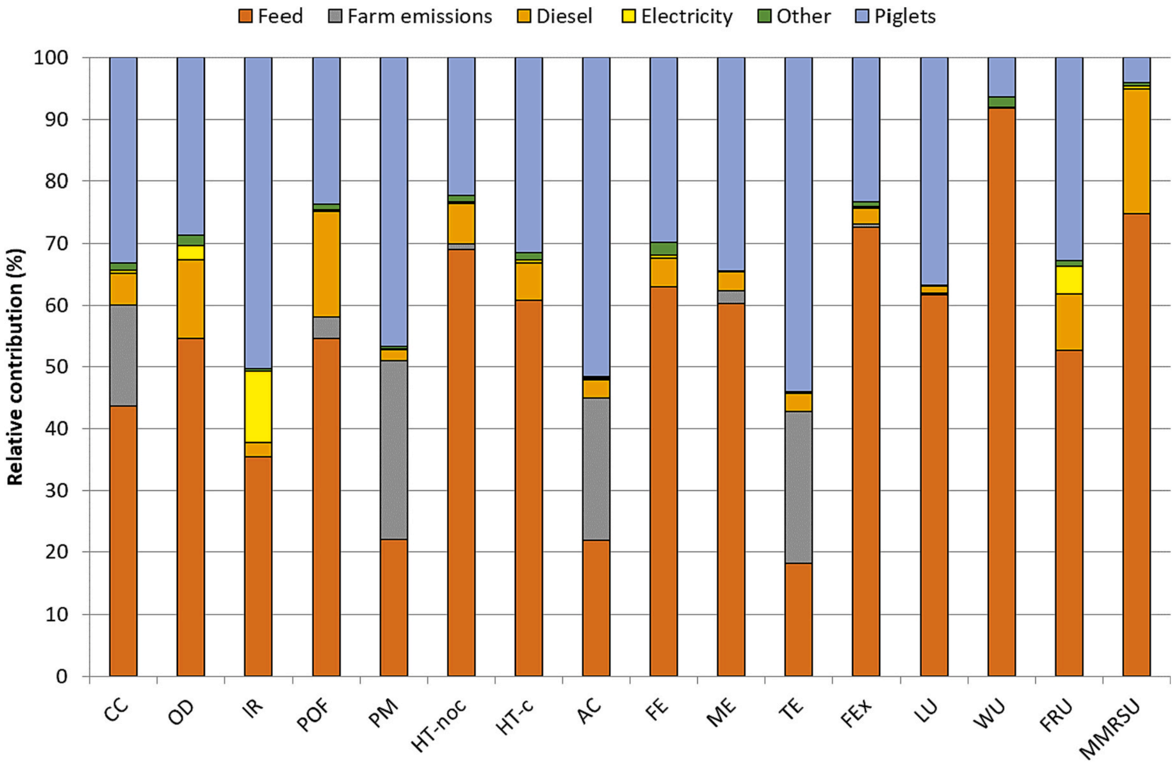


Fig. 3. (*continued*).

- Human toxicity, cancer (HT-c - CTUh);
- Acidification (AC - mol H+ eq);
- Eutrophication, freshwater (FE - kg P eq);
- Eutrophication, marine (ME - kg N eq);
- Eutrophication, terrestrial (TE - mol N eq);
- Ecotoxicity, freshwater (FEx - CTUe);
- Land use (LU - Pt);
- Water use (WU - m3 depriv.)
- Resource use, fossils (FRU - MJ);
- Resource use, minerals and metals (MMRU - g Sb eq).

The results of the LCIA impact indicators are calculated for the recommended impact categories according to the EF 3.0 Method (adapted) V1.00 (Fazio et al., 2018), derived from the International Life Cycle Data System, International Reference Life Cycle Data System (ILCD). EF is the methodology recommended by the European Commission (European Commission, 2021), and one of the aims of this project is to assess mitigation technologies that could become useful to make policy recommendations (i.e.: updates to the BATs for pig farming). Furthermore, EF despite is not free of limitations, is currently one of the most updated methodologies providing European coverage (European Comission, 2021). The analysis was carried out using the Simapro software version 9.4.0.2 (PRé Sustainability, 2022).

3. Results

3.1. Baseline

As for Italy, the two farms studied show different results in absolute terms but are similar in relative terms. In fact, the impact per kg live weight is different between the two, mainly due to the different feeds used. On the other hand, the contribution analysis (Fig. 3) clearly showed what the impact hotspots were for the different categories, and these remained consistent between the two. Feed consumption and supply played an important role in all environmental impact categories, and it was responsible for more than 50 % of the total impact for Ozone depletion, Ionising radiation, Photochemical ozone formation, Human toxicity, non-cancer, Human toxicity, cancer, Acidification, Eutrophication, freshwater; Eutrophication, marine, Ecotoxicity, freshwater, Land use, Water use, Resource use, fossils and Resource use, minerals and metals.

The results of the contribution analysis are consistent with previous LCA study on pig livestock production (Bava et al., 2017; García-Gudiño et al., 2020; McAuliffe et al., 2016). The main contribution comes from on-farm pollutant emissions, for climate change (46 % due to methane emission from manure management), particulate matter formation (60 % due to ammonia emission from housing and about 18 % from ammonia emission from manure management) and terrestrial eutrophication (about 60 % from pig housing and 17–18 % from ammonia emission from manure management). In the Spanish farm the purchasing of weaned piglets (which includes farm emissions from the piglet production farm) had a large role. The difference between the results depends on the different rearing phases considered, in addition to the fact that in Spain the farm is an open cycle system and therefore depends on external piglets supply.

3.2. Emission reduction technologies

Tables 4–5 report the comparison of the absolute impacts for the three scenarios: baseline, wet scrubber, and dry scrubber.

The profile of several impact categories (acidification, terrestrial eutrophication, particulate matter) was improved by the emissions reduction achieved by the technologies (wet and dry scrubber). In Spain, impact results for particulate matter reached a maximum reduction of 17 % and 14 % with wet scrubber and dry scrubber respectively. Same occurred with impact to acidification and terrestrial eutrophication, where using wet and dry scrubber (due to the 79 % and 48 % ammonia abatement reduction obtained respectively) resulted in 12 % and 8 %, and 14 % and 9 % impact reduction assessed, respectively. Same trend was observed in Italy, where a reduction of 18 % and 25 % for wet and

Table 4
Absolute environmental results for 1 kg of live weight for the three scenarios in Spain.

Impact category	Unit	Baseline	Wet scrubber	Dry scrubber
CC	kg CO_2 eq	3.075	3.150	3.073
OD	mg CFC11 eq	0.204	0.213	0.204
IR	kBq U-235 eq	0.404	0.414	0.407
POF	g NMVOC eq	8.852	9.113	8.874
PM	disease inc.	3.40E-07	2.82E-07	2.92E-07
HT-noc	CTUh	8.32E-08	8.66E-08	8.35E-08
HT-c	CTUh	2.05E-09	2.24E-09	2.06E-09
AC	mol H+ eq	4.48E-02	3.92E-02	4.11E-02
FE	g P eq	0.567	0.593	0.570
ME	g N eq	15.972	15.932	15.865
TE	mol N eq	0.187	0.161	0.171
FEx	CTUe	103.039	106.190	103.145
LU	Pt	201.931	202.743	201.958
WU	m3 depriv.	20.792	20.914	20.795
FRU	MJ	21.779	22.684	21.887
MMRSU	g Sb eq	0.038	0.040	0.038

dry scrubber scenarios was achieved for acidification in the farm A, and a reduction of 13 % and 18 % was obtained with wet and dry scrubber scenarios, respectively, for farm B (particulate matter, terrestrial eutrophication was reduced). Both, acidification, and terrestrial eutrophication, are closely related with ammonia emissions. Particulate matter is closely related with the concentration of particles in the atmosphere. Therefore, an impact reduction was expected when applying emission mitigation technologies that reduced the amount of those pollutants. However, there are other impact categories which are also related with ammonia, such as freshwater ecotoxicity and to a lesser extent marine eutrophication and human toxicity, non-cancer. In the case of these impact categories, the impact reduction due to pollutant abatement is completely offsetted by the added impact coming from the production and use of the scrubbers. The most clear case is freshwater ecotoxicity, emissions contributing to this impact were reduced in a 41 % by using the dry scrubber, and in a 64 % by using the wet scrubber. However, farm emissions only contributed to less than 1 % of the total impact for this category. Mainly feed followed by diesel were the main impact drivers. Therefore, despite the large emissions reduction achieved, this didn't have a consequence in the overall farm results. This was similar for marine eutrophication (where emissions contribute in less than 2 % to the total impact) and human toxicity, non-cancer (where emissions contribute in less than 1 % to the total impact). In those impact categories where ammonia and PM emissions are not related with the impact, final results were similar or greater than in the baseline, as expected. In total, 13 of the 16 evaluated environmental effect for the wet scrubber and 10 for the dry scrubber showed larger results in the scrubber's scenarios due to scrubber manufacturing and consumables consumption (i.e.: water and citric acid in the case of the wet scrubber, and electricity consumption for both the dry and the wet scrubber). In particular, citric acid was the largest contributor to the wet scrubber impact.

As with the baseline scenario, slightly different values are observed between the two farms in Italy for the alternative scenarios, but the relative differences between the baseline and alternative scenarios follow the same trends between the two farms. Respect to the wet scrubber scenario, the dry scrubber one resulted in better environmental performance for all the evaluated impact categories. Besides this, compared to the baseline, the dry scrubber scenario achieves an impact reduction for 6 of the 16 impact categories (for the wet scrubber scenario, this happens in only 4 impacts) and, compared to the wet scrubber scenario, presents higher impact reductions. In detail, for the three categories also reduced by the wet scrubber, the dry scrubber achieved higher reductions:

- for PM, −18.1 % and − 25.2 % is observed in Farms A and B versus −10.3 % and − 14.2 % in the wet scrubber scenario;
- for AC, −18.0 % and 25.4 % in Farms A and B versus −12.8 % and − 18.1 % in the wet scrubber scenario;
- for TE, −18.4 % and 26.0 % in Farms A and B versus −15.4 % and − 21.7 % in the wet scrubber scenario;

For the impact categories that are not affected by the emission reduction, non-negligible impact increases are observed in the wet scrubber scenario, which in case of Farm B were greater than 50 % for OD, IR, FRU, and greater than 100 % for MMRU. In the case of the dry scrubber, the impact increases remained under 5 % across categories.

Same trend was observed in the results of the emissions reduction scenarios in Spain, despite some variations in the abatement efficiencies obtained. This was because, as in the Italian farms, there were some tradeoffs due to the increase in the use of resources in the wet and dry scrubber scenarios. Overall, it was also the dry scrubber the air treatment technology that showed better results, when excluding the impact categories directly related with PM and ammonia emissions. Impact increase was greater in the case of the wet scrubber due in general to the use of the citric acid, and in particular for MMRU (impact increase of 4.76 % respect the baseline) and HT-c (9.41 % impact increase respect the baseline) due to the technology infrastructure materials and processing. Meanwhile, in the dry scrubber the impact increase was around 1 % only for the impact category IR (mainly due to an increase on electricity consumption) and MMRU and HT-c (mainly due to the metal welding used in the infrastructure), or lower for the rest of impact categories.

Table 5
Absolute environmental impact for 1 kg of live weight for the two farms and the three scenarios in Italy.

Impact category	Unit	Farm A			Farm B		
		Baseline	Wet scrubber	Dry scrubber	Baseline	Wet scrubber	Dry scrubber
CC	kg CO_2 eq	4.952	5.481	4.946	6.039	6.875	6.025
OD	mg CFC11 eq	0.170	0.234	0.172	0.150	0.251	0.153
IR	kBq U-235 eq	0.099	0.127	0.101	0.083	0.127	0.086
POF	mg NMVOC eq	10.282	12.069	10.322	11.211	14.026	11.266
PM	disease inc.	7.67×10^{-7}	6.88×10^{-7}	6.28×10^{-7}	8.68×10^{-7}	7.44×10^{-7}	6.49×0^{-7}
HT-noc	CTUh	3.77×10^{-8}	6.10×10^{-8}	3.78×10^{-8}	5.95×10^{-8}	9.63×10^{-8}	5.97×10^{-8}
HT-c	CTUh	1.30×10^{-9}	1.87×10^{-9}	1.31×10^{-9}	1.83×10^{-9}	2.71×10^{-9}	1.85×10^{-9}
AC	mol H+ eq	0.107	0.093	0.087	0.119	0.098	0.089
FE	g P eq	1.740	1.918	1.745	0.665	0.944	0.672
ME	g N eq	13.780	14.267	13.204	22.510	23.277	21.599
TE	mol N eq	0.468	0.396	0.382	0.522	0.409	0.387
FEx	CTUe	77.429	100.073	76.867	72.881	108.560	71.930
LU	Pt	194.947	200.662	195.025	210.065	219.073	210.171
WU	m3 depriv.	44.573	45.345	44.582	18.602	19.819	18.614
FRU	MJ	13.708	19.313	13.929	14.157	22.983	14.458
MMRSU	g Sb eq	0.009	0.021	0.009	0.013	0.032	0.013

3.3. Sensitivity analysis

Overall contribution of emissions to acidification and terrestrial eutrophication seemed in line with values found in the literature. However, the use of regionalized characterization factors when available can give a closer perspective of the magnitude of the impact for specific regions. Therefore, a sensitivity analysis was carried out to assess the robustness of the results in relation to this methodological choice (global versus regional characterization factors). The characterization factors were selected in consistency with the location of the study at a national level to characterize acidification, and terrestrial eutrophication (Seppälä et al., 2006; Posch et al., 2008). This test was performed for those impact categories and flows where we had the choice to utilize regionalized CFs (thus, ammonia and nitrogen dioxide for acidification and eutrophication, terrestrial). Table 6 reports the detail of the specific characterization factors used for Spain and Italy, both in the original assessment as well as in the sensitivity analysis; it can be noted that the non-specific factors are much higher than the regionalized ones.

Table 7 reports the results of the sensitivity analysis. As expected, using regionalized (smaller) characterization factors, an impact reduction can be observed. In detail, the baseline scenario with unspecified characterization factors, the impact categories affected by ammonia, nitrogen dioxide, and nitrogen oxides emissions have higher impacts in comparison with the results achieved in the sensitivity assessment using the regionalized characterization factors. At the same time, however, these are mitigated to a greater extent in the alternative scenarios than in the sensitivity analysis using regionalized (smaller) characterization factors. The higher relative reductions are achieved for the Italian scenarios despite the regionalized characterization factors are higher than the Spanish ones. This is due to the contribution of piglets that are the main contributors of AC and TE in Spain and whose impacts is not affected by changing in the characterization factors.

4. Discussion

Both technologies evaluated demonstrated their potential to reduce emissions during the pig house phase. However, a comprehensive environmental assessment provided a deeper understanding of the results. The introduction of additional devices that consume resources and energy increases the cumulative impact for many environmental categories. As a result, a variety of trade-offs emerge between categories influenced by emission reduction and those more closely linked to energy and resource use.

The results for both Spain and Italy confirm these trade-offs, although to different degrees. Despite to their non-direct comparability, the contrast of Italian and Spanish results provides similar insights. In general, Italy showed greater improvements in categories positively affected by scrubbers, but at the same time greater trade-offs in other categories.

Impact categories where the contribution analysis showed that ammonia and particulate matter emissions are a significant driver of the impact (such as acidification, particulate matter and terrestrial eutrophication), scrubbers resulted in overall impact reduction. For categories where emission contribution of these pollutants to the overall impact was not significant (i.e.: less than 5 % contribution) results were offset by the impact from producing and using the scrubbers. In the case of the Spanish farm (transition), differences among scenarios weren't large in most cases (both dry and wet scrubber added additional impact of under 10 % in all impact categories). Therefore, the potential benefits of using the mitigation technologies could outweigh these tradeoffs in areas where emissions are a strategic problem. In the case of the Italian farms, differences were larger, in particular for the impact categories related to the use of resources.

Table 6
Characterization Factors regionalized vs unspecific for main contributors to acidification and terrestrial eutrophication impact categories.

Impact category	Flow	Unspecific location	Regionalized SPAIN	Regionalized ITALY
Acidification (mol H+ eq / kg emitted pollutant)	Ammonia	3.02	0.076	0.12
	Nitrogen dioxide, Nitrogen oxides	0.74	0.052	0.065
Eutrophication terrestrial (mol N eq / kg emitted pollutant)	Ammonia	13.47	3.431	8.363
	Nitrogen dioxide, Nitrogen oxides	4.26	0.877	1.48

These differences between both regions were due in one hand to the difference in the electric mix of Spain and Italy. The Italian electric mix has a larger contribution from fossils than the mix used in the Spanish farm. But mainly, the divergence is due to the shorter production cycle of transition piglets in Spain, resulting in a less pronounced impact of the scrubbers.

The Spanish farm environmental analysis showed a considerable contribution to the impact from the purchased piglets. This stage of the pig production was carried out in a different farm, where no scrubbers were installed. This meant that overall impact (including emissions) was the same in all the scenarios (baseline, wet scrubber, dry scrubber) for this stage (piglet rearing) in the Spanish farm. Therefore, differences in impact due to the scrubbers was less noticeable than in the case of the Italian farms. For example, in the case of climate change, piglet production contributes with 33.17 % of the impact (Fig. 2). Thus, scrubbers are only working on potentially reducing the 66.83 % of the total climate change impact. If the scrubber would be applied in all the stages of the farm, emission reduction would occur across the whole production process and impact changes across scenarios would be larger. There were other smaller divergences, due to specific region ecosystem sensitivity and atmospheric conditions reflected in the magnitude of the characterization factors for acidification and terrestrial eutrophication, and to differences in the electric mix used which was resulting in different results for the categories related to use of resources. One mitigation opportunity, particularly for the wet scrubber, is the recycling of the machine's steel components. However, the impact of infrastructure, including disposal, is much lower than that of consumables (mainly citric acid and electricity). Therefore, optimization should be primarily in favor of more efficient use of the scrubbers.

Similarly, evaluating alternative products to citric acid, such as residual acids from other industrial processes, could reduce the farm's environmental footprint. Regarding the use of other acids, the use of sulfuric acid is an alternative. This acid, being a stronger acid, shows better performances respect to the citric acid one and a lower environmental impact for its production. On the other hand, it should be considered that sulfuric acid is more harmful than the citric one and its use would involve safety issue.

In the case of the wet scrubber, another aspect that could reduce environmental impact of the farm is the potential recovery and use of the removed nitrogen. The produced ammonium nitrate can be valorized as mineral fertilizer. This could be particularly feasible in the Italian farms where part of the feed is self-produced on the farm area by cultivation of cereal silage and other fodder crops.

A holistic perspective suggests considering potential impacts on pig welfare, which could translate into improved performance, and social aspects related to the reduction of odor nuisance for worker and local community. In addition, the exploration of alternative energy sources, such as solar panels for scrubber energy requirements, could address the increased energy consumption and mitigate the related impacts. Regarding animal welfare, air quality (mainly ammonia, CO_2 or PM levels) is among those environmental factors with a demonstrated impact on pig welfare, either directly affecting health or indirectly affecting thermoregulation. Increased ammonia (NH_3) concentrations

Table 7

Results of the sensitivity analysis with regard to the characterization factors (CF) reported in Table 6: Impact variation (%) achieved using the regionalized CF vs global CF for the different scenarios: BS: baseline, Dry: dry scrubber; Wet: wet scrubber.

Impact	Unit	Spain			Italy - Farm A			Italy - Farm B		
		BS	Wet	Dry	BS	Wet	Dry	BS	Dry	Wet
AC	mol H+ eq	−22.5 %	−10.3 %	−15.6 %	−68.7 %	−59.9 %	- 62.6 %	−79.6 %	−73.8 %	−68.7 %
TE	mol N eq	−18.4 %	−8.5 %	−12.8 %	−27.6 %	−24.8 %	−25.2 %	−32.0 %	−29.9 %	−28.9 %

impair the function of the respiratory mucosal clearance system thereby predisposing to respiratory infections (Michiels et al., 2015). NH_3 has also negative toxicological effects on other organs, such as spleens, liver, jejunum and heart, and can modify inflammatory markers and beta diversity of intestinal microflora in fattening pigs (Li et al., 2021). Moreover, ammonia levels have been found to be a risk factor for tail biting (Scollo et al., 2017). Although CO_2 has been found to be less harmful, its release influences ammonia release and is an indicator of lack of proper ventilation. With regards to PM, Michiels et al. (2015) found that increasing PM10 concentrations resulted in a higher prevalence of pleurisy lesions and pneumonia, as well as a reduction in performance field conditions. Therefore, an impact of the technologies implemented in the study on pig welfare was expected and the results will be submitted in specific paper.

The sensitivity analysis showed the results to be of variable significance depending on the location of the farms. In LCA applications, regionalized characterization of the impact is recommended whenever possible, to ensure that specific physical, chemical and biological conditions are considered. In the case of acidification and terrestrial eutrophication atmospheric conditions and sensitivity of ecosystems which are specific to the different regions can be determinant for the calculated impact results (Seppälä et al., 2006). In this sense, result showed the potential of wet and dry scrubber to reduce impact depends not only on the emission reduction achieved, but also on region where the emissions are produced. Therefore, results of this study cannot be extrapolated to other regions without considering these methodological aspects. Despite the lower impact for the specific locations of the study, ammonia emissions as well as to other pollutants are becoming more concentrated in smaller regions. In these areas, as emissions grow more concentrated the need of technologies that help reduce these emissions might reduce risks not only to ecosystems but also to human health, and animal well-being in the housing which hopefully will result in better pig performance. In this sense, there are being efforts in Europe to improve NH3 emissions. Indeed a 24 % reduction was reported from 1990 to 2018 although this tendency is slowing down again (EEA (European Environmental Agency), 2019). Regarding the main contributors to emissions specifically in Spain and Italy, according to the latest emission inventories in Spain, agriculture has been reported to contribute with 97 % of NH_3, 20 % of NMVOC, 13 % of NOX and 4 % of PM2.5 from the emissions inventoried (MITECO, 2023). Specifically, it has been estimated that there are more than 65 thousand tons per year of NH_3 emitted in Catalonia. As for Spain, in Italy also more than 90 % of ammonia emitted come from the agricultural sector, with its potential for adverse effects on public health and the environment. Therefore, the importance of researching potential pollutant mitigation technologies for the agricultural sector. The tendency in the sector is for its intensification, farms get bigger and are also being gradually concentrated in specific regions. Therefore, even if results show less emission reduction potential in these regions, given the large numbers of pig production and that the tendency is to continue intensifying, the contribution of technologies to reduce pollutants is not despicable. Furthermore, the potential environmental benefits from implementing these technologies are related with other social benefits. Animal production contributes to food security and provides with job opportunities in rural areas, one of the aims from Sustainable Development Goals. Technologies like the assessed scrubbers can help to reduce the pig production environmental footprint aiding the achievement of the target 2.4 from the sustainable development goal (SDG) 2 on Food hunger, and the target 12.2 from SDG 12 on a Responsible Consumption and Production. Moreover, animal welfare despite not being explicitly addressed in the SDGs, is clearly related to the achievement of some requirements of the SDGs (Keeling et al., 2019).

Finally, to achieve a sustainable environmental performance of the pig sector, we need a multifactor approach (Degré et al., 2007; Gislason et al., 2023), where these technologies would be one part of the whole picture. This includes aspects such as optimized animal performance through breeding and genetic selection balanced with animal welfare. Also, manure management technologies, need to be addressed together with appropriate feeding strategies. All this while trying to optimize the efficiency in the use of resources. In summary, different mitigation strategies need to be combined to obtain optimal environmental results.

5. Conclusions

This study assessed the use of wet and dry scrubbers in a Mediterranean context, with the aim of reducing the in-house emissions in pig fattening farms. Life cycle Assessment showed to be a useful tool to assess the overall balance between the achieved emission reduction and the added impacts from implementing these technologies. Both wet and dry scrubber showed their potential for emission reduction of pig housing in the two assessed farms Italy and the farm located in Spain. This is a non-negligible aspect in areas with high emissions concentration due to high farming density. Moreover, the potential improvement of social and animal wellbeing aspects as well as improvements in animal performance should be furtherly explored. However, for a holistic assessment of the sustainability of the two analyzed solutions, beside the environmental aspect, also the economic dimension should be evaluated. The adoption of the scrubbers involves an increase of the cost for pig rearing due to the required investment as well as to the operativity costs. In this context, in the absence of an additional remuneration from the agri-food industry and/or of specific subsidy framework the adoption of the dry and wet scrubbers will be limited and, consequently, also the related environmental benefits will be negligible.

Future optimization of the assessed technologies should investigate the use of recycled resources options, the improvement of working efficiency of the assessed technologies, the use of renewable energy and, for the wet acid scrubber, the valorization of the mineral fertilizer produced.

CRediT authorship contribution statement

Marta Ruiz-Colmenero: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Michele Costantini:** Conceptualization. **Ariadna Bàllega:** Formal analysis, Data curation. **Michele Zoli:** Conceptualization. **Miquel Andón:** Formal analysis, Data curation. **Miriam Cerrillo:** Formal analysis, Data curation. **Emma Fàbrega:** Data curation. **August Bonmatí:** Writing – review & editing, Funding acquisition, Conceptualization. **Marcella Guarino:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Jacopo Bacenetti:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgement

This work was supported by the project Life-MEGA [LIFE18 ENV/IT/000200], which has received funding from the Life programme of the European Union.

The content, discussion and opinions of this article are fully attributable to the authors and may not in any circumstances be regarded as stating an official position of the European Commission.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.171197.

References

Andretta, I., Hickmann, F.M., Remus, A., Franceschi, C.H., Mariani, A.B., Orso, C., Pomar, C., 2021. Environmental impacts of pig and poultry production: insights from a systematic review. Frontiers in Veterinary Science 8, 750733.

Associazione Nazionale Allevatori Suini (ANAS) (2023). Statistiche suinicultura italiana ed europea 2022 – Tabelle statistiche. Roma, 2022 (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.anas.it/files/circolari/2023 00001.PDF).

Bacenetti, J., Fusi, A., 2015. The environmental burdens of maize silage production: influence of different ensiling techniques. Anim. Feed Sci. Technol. 204, 88–98.

Bava, L., Zucali, M., Sandrucci, A., Tamburini, A., 2017. Environmental impact of the typical heavy pig production in Italy. J. Clean. Prod. 140, 685–691. https://doi.org/10.1016/J.JCLEPRO.2015.11.029.

Behera, S.N., Sharma, M., Aneja, V.P., Balasubramanian, R., 2013. Ammonia in the atmosphere: a review on emission sources, atmospheric chemistry and deposition on terrestrial bodies. Environ. Sci. Pollut. Res. 20, 8092–8131.

Bovo, M., Santolini, E., Barbaresi, A., Tassinari, P., Torreggiani, D., 2022. Assessment of geometrical and seasonal effects on the natural ventilation of a pig barn using CFD simulations. Comput. Electron. Agric. 193, 106652.

Conti, C., Costantini, M., Fusi, A., Manzardo, A., Guarino, M., Bacenetti, J., 2021. Environmental impact of pig production affected by wet acid scrubber as mitigation technology. Sustain. Prod. Consum. 28, 580–590.

Costantini, M., Bacenetti, J., Coppola, G., Orsi, L., Ganzaroli, A., Guarino, M., 2020. Improvement of human health and environmental costs in the European Union by air scrubbers in intensive pig farming. J. Clean. Prod. 275, 124007.

DACC, 2021. Informe anual del sector porcí. Elaborat del Grup de Gestió Porcina, Universitat de Lleida. Observatori del Porcí - Anual 2021 (gencat.cat). Last access (5 Jan 2023).

De Vries, J.W., Melse, R.W., 2017. Comparing environmental impact of air scrubbers for ammonia abatement at pig houses: a life cycle assessment. Biosyst. Eng. 161, 53–61. https://doi.org/10.1016/j.biosystemseng.2017.06.010.

Degré, A., Debouche, C., Verheve, D., 2007. Conventional versus alternative pig production assessed by multicriteria decision analysis. Agron. Sustain. Dev. 27, 185–195.

Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermott, A., Zeger, S.L., Samet, J.M., 2006. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. JAMA 295, 1127–1134.

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

EEA (European Environmental Agency), 2019. EMEP/EEA air pollutant emission inventory Guidebook 2019. Volume 3.B - Manure management.

European Commission, 2021. Commission Recommendation of 16.12.2021 on the Use of the Environmental Footprint Methods to Measure and Communicate the Life Cycle Environmental Performance of Products and Organisations.

FAO, 2018. Environmental Performance of Pig Supply Chains: Guidelines for Assessment (Version 1). Livestock Environmental Assessment and Performance Partnership, Rome, FAO, p. 172.

Fazio, S., Castellani, V., Sala, S., Schau, E. M., Secchi, M., Zampori, L., & Diaconu, E. (2018). Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, version 2.0. from ILCD to EF 3.0, EUR29600 EN, European Comission, Ispra, 2018. In ISBN 978-92-79-98584-3, doi:https://doi.org/10.2760/002447, PUBSY no. JRC114822. doi:https://doi.org/10.2760/671368.

García-Gudiño, J., Monteiro A, N.T.R., Espagnol, S., Blanco-Penedo, I., Garcia-Launay, F., 2020. Life cycle assessment of Iberian traditional pig production system in Spain. Sustainability 12(2):627. https://doi.org/10.3390/su12020627.

Gislason, S., Birkved, M., Maresca, A., 2023. A systematic literature review of Life Cycle Assessments on primary pig production: impacts, comparisons, and mitigation areas. Sustainable Production and Consumption 42, 44–62.

Hietala, S., Heusala, H., Katajajuuri, J.M., Järvenranta, K., Virkajärvi, P., Huuskonen, A., Nousiainen, J., 2021. Environmental life cycle assessment of Finnish beef–cradle-to-farm gate analysis of dairy and beef breed beef production. Agric. Syst. 194, 103250.

Hristov, A.N., Oh, J., Firkins, J.L., Dijkstra, J., Kebreab, E., Waghorn, G., Makkar, H.P.S., Adesogan, A.T., Yang, W., Lee, C., Gerber, P.J., Henderson, B., Tricarico, J.M., 2013. Special topics—mitigation of methane and nitrous oxide emissions from animal operations: I. A review of enteric methane mitigation options. J. Anim. Sci. 91 (11), 5045–5069.

IPCC (Intergovernmental Panel on Climate Change), 2019. 2019 Refinement to the 2006 Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and other land use. Chapter 10: Emissions from livestock and manure management.

ISO, 2006a. ISO 14040, Environmental Management - Life Cycle Assessment – Principles and Framework. International Organization for Standardization, Geneva (Switzerland).

ISO, 2006b. ISO 14044, Environmental management - Life Cycle Assessment - Requirements and Guidelines. International Organization for Standardization, Geneva (Switzerland).

Keeling, L., Tunón, H., Olmos Antillón, G., Berg, C., Jones, M., Stuardo, L., Swanson, J., Wallenbeck, A., Winckler, C., Blokhuis, H., 2019. Animal welfare and the United Nations sustainable development goals. Front. Vet. Sci. 6, 336.

Li, Y., Zhang, R., Li, X., Li, J., Ji, W., Zeng, X., Bao, J., 2021. Exposure to the environmental pollutant ammonia causes changes in gut microbiota and inflammatory markers in fattening pigs. Ecotoxicol. Environ. Saf. 208, 111564.

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

Michiels, A., Piepers, S., Ulens, T., Van Ransbeeck, N., Sacristán, R.D.P., Sierens, A., Haesebrouck, F., Demeyer, P., Maes, D., 2015. Impact of particulate matter and ammonia on average daily weight gain, mortality and lung lesions in pigs. Prev. Vet. Med. 121 (1-2), 99–107.

MITECO, 2023. Inventory Informative Report. Ministerio para la Transición Ecológica y el Reto Demográfico Secretaría General Técnica. Submission to the secretariat of the geneva convention and emep programme reporting to the european commission under directive (eu) 2016/2284. Inventario Nacional de Contaminantes Atmosféricos (miteco.gob.es). Last access 5 Jan 2023.

Ndegwa, P.M., Hristov, A.N., Arogo, J., Sheffield, R.E., 2008. A review of ammonia emission mitigation techniques for concentrated animal feeding operations. Biosyst. Eng. 100 (4), 453–469.

Notarnicola, B., Tassielli, G., Renzulli, P.A., 2012. Modeling the Agri-food Industry With Life Cycle Assessment. Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products, pp. 159–183.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science (New York, N.Y.) 360 (6392), 987–992. https://doi.org/10.1126/science.aaq0216.

Posch, M., Seppälä, J., Hettelingh, J.P., Johansson, M., Margni, M., Jolliet, O., 2008. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int. J. Life Cycle Assess. 13, 477–486.

PRé Sustainability. (2022). SimaPro 9.4.0.2.

Scollo, A., Gottardo, F., Contiero, B., Edwards, S.A., 2017. A cross-sectional study for predicting tail biting risk in pig farms using classification and regression tree analysis. Prev. Vet. Med. 146, 114–120.

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.P., 2006. Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator (14 pp). Int. J. Life Cycle Assess. 11, 403–416.

Singaravadivelan, A., Sachin, P.B., Harikumar, S., Vijayakumar, P., Vindhya, M.V., Farhana, F.B., Mathew, J., 2023. Life cycle assessment of greenhouse gas emission from the dairy production system. Trop. Anim. Health Prod. 55 (5), 320.

Tsangas, M., Papamichael, I., Banti, D., Samaras, P., Zorpas, A.A., 2023. LCA of municipal wastewater treatment. Chemosphere 341, 139952.

Van der Heyden, C., Demeyer, P., Volke, E.I.P., 2015. Mitigating emissions from pig and poultry housing facilities through air scrubbers and biofilters: state-of-the-art and perspectives. Biosyst. Eng. 134, 74–93.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230.

Yan, X., Ying, Y., Li, K., Zhang, Q., Wang, K., 2024. A review of mitigation technologies and management strategies for greenhouse gas and air pollutant emissions in livestock production. J. Environ. Manag. 352, 120028.

Zampori, L., Pant, R., 2019. Suggestions for updating the product environmental footprint (PEF) method. In Publications Office of the European Union. https://doi.org/10.2760/424613.