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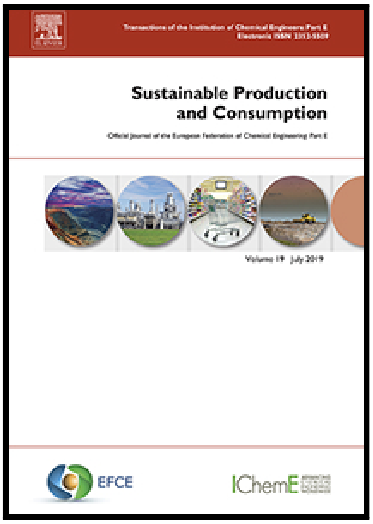

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Environmental impact of pig production affected by wet acid scrubber as mitigation technology

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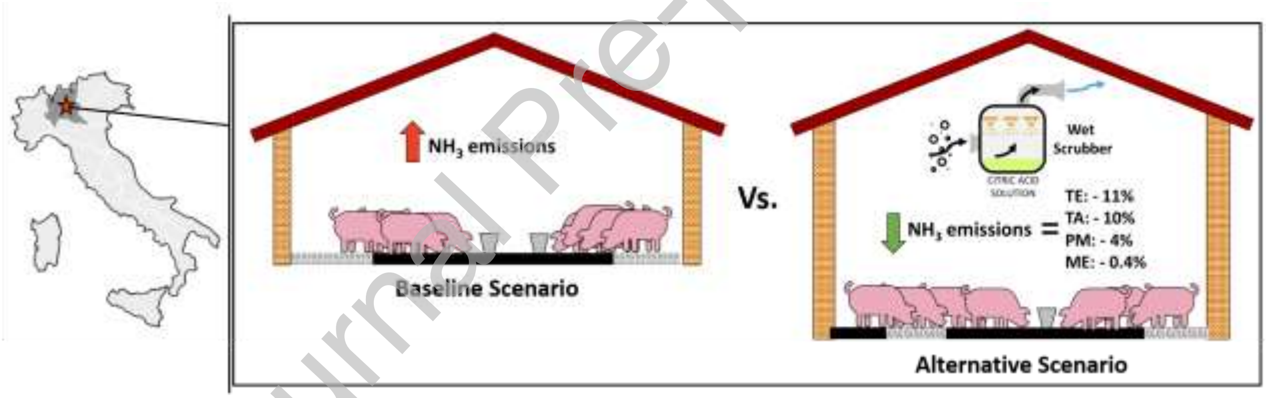
Graphical Abstract



Abstract

Ammonia (NH_3) is the most common air pollutant in pig farms, affecting animals and workers' health, and causing damages to ecosystems. Hence, there is a need to reduce NH_3 emissions. Many mitigation strategies can be applied to limit gaseous emissions, such as the application of air treatment technologies.

In this study, the environmental impact of a typical Italian pig farm, adopting a wet acid scrubber to abate NH_3 emissions, was evaluated using the Life Cycle Assessment approach. 1 kg of live weight (LW) was selected as Functional Unit. Two scenarios were considered. The baseline scenario (BS) represents the situation as it is, while the alternative scenario (AS) a wet scrubber prototype (with 70% NH_3 removal efficiency) was adopted. For 8 of the 12 evaluated impact categories, AS shows the highest environmental impact, due to the scrubber construction and maintenance. However, it was the best for those impact categories most affected by NH_3. Observed reduction ranged from 10% (for acidification, TA, and terrestrial eutrophication, TE) to 0.4% (for marine eutrophication, ME). The climate change impact was 3.55 kg CO_2 eq kg^{-1} LW and 3.65 kg CO_2 eq kg^{-1} LW for BS and AS, respectively. For almost all impact categories, the consumable materials for wet scrubber operation represented around 85% of the total impact of the scrubber. The results of the sensitivity analysis showed that variation in NH_3 removal efficiency had the greatest effect on particulate matter formation, TA, and TE. The achieved results provide a first quantitative indication of the environmental benefits that can be achieved using wet acid scrubber in naturally ventilated pig facilities.

Keywords

Pig farm; Air quality; Ammonia; Wet acid scrubber; Environmental impact; Life Cycle Assessment

1. Introduction

Western Europe is characterised by medium to large-scale intensive pig farms. The European main pork meat producer countries are Germany (5.34 million t product mass), Spain (4.53 million t), France (2.18 million t), Poland (2.08 million t), Denmark (1.58 million t), the Netherlands (1.54 million t), Italy (1.47 million t) and Belgium (1.07 million t) (Pigmeat, 2020). Italy houses 8.4 million pigs on approximately 24,950 farms. The pig population is mainly concentrated in the northern part of the country, in particular in Lombardy (52%), Piemonte (14%), Emilia-Romagna (13%), and Veneto (9%) regions (ISMEA, 2019). The Italian pig sector presents a high degree of specialisation in favour of heavy pigs (over 110 kg, with a minimum slaughter weight of 160 kg) used for the traditional production of dry-cured hams (Bava et al., 2017). Currently, in Italy, there are 21 Protected Designations of Origin (PDO) for dry-cured hams and 18 Protected Geographical Indications (GPI) (e.g. Parma ham, San Daniele ham, speck, mortadella) (ISMEA, 2019).

Ammonia (NH_3), odours (VOCs, volatile organic compounds) (Schauberger et al., 2018), particulate matter (PM) (EEA, 2019a), and greenhouse gases (GHG), such as methane (CH_4) (Marszałek et al., 2018), are the most abundant pollutants emitted by pig farms. In the European Union, the agricultural sector is responsible for 92% of NH_3 emissions (EEA, 2018), mainly generated by animal manure (McIlroy et al., 2019) and inorganic N-fertilisers (Schauberger et al., 2018). In 2018, NH_3 emissions from the agriculture sector in Italy were 345 Gg (94.2%), of which the pig sector category represents 9.1% of total national emissions (ISPRA, 2020). NH_3 contributes to indirect emissions of nitrous oxide (N_2O) as well as to acid deposition and eutrophication, causing changes in biodiversity and ecosystem functioning (Kebrab et al., 2016; Schauberger et al., 2018). Moreover, NH_3 plays a significant role in the formation of particulate aerosols in the atmosphere. Secondary aerosols, which have diameters of less than 10 (PM_{10}) and 2.5 microns ($PM_{2.5}$), are formed in the atmosphere from chemical reactions involving mainly NH_3, nitrogen oxides (NOx), and sulphur dioxide (SO_2) (Behera et al., 2013; Hristov, 2011). This is a concern because fine PM is capable of penetrating deep into the alveolar region and entering the bloodstream, increasing the risk of cardiovascular and respiratory diseases, and thus having an adverse impact on human health

(Dominici et al., 2006). In 2016, $PM_{2.5}$ concentration in Europe is estimated as contributing to more than 400,000 premature deaths (EEA, 2019b), whereas in the Po valley, it has been estimated that high PM levels lead to a reduction in life expectancy of about 36 months (Kiesewetter et al., 2015).

Regarding GHG, globally the pig sector contributes 9% to total emissions from the livestock sector. Among the main emission sources, feed production is the largest (48%), followed by manure storage and processing (27.4%), post-farm emissions from post-farm activities and transport (5.7%), and finally on-farm energy consumption (3.5%) (Gerber et al., 2013). N_2O is mainly emitted from manure management, whereas methane (CH_4) comes from both the enteric fermentation and manure management (IPCC, 2019).

Finally, odours, besides being responsible for annoyance to nearby residents, can cause airway irritation (Conti et al., 2020) and respiratory diseases in farmers and agricultural workers (Maesano et al., 2019).

As pollutants from the livestock sector lead to many environmental problems, affecting the atmosphere, the neighbourhood, the health of both public and pig workers, as well as pig welfare, many mitigation strategies can be applied to limit gaseous emissions (Calvet et al., 2017; Burchill et al., 2019). GHG, NH_3, and VOCs reduction can be achieved by various methods, such as nutritional strategies (Andretta et al., 2018), frequent slurry removal (Hoff et al., 2006), , use of closed slurry tanks or pits (Guarino et al., 2006), slurry injection techniques that permit to spread slurry into the soil through anchors and avoiding the superficial spreading with plates (Bacenetti et al., 2016b), use of treatment systems (e.g. acidification, anaerobic digestion, solid-liquid separation, nitro-denitro, etc.) or use of additives during storage (Fangueiro et al., 2009; Finzi et al., 2019), and, finally, the application of air treatment technologies (Van der Heyden et al., 2015). Concerning air cleaning systems, they are mentioned in the Best Available Techniques (BAT) reference document for the intensive rearing of poultry or pigs (Santonja et al., 2017). According to Decision (EU) 2017/302 among BAT available for the intensive rearing of poultry or pigs, BAT 30, point c, refers specifically to air cleaning systems, such as biofilter, bioscrubber (or biotrickling filter), dry filter, two-stage or three-stage air cleaning system, water scrubber, water trap and wet acid scrubber (EU, 2017). In Northern European piggeries, the wet acid scrubber is the most widely applied air cleaning technology (Costantini et al., 2020), in order to comply with regulations, such as the National Emission Ceilings and the EU Clean Air Policy Package that limit the emission of NH_3, GHG and other pollutants (Jacobsen et al., 2019). The wet acid scrubber is an end-of-pipe technique, used in forced ventilated animal house, for removing pollutants from the exhaust air. The air gets withdrawn from the pigsties, washed, thanks to the passage through an inert packing material sprayed with an acid solution (usually sulphuric acid), and finally returned to the barns. The intensive contact between the air and liquid enables soluble pollutants to pass from gas to the liquid phase. In this way, NH_3 is captured by the acid solution, leading to the production of ammonium salt (Santonja et al., 2017). In the acid scrubber, most of the trickling water is recirculated, the other part is discharged and replaced by fresh water (Melse and Ogink, 2005). Compared to biotrickling filters, acid and wet scrubbers present higher NH_3 removal efficiency, less discharge water and higher nitrogen concentration into the water discharged (Costantini et al., 2020; De Vries and Melse, 2017). Abatement NH_3 removal efficiencies ranging from 70 to 99% are reported for wet acid scrubber using sulphuric acid solution, in mechanically ventilated pig housing facilities (Costantini et al., 2020; Van der Heyden et al., 2015). NH_3 removal efficiency depends on the pig barn structure, ventilation (e.g., natural or mechanical), and type of acid used. The removal efficiency is usually calculated considering the difference in the NH_3 concentration between the inlet and outlet air from the scrubber. In particular, higher NH_3 removal efficiency (> 90%) is reported for wet acid scrubber using sulphuric acid solution and installed in mechanically ventilated facilities (Melse and Ogink; 2005; De Vries and Melse, 2017; Dumont, 2018) while lower efficiencies were recorded for devices using acids less strong than the sulphuric one (e.g., citric acid) and installed in naturally ventilated facilities (Starmans and Melse, 2011). When citric acid is used instead of sulfuric one, despite lower removal efficiency (around 70%), the management of the scrubber is easier being the citric acid safer to handle (Jamaludin et al., 2018).

For the other air cleaning technologies, installed in mechanically ventilated pig housing facilities, Melse and Ogink (2005) reported 70% NH_3 removal efficiency for biotrickling filters, Van der Heyden et al. (2015) an average of 64% for biological air scrubbers, Van der Heyden et al. (2016) 86% for biological air scrubbers with nitrification tank, and Dumont (2018) 70% for bioscrubbers.

The environmental impact of pig production systems using air treatment technologies remains poorly documented in the literature. De Vries and Melse (2017) compared the environmental impact of three different types of air scrubbers in piggeries (acid scrubber, biotrickling filter nitrification only, and biotrickling filter with nitrification and denitrification). They concluded that the scenario with acid scrubbers showed the lowest environmental impact in all impact categories and in particular had greatest effects on NH_3-related impact categories (i.e. acidification, particulate matter formation, and marine eutrophication). So, acid scrubbers have been suggested as the most appropriate technology for NH_3 emissions abatement at pig farms.

Scrubbers usage in pig farms located in North Europe countries, such as Belgium and Netherlands, is consolidated (Zhuang et al., 2019), and it represent a way to improve the environmental sustainability of pig farming, as they reduce NH_3 emissions and their related impact (De Vries and Melse, 2017). The environmental problems associated to NH_3 emissions are well known and described above. As it is mentioned that agriculture is the largest contributor to NH_3 emissions. Therefore, the treatment of NH_3 from intensive pig farms represents a crucial issue to ensure sustainability both in meat production and environmental protection. With regards to this last aspect, Costantini et al. (2020) explored the effect that the large-scale implementation of wet acid scrubbers in pig housing facilities could have in the European Union. They concluded that the abatement of NH_3, obtained by the application of wet acid scrubber, can reduce both the human health impact and environmental costs.

Even if the construction and maintenance of scrubbers involves the consumption of acid, energy, and materials, optimising their design and operation can facilitate the simultaneous reduction of other pollutants, such as odour, GHG and PM in an efficient and cost-effective manner (Van der Heyden et al., 2015), improving the environmental sustainability. Moreover, the ammonium citrate or ammonium sulphate formed can be used as a fertiliser for crop production (De Vries and Melse, 2017; Jamaludin et al., 2018) constituting an environmental credit by means of mineral fertilizer replacement and thus the avoidance of its production.

Finally, consumer behaviour towards a more sustainable pig production is increasing. The use of air cleaning technologies in pig farms can move to this direction.

Despite the numerous current and future benefits offered by air scrubbers in piggeries, they do not represent a consolidated method to reduce emissions and related impacts in southern European regions, such as Italy and Spain. In these countries, pigs, during the fattening phase, are usually housed in naturally ventilated buildings thanks to the warm climate (Aguilar et al., 2010 Estellés et al., 2009). However, in order to comply with current and future regulations, the implementation of air scrubbers is expected to expand in intensive livestock production areas across Europe.

This study aims to evaluate the environmental performance of a typical Italian pig rearing systems paying particular attention to the environmental effectiveness of a wet acid scrubber as a mitigation solution to reduce NH_3 emissions from livestock housing and the related environmental impacts.- For this purpose, a pig farm in the Po valley area (province of Brescia), specialised in the production of heavy pigs, was evaluated considering two scenarios: with (Alternative) and without (Baseline) the adoption of a wet acid scrubber. The novelty of this study is to quantify the impact variation related to the implementation of an air treatment solution. For this purpose, the Life Cycle Assessment (LCA) approach was applied.. Besides, this LCA study aims to identify the environmental processes with the greatest impact, how the impact varies between farms using or not using a wet acid scrubber, and margins for improvement.

To the authors' knowledge, this is the first LCA study considering the application of air scrubber for ammonia abatement at Italian pig houses. Indeed, De Vries and Melse (2017) assess and compare the environmental impact of three types of air scrubbers in conventional Dutch housing system. Typical Dutch farms are mechanically ventilated and bring pigs to a slaughter weight around 105-110 kg. Whereas, Bava et al. (2017) and Pirlo et al. (2016) assessed the environmental impact of Italian heavy pig production without considering the implementation of air treatment technologies to abate NH_3 emissions.

2. Material and methods

This LCA study was carried out following the ISO Standards 14040 and 14044 (ISO, 2006; ISO, 2018).

2.1. Goal and scope definition

The goal of this study is to evaluate, for an intensive pig farm specialising in the production of heavy pigs and located in the province of Brescia (Po valley), the potential reduction in environmental impact linked to the installation of a wet acid scrubber.

The Po valley is an area, located in Northern Italy, characterized by the high concentration of agricultural and livestock activities. Due to the concurrent high density of anthropogenic sources and its orographic and meteorological characteristics it is characterised by the frequent occurrence of stagnant meteorological conditions, particularly unfavourable for pollutant dispersion. In this context, considering the need of supporting farmers in the direction of abating NH_3 emissions,

The evaluated farm is representative of the intensive pig farming system characterising northern Italy (housing facilities with natural ventilation; low self-sufficiency for feed; production of heavy pigs) (Bava et al. 2017). Regarding the house facilities and in particular their ventilation, the conditions are similar to the ones characterising the pig rearing systems in other European countries such as Germany and Denmark (26% and 13% of the EU pig herd, respectively).

The outcomes of this study could be useful for farmers and their associations to understand the actual environmental impacts of the pig production process and the consequences and benefits arising from the reduction of NH_3 emissions. Moreover, they can be useful for companies and technicians working with farmers to offer innovative solutions. Finally, these preliminary results can provide useful information to those organisations directly involved in the development of policies and technical reference documents, in addition to being transferred to stakeholders interested in the topic.

2.2. Farm description

The analysed farm is in Orzinuovi (Brescia) (45°25'44" N 9°58'04" E) Lombardy, Italy. It is an intensive farrowing to finishing farm, which means that it produces piglets and raises them to market weight. In this case, heavy pigs for PDO dry-cured ham consortia are produced. The Utilised Agricultural Area (UAA) for cultivation is 100 ha, dedicated to maize cultivation and entirely utilised as feed for animals.

The animals are housed in an indoor system, with different specific conditions depending on their growth stage. During lactation, sows are kept in farrowing crates where they are confined between bars to reduce the risk of the sow crushing her new-born piglets. After 3 weeks, piglets are weaned and placed in a nursery, and the sow is returned to the gestation barn. Here, all females are artificially inseminated and remain housed in the gestating housing section for 100 days, the gestation period. After the piglets reach approximately 25-35 kg, they are placed in a growing-finishing barn where they remain until they reach 160 kg, which corresponds to 9 months (minimum live weight and age required by PDO regulation). Boars are used to collect semen for artificial insemination.

The pigs are housed in pens, in closed mechanically ventilated buildings for farrowing pigs, and in closed naturally ventilated buildings for fattening pigs. Electrical heaters are used in farrowing and nursery houses for new-born piglets. All the pig production systems involve electricity consumption for illumination, feeding processes, and manure management. The feeding process also requires diesel fuel combustion for grinding, mixing, and pelleting operations.

Pig excreta are handled as slurry, mainly removed using a vacuum system, and then stored in ponds located outside the pig buildings where natural crust formation takes place. The slurry is spread with an umbilical system in accord with the Nitrate Directive (EU, 1991). Only maize grain is partially produced on-farm (1300 t year^{-1} at commercial moisture of 14%) whereas all other feed ingredients are purchased, showing very low feed self-sufficiency (4% of total feed consumption, as fed). Regarding maize, the cultivation is carried out in irrigated fields and following the indications for integrated production (Negri et al., 2014). Water for drinking and cleaning water is taken from a well.

Two different scenarios were considered, Baseline (BS) and Alternative (AS). The BS represents the situation as it was recorded and described above. The AS represents the same situation but envisages the implementation of a wet acid scrubber technique in the fattening barns, which are the most affected by poor air quality (Dumont et al., 2014). Consequently, the zootechnical parameters were the same for both scenarios but in AS data related to wet acid scrubber construction and consumption were included. Regarding AS, the wet acid scrubber is installed inside the barn. It has two air treatment towers, the first tower, connected to the air inlet, is filled with water, while the second tower is filled with a citric acid solution and it is connected to the air outlet. Thus, the air gets withdrawn from the pigsty, it gets washed thanks to the passage through the two tanks, and it is finally returned to the shelter. Even if it is still at prototype stage, an investment cost of 22,000 € can be taken into account for the wet acid scrubber (excluding the installation costs).

The comparison between the environmental impact of the two scenarios considered highlights the effectiveness of wet acid scrubber as a mitigation solution in intensive pig housing facilities. The environmental trade-off among the different impact categories could occur; in fact, despite the reduction of NH_3 emissions, the adoption of wet acid scrubber technology involves the consumption of acid and energy for its functioning as well as of materials for its manufacturing and maintenance.

2.2.1.Functional Unit and system boundary

In developing an LCA according to ISO 14044 (ISO, 2018), the Functional Unit (FU) must be clearly defined and measurable. FU describes the quantified performance of the function of the studied system and it provides a reference to which the inputs and outputs can be related, enabling comparison among different studies. In this study, the selected FU was 1 kg of pig mass, referred to as live weight (LW) at the farm gate, in accordance with the Food and Agriculture Organization (FAO) guidelines “Environmental performance of pig supply chain” (FAO, 2018).

Regarding the system boundary, considering that all the steps of production system subsequent to the fattening phase are not affected by the wet acid scrubber, a “*cradle to farm gate*” approach was adopted. Consequently, all on-farm activities were included that related to crop cultivation and animal and slurry management, as well as all upstream off-farm activities, starting from raw material extraction, related to the production and supply of the inputs consumed. For crop intended for feed production, the following activities were considered: raw material extraction (e.g. fossil fuels and minerals), manufacture (e.g. seeds, fertilisers, and agricultural machines), use (e.g. diesel fuel consumption, engine exhaust gas emissions, and fertiliser-related emissions), maintenance and final disposal of machines. Feed additives, such as minerals, vitamins, and amino acids were included in the assessment. On-farm emissions of NH_3, N_2O, and CH_4 from enteric fermentation, slurry management (e.g. housing and storage), and field spreading were included within the system boundaries.

Conversely, the following aspects were excluded from the analysis:

- the production and maintenance of farm infrastructure (e.g. pig housing, slurry and manure storage, silos) because their lifespan is higher than 3-years and their impact was highlighted as negligible in a life cycle perspective (Lovarelli and Bacenetti, 2017),
- veterinary medicines and other farm chemicals (e.g. cleaning and disinfection) were excluded, similar to Anestis et al. (2020) and Monteiro et al. (2019).

The soil organic carbon was considered to be in a steady-state for all arable land destined for annual crop production, except for the soybean share imported from South America, for which emissions related to direct land use changes (LUC) have been included. Since soybean is totally imported, LUC accounts for a large amount of CO_2 emissions in animal feed supply chain. For this reason, it is important to include this parameter in the evaluation, as reported by Bava et al. (2017).

Figure 1 shows the system boundary for the two scenarios considered. No allocation procedure was applied because the farm sells only finished heavy pigs.

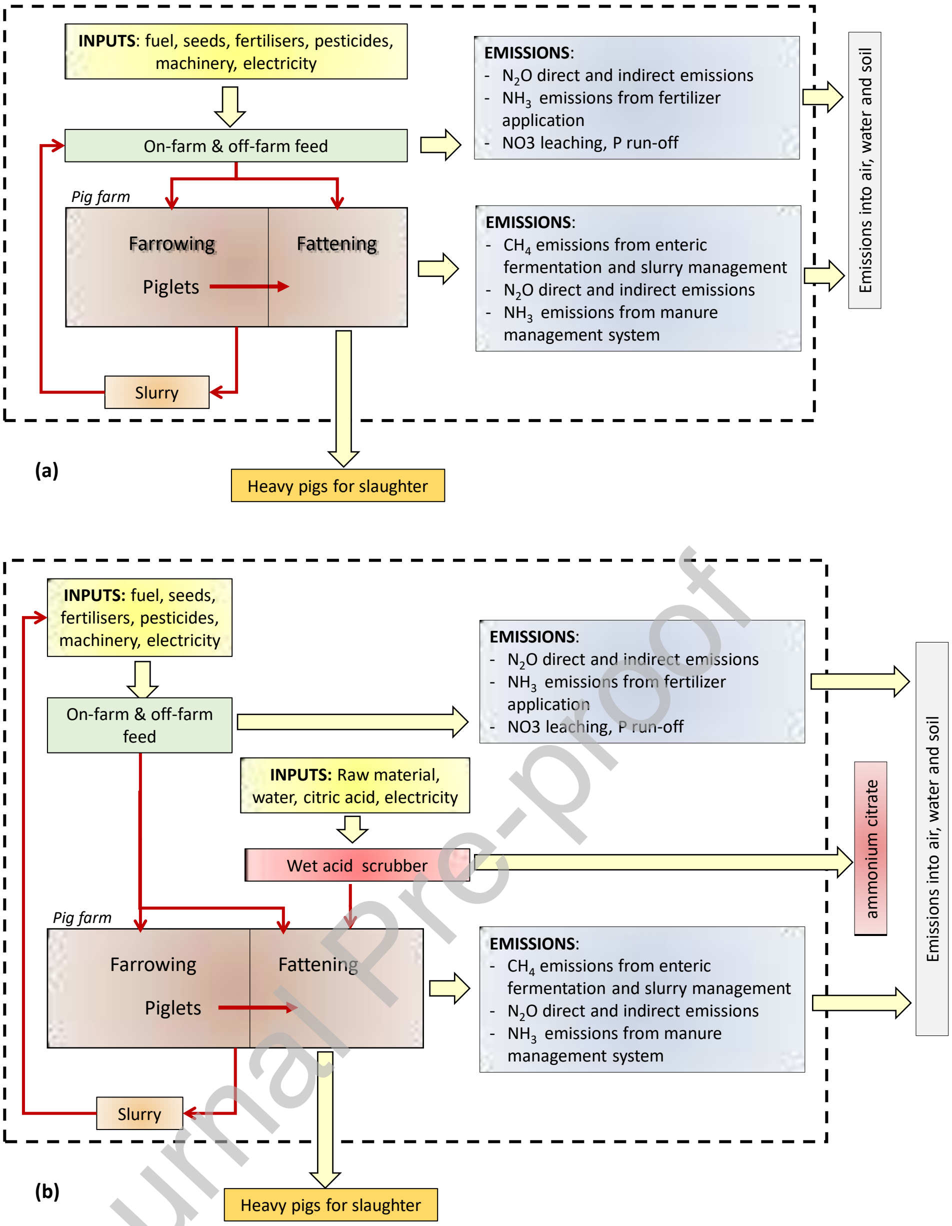


Figure 1. System boundaries for Baseline Scenario (a) and Alternative Scenario (b)

2.3. Life Cycle Inventory

Primary data concerning farm activities were collected from a questionnaire compiled by the farmer and through personal interviews with the farmer, including the following items: number of animals for each category, housing and ventilation system, slurry management, feed and diets, length and mass of animals in each sub-phase, electricity and fuel consumption. Specifically, the farmer provided all information regarding herd composition, crop production, animal diets, excreta management, cultivation practice and field operations, fertiliser, fuel, and electricity consumption. Concerning the diet supplied by the farmer, the formulation is mainly based on maize, wheat bran, soybean meal, soybean oil, fish meal, and mineral-amino acid-vitamin additive. However, feed material inclusion rates are confidential and therefore not shown.

In AS, taking into consideration the adoption of wet acid scrubber using citric acid, a 70% reduction of NH_3 emissions was considered during animal housing, being the scrubber installed inside the barns. Moreover, according to Santonja et al. (2017) in some Western-European countries and regions, such as the Netherlands, Flanders, Germany, and Denmark this is the required minimum removal efficiency in pig houses.

The inventory data related to scrubber energy, water, and acid consumption as well as raw materials and energy needed for the construction of the machinery were taken from the literature (Simpson et al., 2012; Van der Heyden et al., 2015; De Vries and Melse, 2017). According to Melse and Ogink (2005), it was assumed that the washing water is partially recirculated to reduce water consumption.

Table 1 reports the main inventory data related to productive parameters adopted in the analysis of BS and AS. **Table 2** reports inventory data related to wet acid scrubber used only for the AS. For wet acid scrubber a mass of 500 kg and 8 years of lifespan were considered.

Table 1. Average zootechnical data for the farm

	Piglets	**Fatteners 1**	**Fatteners 2**	**Sows lactating**	**Sows nursery and dry period**	**Replacement males and females**
LW at entering the stage, kg	7	31	80	180	160	40
LW at leaving the stage, kg	30	80	167	200	200	120
Duration of the stage, days	65	72	125	28	129	120
Feed intake, kg animal^{-1} day^{-1}	0.6	1.4	2.4	4	2.2	3.1
Diet CP content, % of dry matter	16.1	14.3	13.3	14.3	11.3	14.4
Daily weight gain, kg animal^{-1} day^{-1}	0.27-0.43	0.69-0.71	0.70	-	-	0.67
Feed consumption, kg year^{-1}	647,145	1,300,860	2,167,215	413,545	313,900	226,313

Feed Conversion Ratio, kg feed kg LW gain^{-1}	1.46	1.74	2.94	n.a.	n.a.	n.a.

LW = Live Weight; n.a. = not available

Table 2. Wet acid scrubber inventory data (expressed per kg of NH_3 removed)

Consumable	Unit	Amount
Water	dm^3	132
Citric acid	kg	5.67
Electricity	kWh	6.25

Regarding the emissions, the two main emission sources considered were:

- emissions related to maize cultivation including the nitrogen and phosphorous compounds released into water and air due to crop fertilisation (NH_3 volatilisation, nitrate leaching, denitrification, and phosphorous run-off) and the pollutants (dust, VOC, NMVOC, hydrocarbons, nitrogen oxides, etc.) in the exhaust gas emitted by tractor engines and due to diesel combustion;
- emissions related to livestock activities, including CH_4 emissions from enteric fermentation and slurry management, direct and indirect N_2O emissions, NH_3 emissions from manure management system.

Field emissions of N and P compounds into the air, water, and soil were evaluated using the model EFE-So, (Estimation of Fertilisers Emissions-Software, available at http://www.sustainable-systems.org.uk/tools.php) (Fusi and Bacenetti, 2014), which assesses the NH_3, N_2O, nitrates (NO_3), and phosphate (PO_4) emissions taking into account soil type, climatic conditions and agricultural management operations, similarly to Brentrup et al. (2000) and Bacenetti et al. (2016b). Volatilisation of NH_3 from the slurry application was assessed considering (i) air temperature, (ii) time between the application and rainfall or incorporation in the soil; (iii) infiltration rate, according to the fertiliser application circumstances (e.g. presence of crop residues on the soil). NH_3 emissions from mineral fertiliser applications were evaluated taking into account the type of fertiliser, climatic conditions, and soil properties (e.g. pH, texture). Finally, N_2O emissions were computed considering the emission factor proposed by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2006).

Pollutant emissions due to fuel combustion in the tractor engines were estimated according to Lovarelli and Bacenetti (2017), taking into account working time, the field shape, age of tractors, and related emissions stages.

For the emissions related to livestock activities, CH_4 emissions from enteric fermentation and slurry management were estimated following the Tier 1 approach equations, as suggested by IPCC (2019). The N_2O direct and indirect emissions from manure management that occur during animal housing and slurry storages were estimated following the Tier 2 method proposed by IPCC (2019). The excreted nitrogen (N) was estimated by calculating N retention and N intake. For N intake, data about Dry Matter Intake (DMI) and Crude Protein (CP) percentage were provided by the farmer. The NH_3 emissions from the manure management system (housing and storage) were estimated using the European Environment Agency (EEA) Tier 2 approach (EEA, 2019a), on the basis of the total amount of N excreted by the animals. Further information on air emissions estimation can be found in **Table 3**.

Table 3. Inventory data used for the estimation of emissions from animal housing and manure management

Item	Value	Source
Pigs population	9760	Primary data
Diet DM content (average)	87%	Primary data
Average LW, piglets	23.5 kg	Primary data
Average LW, fatteners 1	40 kg	Primary data
Average LW, fatteners 2	103 kg	Primary data
Average LW, sows lactating	200 kg	Primary data
Average LW, sows nursery and dry period	180 kg	Primary data
Average LW, replacement males and females	80 kg	Primary data
CH_4 Enteric fermentation emission factor	1.5 kg [CH_4] head^{-1} yr^{-1}	Tier 1 IPCC, 2019
$VS_{rate(T,P)}$ – finishing swine	5.3 kg [VS] t^{-1} [live weight] day^{-1}	Tier 1 IPCC, 2019
$VS_{rate(T,P)}$ – breeding swine	2.4 kg [VS] t^{-1} [live weight] day^{-1}	Tier 1 IPCC, 2019
$EF_{T,S,P}$ emission factor for direct CH_4 emissions from manure management	111.6 g [CH_4] kg^{-1} [VS]	Tier 1 IPCC, 2019
Emission factor for direct N_2O emissions from manure management	0.005 kg [N_2O-N] kg^{-1} [Nitrogen excreted]	Tier 2 IPCC, 2019
Emission factor for indirect soil N_2O emissions due to nitrogen leaching and runoff from manure management	0.01 kg [N_2O-N] kg^{-1} [NH_3-N + NOx-N volatilised]	Tier 2 IPCC, 2019
EF_{hous_slurry} – finishing pigs	0.27 kg [NH_3-N] kg^{-1} [TAN excreted] head^{-1}	Tier 2, EEA 2019
EF_{hous_slurry} – sows and piglets	0.35 kg [NH_3-N] kg^{-1} [TAN excreted] head^{-1}	Tier 2, EEA 2019
$EF_{storage\_slurry\_NH3}$ – all animal category	0.11 kg [NH_3-N] kg^{-1} [TAN in storages] head^{-1}	Tier 2, EEA 2019

Background data regarding the production and supply of the inputs (i.e. feed additives and off-farm feeds including soybean meal and related LUC, diesel fuel, electricity, seeds, fertilisers, pesticides, and agricultural machinery) were obtained from the Ecoinvent Database v.3 (Weidema et al., 2013).

2.4. Life cycle impact assessment (LCIA)

The inventory data were transformed into potential environmental impacts using the characterisation factors defined by ILCD (International Reference Life Cycle Data System) midpoint method (ILCD, 2011). This method has been endorsed by the European Commission. For this study, 12 impact categories were evaluated:

- Climate Change (CC, kg CO_2 eq),
- Ozone Depletion (OD, kg CFC-11 eq),
- Particulate Matter Formation (PM, kg $PM_{2.5}$ eq),
- Human Toxicity–No Cancer Effect (HTnoc, CTUh),
- Human Toxicity–Cancer Effect (HTc, CTUh),
- Photochemical Ozone Formation (POF, kg NMVOC eq),
- Acidification (TA, mol H+ eq),
- Terrestrial Eutrophication (TE, mol N eq),
- Freshwater Eutrophication (FE, kg P eq),
- Marine Eutrophication (ME, kg N eq),
- Freshwater Ecotoxicity (FEx, CTUe),
- Mineral, Fossil and Renewable Resource Depletion (MFRD, kg Sb eq).

Besides these impact categories, also the Cumulative Energy Demand (CED, MJ) was evaluated to better explore the impact of the wet acid scrubber operationing on the energetic performance of the fattening system. Method to calculate Cumulative Energy Demand (CED), is based on higher heating values (HHV).

2.5. Sensitivity analysis

To explore the robustness of the environmental results achieved, a sensitivity analysis was carried out to investigate the influence of the wet scrubber abatement efficiency as well as a system expansion regarding the ammonium citrate produced by the ammonia abatement in the scrubber (due to the reaction with citric acid).

Variation in emission abatement was considered since, in naturally ventilated buildings, emissions are affected by ventilation differences. In cold seasons, windows are kept closed most of the time, which is not the case in warm seasons. In addition, it is known that temperature is positively correlated with NH_3 emissions (Vilarrasa-Nogué et al., 2020), thus in warm seasons NH_3 volatilisation is higher and it is more difficult to capture this gas in naturally ventilated buildings. Consequently, NH_3 removal efficiency of 80% has been assumed for cold seasons and 60% for warm seasons. Moreover, fluctuations in NH_3 removal efficiencies for acid scrubbers have been reported also by Melse and Ogink (2005) and Van der Heyden et al. (2015). The consumables used for the wet acid scrubber operation were varied accordingly.

Regarding the ammonium citrate produced by the NH_3 emission reduction process in the alternative scenario, no allocation and no system expansion were applied to consider this additional product. This was because, on this farm, the N requirements of the different crops are supplied by the pig slurry and because getting value from it as a fertiliser would involve storage and transport out of the farm. However, ammonium citrate can be considered as a mineral fertiliser, and taking into account that the nitrogen contained is in ammoniacal form, an efficiency of 100% can be assumed (1 kg of N in the ammonium citrate substitute 1 kg of N from mineral fertiliser) (Bacenetti et al., 2016). To quantify the potential benefits related to the fertiliser value of this co-product, a systems expansion was applied, with the N contained in the ammonium citrate being assumed to substitute for an equal mass of N from mineral fertiliser.

2.6. Uncertainty analysis

Monte Carlo analysis is an important tool used in many LCA assessments to test the reliability and robustness of systems, structures or solutions (Lesage et al., 2018; Pexas et al., 2020; Bacenetti, 2019). This tool simulates a probable range of outcomes given a set of variable conditions and can be applied within a Life Cycle Inventory framework to capture parameter variability (Guo and Murphy, 2012). Thus, it is a technique employed to quantify variability and uncertainty using probability distributions.

In this study, a Monte Carlo approach, considering 1,000 iterations and a confidence interval of 95%, was applied for the quantification of potential uncertainties associated with data inputs in the model.

3. Results

The potentials environmental impacts of 1 kg of pig live weight at the farm gate for both scenarios are reported in **Table 4**. For 8 of the 12 evaluated impact categories, AS shows a higher impact than BS, due to the impact associated with the use of the wet scrubber. As a result of the reduction of NH_3 emissions in fattening barns (70%), AS has a lower impact for TE , TA , PM , and ME , which are the impact categories influenced by NH_3. This confirms the relevance of NH_3 emissions as an important source of acidification and eutrophication. For these impact categories, the impact for 1 kg of pig LW is lower in AS because the environmental benefits related to the reduction of ammonia emissions offsets the impact increase due to construction, maintenance, and operation of the scrubber. For the remaining impact categories (OD, HTnoc, HTc, POF, FE, FEx, and MFRD), AS is associated with an increase in the impact ranging from 0.9% (FEx) to 102% (MFRD). Indeed, the higher energy and resource consumption related to the construction, maintenance, and operation of the scrubber worsens the results for these impact categories. Although the reduction of NH_3 emissions slightly affects the formation of indirect N_2O, the construction, maintenance, and operation of the scrubber involve GHG emissions that offset the impact reduction related to lower N_2O emissions.

Figure 2 shows the relative contributions to the overall environmental impact of the production factors and of the emissions sources for BS and AS, respectively. According to the results, for all the evaluated impact categories, feed is the most important contributor to the environmental impact of pigs: in BS its contribution ranges from 99% for HTnoc to 40% for CC.

Table 4. Absolute environmental impact for the two scenarios (FU = 1 kg of pig LW; Δ = impact variation of AS compared to BS).

Impact category	**Acronym**	**Unit**	**BS**	**AS**	**Δ**
Climate change	CC	kg CO_2 eq	3.55	3.65	2.85%
Ozone depletion	OD	kg CFC-11 eq·10^{-7}	3.12	3.32	6.53%
Human toxicity, non-cancer effects	HTnoc	CTUh·10^{-7}	7.08	7.29	3.00%
Human toxicity, cancer effects	HTc	CTUh·10^{-8}	1.90	2.24	17.45%
Particulate matter	PM	g $PM_{2.5}$ eq	3.28	3.16	-3.62%
Photochemical ozone formation	POF	kg NMVOC eq·10^{-2}	1.08	1.13	4.66%
Acidification	TA	mol H+ eq	0.12	0.10	-10.16%
Terrestrial eutrophication	TE	mol N eq	0.51	0.46	-10.98%
Freshwater eutrophication	FE	kg P eq·10^{-4}	4.49	4.65	3.57%
Marine eutrophication	ME	kg N eq·10^{-2}	1.93	1.92	-0.36%
Freshwater ecotoxicity	FEx	CTUe	23.74	23.95	0.91%
Mineral, fossil & renewable resource depletion	MFRD	kg Sb eq·10^{-5}	2.42	4.88	101.84%

In particular, for CC, CH_4 emissions and feed purchase (due to the use of inputs such as fuel, machinery, fertiliser, pesticides, and transport) are the most significant processes. In particular, CH_4 emissions account for 49.6% and 48.2%, and feed accounts for 40.3% and 39.1%, in BS and AS, respectively. Among feed ingredients, soybean and maize have been identified as the most significant environmental processes for CC, accounting for 50 and 40%, respectively. About 10% is attributable to electricity, and to direct and indirect N_2O emissions. In particular, electricity is responsible for about 5.0% and 4.8%, and N_2O emissions for 5.1% and 4.6%, in BS and AS, respectively.

Excluding feed, NH_3 emissions from storage and housing are mainly responsible for TA and TE. For TA, they range from 44% to 36%, in BS and AS, respectively; for TE, they account for 45% and 37%, in BS and AS, respectively. Finally, NH_3 emissions are also important for PM and ME. In particular, for PM they contribute about 34% and 26%, in BS and AS, respectively; whereas for ME they account for 8.1% and 6.1%, in BS and AS, respectively.

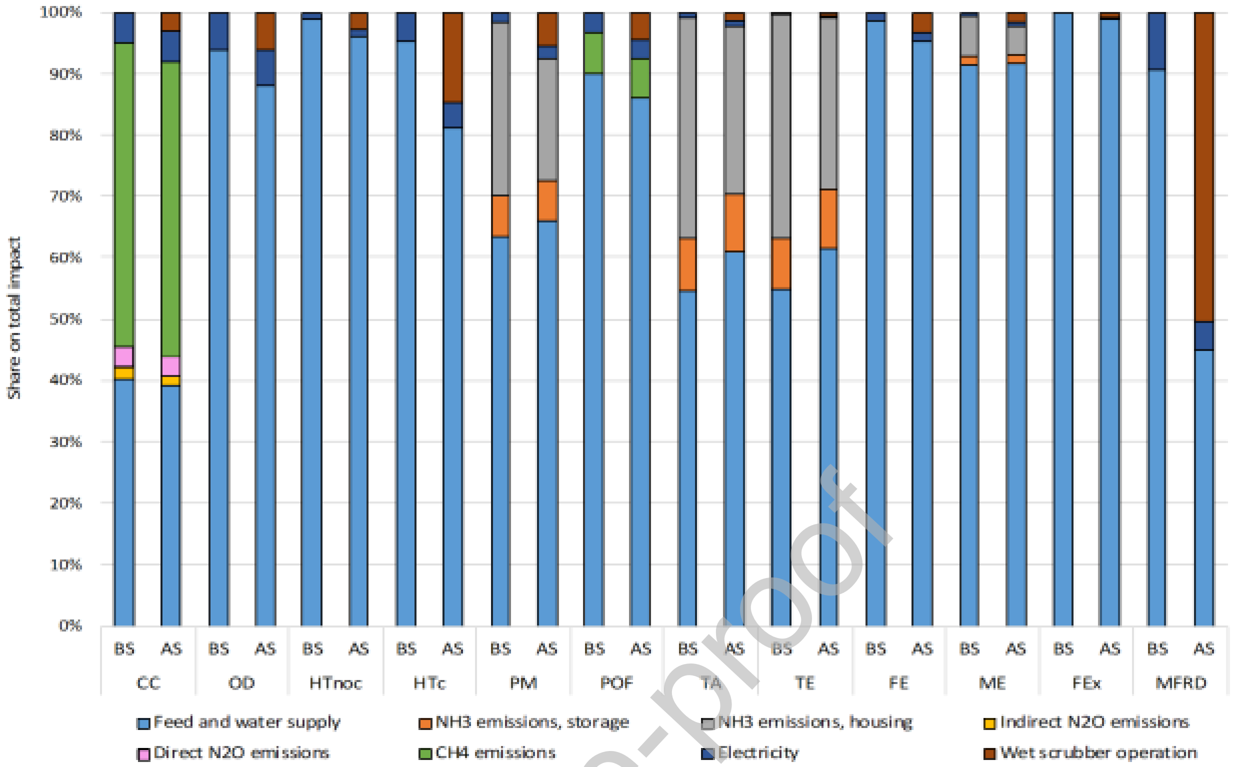


Figure 2. Contribution of different inputs and outputs to environmental impact categories in BS and AS. BS: baseline scenario; AS: alternative scenario

The abatement efficiency of the wet acid scrubber in AS leads to a reduction of impacts related to NH_3 emissions. Also, N_2O emissions show a slight reduction and result in a small decrease in CC impact (-0.01%), since indirect N_2O emissions are reduced. The contribution of the wet scrubber in AS to the environmental impact of 1 kg of pig LW at the farm gate registers the highest relative contribution for MFRD (50%) and the lowest for TE (0.6%), as shown in **Figure 2**. For all impact categories, the consumable materials for scrubber operation (energy, citric acid, and water) represent around 93% of the total impact of the scrubber operation, except for HTc, in which it corresponds only to 57% with the remaining 43% of the impact related to its construction and electricity consumption, as shown in **Figure 3**. Therefore, for all the evaluated impact categories, the production of citric acid is by far the main contributor followed by electricity and water supply. The latter has a negligible impact (<0.1%) for all the impact categories except for the human toxicity-related impact categories (about 0.5%).

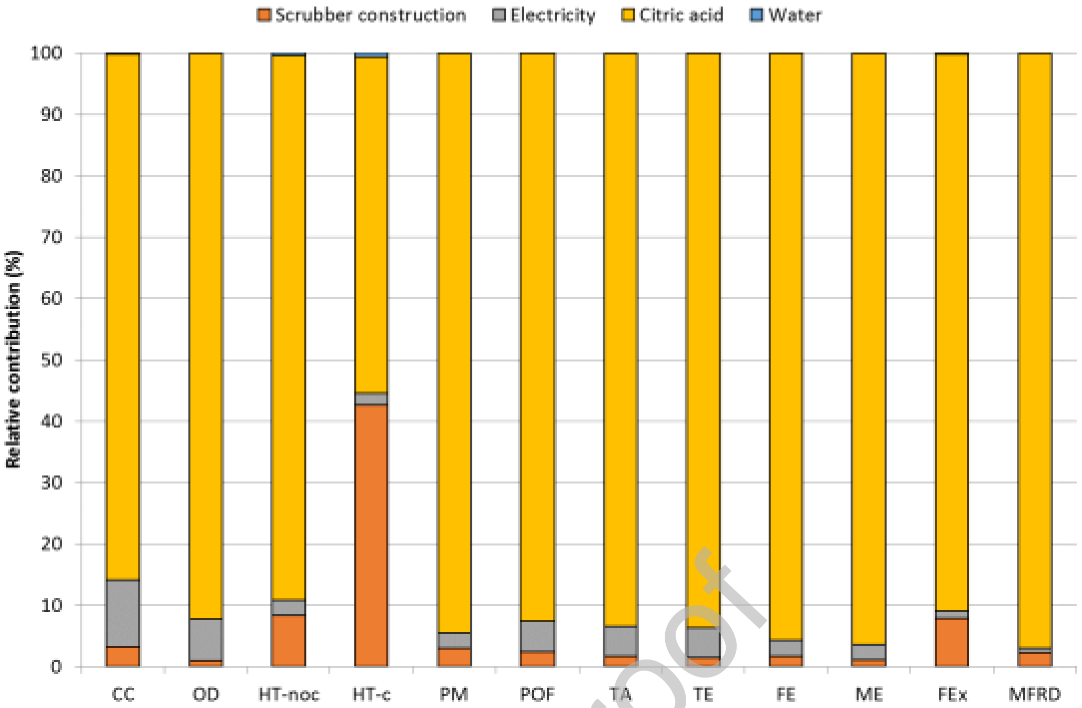


Figure 3. Relative contribution for the wet acid scrubber operation

Table 5 reports the results for CED. The compassion between the two scenarios show how AS shows higher values compared to BS expect than for the CED related to Renewable, biomass. The differences, ranging from +5% to +17% are (as expected) related to the consumption of electricity.

Table 5. CED: results Comparison between BS and AS

Impact category	Unit	BS	AS
Non renewable, fossil	MJ	17.158	18.878
Non-renewable, nuclear	MJ	1.714	1.826
Non-renewable, biomass	MJ	2.673	2.673
Renewable, biomass	MJ	16.657	17.532
Renewable, wind, solar, geothe	MJ	0.187	0.213
Renewable, water	MJ	0.662	0.777

3.1. Sensitivity analysis results

Table 6 shows the impact variation for 1 kg of pig LW at the farm gate in the alternative scenario considering possible different levels of NH_3 emission abatement efficiency. As expected, the results show that, as NH_3 abatement efficiency increases, the impact for the categories related to its emissions (i.e. PM, TA, TE, and ME) is reduced, and vice versa. The variations for these impact categories reach a maximum of ±2.5% for TE. The remaining impact categories, on the other hand, show an opposite trend, due to the consumables for the scrubber operation which are greater as the abatement efficiency increases. Among these, the impact category showing the greatest variability is MFRD, which varied by ±4.0%.

Table 6. Sensitivity analysis results, expressed as percentage change in the impacts respect to the alternative scenario, in which 70% NH_3 abatement for the wet acid scrubber was considered.

	Ammonia abatement efficiency	
Impact category	**60%**	**80%**
Climate change	-0.31%	+0.31%
Ozone depletion	-0.66%	+0.66%
Human toxicity, non-cancer effects	-0.07%	+0.07%
Human toxicity, cancer effects	-1.59%	+1.59%
Particulate matter	+0.53%	-0.53%
Photochemical ozone formation	-0.57%	+0.57%
Acidification	+2.25%	-2.25%
Terrestrial eutrophication	+2.51%	-2.51%
Freshwater eutrophication	-1.13%	+1.13%
Marine eutrophication	+0.02%	-0.02%
Freshwater ecotoxicity	-1.20%	+1.20%
Mineral, fossil & renewable resource depletion	-4.04%	+4.04%

Regarding the system expansion applied to utilise the value of ammonium citrate as a mineral fertiliser, the sensitivity analysis highlighted a small impact variation. When the N in the ammonium citrate replaces the same amount of N fertiliser, the impact reduction for the alternative scenario ranges from 0.31% for TE to 4.05% for MFRD (with CC, PM, TA, FE, ME, and TE reduced by less of 1% and only HT-noc, FEx and MFRD by more than 2%).

3.2. Uncertainty analysis results

To test the robustness of the achieved results while comparing the two scenarios, a quantitative uncertainty analysis was carried out by using the Monte Carlo technique (1,000 iterations and a confidence interval of 95%) as a sampling method. The results are reported in **Figure 4**.

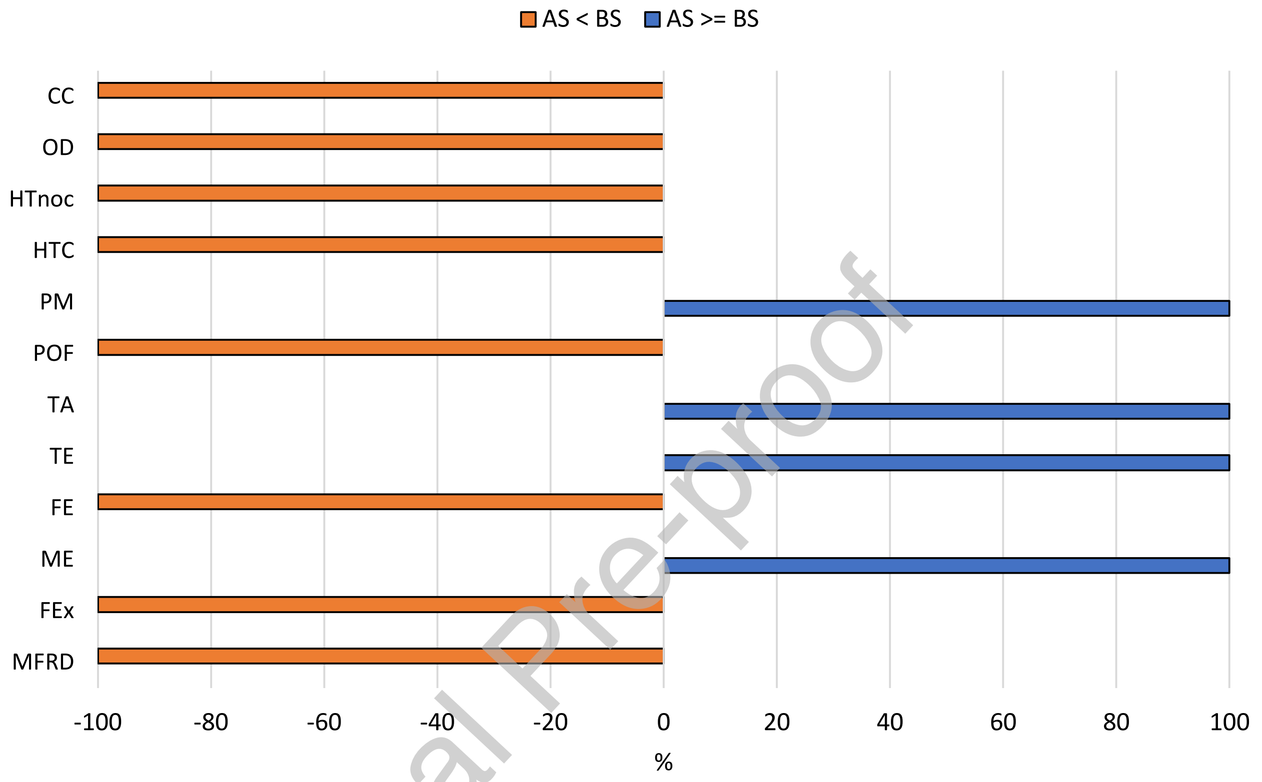


Figure 4. Uncertainty analysis results regarding the comparison between Baseline Scenario and Alternative Scenario.

The bars represent the probability that the environmental impact of BS is higher than or equal to the AS one, while those on the left represent the opposite probability. The uncertainty due to the selection of the data from databases, partial model adequacy, and variability of data does not significantly affect the comparison between baseline and alternative scenarios for all the evaluated impact categories.

4. Discussion

Previous LCA studies, carried out in different European countries, have found the CC indicator to range from 2.25 to 9.35 kg CO_2 eq kg^{-1} LW (Dourmad et al., 2014; Monteiro et al., 2019; Pirlo et al., 2016).

In this study, CC was 3.55 to 3.65 kg CO_2 eq, in line with LCA studies carried out in Greece (Anestis et al., 2020), Italy (Bava et al., 2017; Pirlo et al., 2016), and Spain (González-García et al., 2015). Bava et al. (2017) assessed the environmental impact of 6 intensive pig farms located in Northern Italy, producing heavy pigs. They reported an average CC of 4.25 kg CO_2 eq kg^{-1} LW. Pirlo et al. (2016) obtained similar results (3.3 kg CO_2 eq) using an economic allocation. They considered both the breeding and growing-fattening phase of heavy pig production and showed that 70% of the environmental impact could be attributable to the growing-fattening phase. Monteiro et al. (2019) found different results for the environmental impact of 8 pig farms located in Italy, but this may have been affected by the use of a local pig breed, the lower number of fattening pigs considered, and the inclusion of grazing emission and soil carbon sequestration. Finally, Anestis et al. (2020) and González-García et al. (2015) assessed the impact related to the production of pigs. Although the LW of fattening pigs considered was lower (around 105 kg), the values in those studies are close to those reported here. The most influential subsystems in CC are GHG emissions and feed production, as also reported by Bava et al. (2017), Dourmad et al. (2014), González-García et al. (2015) and McAuliffe et al. (2016).

In this study, feed was identified as the most important contributor to the environmental impact of pig farming. This is in line with the results of many other studies (Bava et al., 2017; Pirlo et al., 2016; Reckmann et al., 2013). In particular, soybean meal and oil represent the main protein sources. The replacement of soybean sourced from South America (mainly Argentina and Brazil) with locally produced material could certainly affect the final impact, as the contribution from transportation distances (e.g. diesel) and relative emissions other than emissions related to land-use change drastically reduce (van Zanten et al., 2018). Alternatively, other protein sources could be introduced, such as peas, rapeseed meal, and sunflower, even if optimising nutrient-use efficiency is probably the most effective step (Eriksson et al., 2005; Monteiro et al., 2016). In this regard, Andretta et al. (2018) evaluate the potential environmental impact of Brazilian pig production using precision feeding systems during the growing-finishing phase instead of the conventional feeding system. They obtained lower environmental impact for the precision daily feeding by group and by individual programmes compared with the conventional feeding program (4% and 6% savings in potential climate change impact, respectively).

For the other impact categories, the results cannot be compared because of the different units of measurement related to the choice of different characterisation methods. In this study, results have been calculated according to LCIA methodology, whereas, among the works mentioned above, Bava et al. (2017), Monteiro et al. (2019), and Pirlo et al. (2016) performed their evaluations using CML Baseline method. Moreover, different methodological choices (e.g. functional unit selected, system boundaries, emissions inventory, allocation factor choice) significantly influence the impacts and a substantial difference in the environmental impacts occurs.

Regarding air scrubbers in piggeries, De Vries and Melse (2017) assessed the environmental impact of an acid scrubber, and two kinds of biotrickling filter (nitrification only, and with nitrification and denitrification). For the acid scrubber, with a 90% NH_3 removal efficiency, they found that CC was 5.31 kg CO_2 eq, for biotrickling filter with nitrification only and 70% of NH_3 removal efficiency it was 6.73 kg CO_2 eq, and for biotrickling filter with nitrification and denitrification and 70% NH_3 removal efficiency it accounted for 121 kg CO_2 eq. Unfortunately, these results are not comparable since they use as FU 1 kg [NH_3-N] entering the scrubber. However, they similarly observed that the greatest NH_3-abatement effects can be observed on TA, PM, and ME, confirming that acid scrubbers are an effective tool to reduce NH_3-related impacts. Also, the sensitivity analysis highlighted the effect of changing the abatement efficiency on NH_3-related impacts; the higher is the removal efficiency, the lower are PM, TA, TE, and ME impacts. It can be concluded that implementing wet acid scrubbers can effectively mitigate NH_3-related impacts from pig housing. However, considering that a wide range of mitigation techniques is available for reducing NH_3 (Finzi et al., 2019; Philippe et al., 2011) and GHG emissions (Marszałek et al., 2018) in pig production, there is a need for future studies that, by combining different mitigation strategies, identify the best farm design in order to reduce the releases both inside pig houses and outside (e.g., during manure storage and spreading).

Moreover, the improvement of air quality and environmental conditions inside piggeries will improve the health of workers and animals living in the barns (Cao et al., 2021; Costantini et al., 2020), leading to a reduction of the insurgence of respiratory diseases and to a better evaluation at slaughterhouse for what concern lungs score. Although farmers are not open to innovation, data proving a beneficial effect on animal performance and welfare (i.e. higher feed conversation rate; reduced respiratory problems) will help to persuade them to test air treatment solutions.

5. Conclusions

The present study reports preliminary results for the environmental impact of a farm producing heavy pigs where a wet acid scrubber for air treatment has been installed to reduce NH_3 emissions in pig barns naturally ventilated. Though feed is the main factor responsible for the environmental load, the use of a wet acid air scrubber leads to an impact reduction for all the impact categories influenced by NH_3 (TA, TE, PM, and ME). Though emission from pig barns only represents part of the NH_3 emission during pig rearing, the application of the wet acid scrubber is an effective strategy to reduce the environmental impact of heavy pigs for NH_3-related impact categories. However, at the same time, it worsens other impact categories, such as CC, OD, POF, toxicity-related impact categories, and MFRD. To reduce the environmental load for these latter impact categories, the adoption of mitigation strategies at the feed level is fundamental and more promising. To improve the environmental performance of scrubber, efforts could be made to reduce water and citric acid consumption by increasing their recirculation. At the same time, a further small impact reduction could arise by realising the fertiliser value of ammonium citrate salt (formed by the reaction between NH_3 and citric acid). The outcomes of this study can be upscaled to other European countries were pig rearing takes place mainly in naturally ventilated facilities.

Future research activities should focus on the development of a microclimatic tool able to continuously monitor the air quality inside barns, to allow automatic management of the activation of the abatement system so that NH_3 levels fall within established thresholds, thus reducing NH_3 emissions and minimising energy consumption associated with its operation. This new technology, when completely automated, would help farmers to monitor pollutants and to control the environmental impact without unnecessary operation. Besides this the economic impact of wet acid scrubber on the economic performances of the process should be evaluated considering the increase of the production cost and, on the other side, the willingness to pay of consumer for pig meat produced in pig barns with improved air quality.

Declaration of Competing Interest

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

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