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Life cycle assessment of swine manure management: A comparison of different management systems with Montecarlo simulation

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ABSTRACT

The agricultural industry deeply impacts in the environment due to methane, an important greenhouse gas (GHG), and ammonia emissions that causes acidification and eutrophication. Recognising the urgency of addressing the environmental impact, this study analyses different manure management strategies coupled with diverse energy sources. The principal analytical tool employed was Life Cycle Assessment (LCA), with a focus on evaluating environmental impacts and discerning the most sustainable approach within this context. In addition, Monte Carlo Analysis (MCA) was applied to explore how emissions may fluctuate in response to variations of manure composition. This research contributes to ongoing efforts to align agricultural practices with sustainability goals and reduce the environmental impact. Five scenarios proposed on the swine manure management, based on biogas and solar energy, demonstrate a substantial positive impact on the climate change category when an anaerobic digestion stage is incorporated into the process. Conversely, the impacts related with ammonia emissions were not significantly reduced with the introduction of renewable technologies in the farming. The MCA revealed a high dependence on the chemical composition of the manure for the impacts climate change and acidification in case of the simplest scenarios studied, without biogas production. The application of a solar energy system improves the energy balance and consequently reduce the overall environmental impact. In this sense, hybrid panels that simultaneously generate thermal and electric energy presented the highest energy recovery but significantly higher impacts on eutrophication, toxicity and resource use, due to the higher complexity of materials of these systems.

1. Introduction

The agricultural sector plays a significant role in the generation of greenhouse gas (GHG) emissions. Key activities within this sector, such as agriculture, livestock farming, forestry, and mining, contribute to this impact through various means (Gołasa et al., 2021). These include release of methane, ammonia and nitrous oxide emissions, deforestation and land-use changes, the utilization of fossil fuels in mining operations, the transportation and distribution of primary products. According to the latest projections, it is anticipated that by 2050, more than 50 % of GHG emissions will be attributed to activities associated with this sector (European Parliament, 2018). Mitigating these emissions requires a fundamental transformation of the agricultural sector. This transformation involves the adoption of more sustainable practices and the incorporation of cleaner technologies, such as substituting fossil fuels used in the sector activities by renewable energy sources, as a crucial step (Zheng et al., 2019). The strategy entails establishing a strong connection between the energy and agricultural sectors. This integration will not only lead to a reduction in GHG emissions but also contribute to a decrease in overall energy costs (Chen et al., 2023; Kim et al., 2022).

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Livestock farming is a significant contributor to greenhouse gas (GHG) emissions. Methane is generated during the digestive processes of animals and manure storage, while nitrous oxide mainly arises from soils after manure application (Kougias and Angelidaki, 2018). Consequently, manure, as an organic waste by-product of livestock operations, has a considerable environmental impact (Loyon et al., 2016). Globally, agriculture accounts for 39.6 % of methane emissions, which in turn is responsible for 30 % of global climate change (International Energy Agency, 2022). The sector also contributes to 85.7 % of ammonia emissions, with swine farms alone responsible for 11 % of total agricultural emissions (Van Damme et al., 2021). Beside emissions, poor management practices are related with acidification and eutrophication, which could have consequences for human health (Wyer et al., 2022). Biogas production not only mitigates GHG release but also presents a sustainable path for reducing agriculture's overall environmental footprint.

In response to this situation, specific legislation aimed at reducing the environmental impact of manure management, with a focus on mitigating ammonia and GHG emissions, has been introduced. One promising strategy to address these challenges is the utilization of manure as feedstock for bioenergy production, particularly through anaerobic digestion, which can convert organic waste into biogas. This approach not only reduces methane emissions from manure storage—a gas with a significantly higher global warming potential than CO_2 (Mar et al., 2022) —but also provides valuable by-products such as biofertilisers and renewable energy (Chozhavendhan et al., 2023). In Spain alone, the potential for biomethane production from animal manure is estimated at 25.48 TWh (Bumharter et al., 2023; Calero et al., 2023), highlighting the opportunity to integrate agricultural waste into the energy sector (Kabeyi and Olanrewaju, 2022).

The transformation of the livestock sector necessitates integration into the energy production sector, demanding innovative solutions to address increasing energy needs and reduce reliance on oil and natural gas. Another strategy with a dual impact, aimed at mitigating GHG emissions and enhancing the economic sustainability of livestock activities, involves the hybridisation of different renewable energy sources, maximizing the use of locally available resources. A distinctive characteristic of farms in Spain is their frequent location in remote areas, often lacking access to the electricity grid, and reflecting a decentralized industry structure aimed at reducing environmental impact and limiting the concentration of farming operations near urban areas considering the directives derived from the "Sectoral Organisation of Pig Farming" and "Register of Emissions and Pollutant Sources" in Spain (MAPA, 2020; MITECO, 2006). In such settings, harnessing energy from sources, such as wind or solar power, can represent the most optimal alternative (Jahangir et al., 2022; Lombardi et al., 2020). This approach not only helps mitigate the effects of GHG emissions, but also enables the achievement of complete energy self-sufficiency for these agricultural operations (Buragohain et al., 2021).

The transformation of the livestock production into a more sustainable process sector necessitates comprehensive examination from various perspectives regarding the impacts. To facilitate this assessment, life cycle analyses provide a valuable framework for evaluating and contrasting the environmental repercussions of diverse processes over their entire lifespan (Andersson and Börjesson, 2021). This approach assists in identifying areas that require enhancement and facilitates the adoption of more sustainable decision-making. In this study, the management cycle of swine manure from intensive farms was examined under five distinct scenarios corresponding to the following renewable technologies: covered slurry storage ponds to reduce emissions, biogas production via anaerobic digesters, and the incorporation of photovoltaic or hybrid solar panels (García Álvaro et al., 2023). The primary objective is to identify and contrast critical issues within the life cycle assessment, with a particular focus on established categories, such as climate change impact, land and water usage and particulate matter emissions. The proposed scenarios will be compared with a base case (scenario 1), which represents the conventional use of the swine manure as fertiliser in the field.

Manure management methods and technologies have been previously evaluated through LCA (Table 1). The study herein presented uses a novel approach, implementing not only biogas production, but also integrating of two kind solar panels, delivering additional environmental benefits beyond biogas production. Previous studies, such as Lijó et al. (2014) or Lyng et al. (2015) focused only on biogas production and processing. Cherubini et al. (2015) and Hollas et al. (2021) studied impact of pig manure storage. Unlike previous studies, a multi-scenario analysis provides a greater versatility than single-system assessments, such as the works of Fernandes et al. (2023) or Luo et al. (2013). Similarly, some researchers have reported GHGs and ammonia emissions, quantifying the effects of anaerobic digestion and the integration of renewable energy (Vu et al., 2015), without taking into account other impacts determined in a complete LCA study.

The research was conducted using the experimental results of the project "LIFE Smart Agromoblity" (www.lifesmartagromobility.eu), which is based on the construction and operation of a biomethane production installation inside a pig farm and it was financed by the LIFE program call of the European Commission. The primary method employed in this study was life cycle assessment (LCA), which was applied to five different scenarios explained in the next section. The study's key objectives were as follows: 1) to calculate the environmental impacts of different manure management practices and different renewable energy technologies to determine the most environmentally sustainable option through LCA analysis. 2) to calculate how emissions vary depending on the composition of manure using a Monte Carlo analysis (MCS).

1.1. System description

Data for the different scenarios studied were obtained from the pig farm and the prototype plant built in the LIFE Smart Agromobility project. Manure collection and storage of the farm consisted in the conventional configuration composed of a storage pit below animal confinement, where manure remains about 45 days before land application. To this basic configuration different modifications were projected and studied to evaluate the environmental impacts. The first variation considered was covering the pit, reducing emissions and using manure for land application after 45 days, following the recommendation of the authors (Baldé et al., 2016; Maldaner et al., 2018). The next variation was the production of biogas, following the strategy and information available in the LIFE Smart Agromobility project. In this process, manure is directly pumped into an anaerobic digester, where it is digested over a period of 40 days with a biogas and digestate production. The digestate was then stored and used (Vu et al., 2015) for land applications after 28 days. In this case, different energy technologies were evaluated in combination to the biogas production: photovoltaic (PV) and hybrid solar panels producing electricity and heat for the facility consumption. Electricity sourced from the grid was considered in absence of solar panels.

In summary, the scenarios studied are explained below and presented in Fig. 1.

- **Scenario 1:** Conventional techniques were employed to convert manure effluent into organic fertiliser, which was then directly applied to the soil. This organic fertiliser reduces or eliminates the need to manufactured synthetic fertilisers. The energy demand involved in transporting swine manure from off-site storage to the field application location was considered.
- **Scenario 2**: This scenario closely resembles Scenario 1, with the key difference being that the slurry storage is located externally and covered to prevent direct contact between liquid and air.
- **Scenario 3**: In this scenario, the swine manure effluent was moved to an anaerobic digester of the "covered pond-type" through a pumping

Table 1
Literature review of LCA manure management including a stage of anaerobic digestion.

Study	Scope	Raw material	Functional unit	Digestion	Scenarios compared	Location
Lijó et al. (2014)	Anaerobic mono-digestion of two different substrates	Pig slurry & maize silage	1 tonne of feedstock	Mono	1 (4 subsystems)	Italy
Lyng et al. (2015)	Organic waste and manure treatment	Manure from cattle and pigs	1 tonne of dry matter per year	Mono	6	Norway
Luo et al. (2013)	Manure treatment systems	Pig manure	Annual production of a typical pig farm	Mono	2	China
T. K. V Vu et al. (2015)	Manure management biogas digesters	Pig manure	100 kg of solid pig manure	Mono	2	Vietnam
Cherubini et al. (2015)	Swine manure mangement	Swine manure	1000 kg of swine carcass	Mono	4	Brazil
Hollas et al. (2021)	Swine manure storage	Swine manure	1 m^3 of swine manure	Mono	3	Brazil
Adghim et al. (2020)	Dairy waste management	Dairy waste	1 tonne of wet manure	Co	2	United Arab Emirates
Fernandes et al. (2023)	Anaerobic digestion of manure	Livestock manure	1 m^3 of biogas	Mono/ Co	3	Portugal
This work	Swine manure management	Swine manure	1000 head of swine livestock	Mono	5	Spain

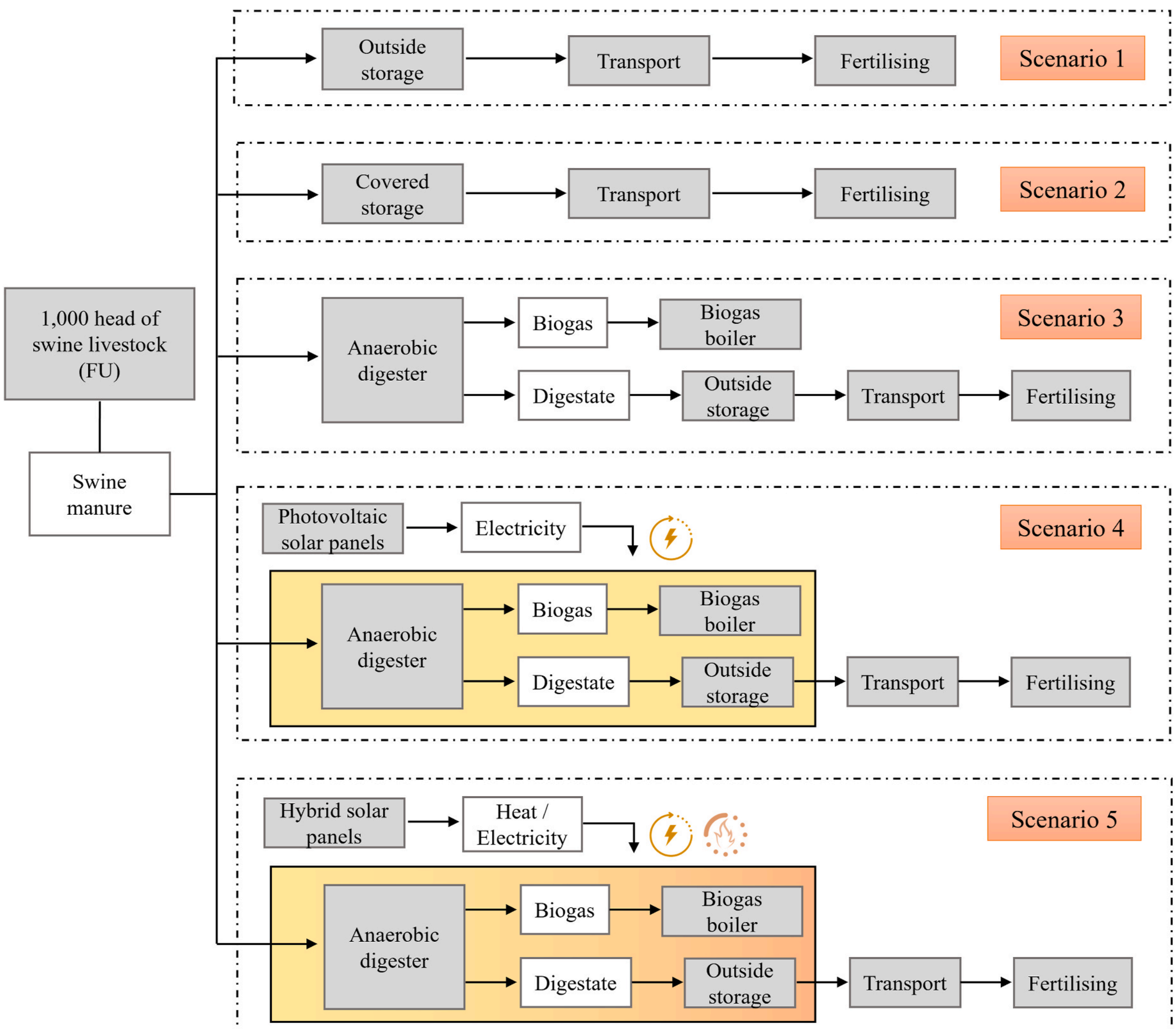

Fig. 1. Scenarios considered in this study for the swine manure management.

system. Within this digester, biogas is generated as a gaseous by-product while the liquid, namely digestate, is retained. The biogas was then conducted into a biogas boiler to generate heat. The digestate is employed as a soil fertiliser using conventional methods involving off-site storage and direct application. Throughout this process, energy requirements and emissions of both anaerobic digestion and digestate transportation were considered.

- **Scenario 4:** Consisted in the material flow described in Scenario 3 and adding a PV solar installation. The energy generated in the solar panels is converted into electricity to power the equipment through a photovoltaic inverter. To the LCA calculations the average production of panels was simulated through a specific software (PVGIS 5.3). Since the daily production of panels is higher than electricity consumption, electricity is delivered to the grid, while night periods require grid consumption.

- **Scenario 5**: Similar to Scenario 4, but using hybrid solar panels that simultaneously generate electricity and heat within a hydraulic circuit. Heat is utilised to sustain the anaerobic digester at the required operational temperature. Same approach of Scenario 4 was used for determination of the electricity and heat generation in an average day.

1.2. Goal and scope

The functional unit (FU) selected for this study was the amount of manure produced by 1000 head of swine livestock, considering that average size of farms in Spain (Instituto Nacional de Estadística, 2020; Woraruthai et al., 2022). Based on the findings of the LIFE Smart Agromobility project, a single pig generates 0.0045 m^3 of manure per day. Given the manure's density from laboratory results of this project (1040 kg/m^3), this corresponds to a production rate of 4.68 kg per pig per day.

This study aimed to evaluate and compare the Environmental Footprint (EF) of manure management options from the perspective of Life Cycle Assessment (LCA). The scope of this LCA is cradle-to-grave, assessing the EF of the following activities: manure storage, anaerobic digestion, digestate storage, field application of both manure and digestate and solar energy production in the farm. According to the results from the LIFE Smart Agromobility, 5 km was considered for transporting manure and digestate to the application field.

The boundaries of the system are (1) cradle, as we are considering an input with no associated impacts due to compliance with European Regulation 2023/1185 (European Commision, 2023) and at the beginning, manure is considered a waste; and (2) grave, as the consumption of biogas and fertilisers was considered (Bandekar et al., 2022). Infrastructure has not been considered according to Commission Recommendation (EU) 2021/2279 (European Commision, 2021), if there is no evidence that infrastructure is relevant, it should be excluded, as in our case.

1.3. Life cycle inventory (LCI)

To perform the LCI, the data input obtained in the LIFE Smart Agromobility project were used, such as manure composition and power consumption of equipment. In the Supplementary Information Section B (Tables B.1 to B.16) the LCI tables for each scenarios, including all references used at each stage, are provided specifying which data is sourced from LIFE Smart Agromobility and which data comes from the literature. Critical factors, such as N_2O emissions, were calculated considering the variations of manure composition (Calero et al., 2023; García Álvaro et al., 2024; Maldaner et al., 2018; Petersen et al., 2016). The manure samples were collected form the pig farm during a year and stored at 4 °C to prevent degradation. Physicochemical characterisation was performed according to standard protocols following the American Public Health Association (APHA) guidelines (Gilcreas, 1966). This characterisation included parameters such as the organic content, dry matter, and nitrogen content. Concurrently, the digestate produced after the anaerobic digestion was also studied. In case of biogas production, the amount of gas produced and its composition were obtained from the anaerobic digester operated in the above mentioned project. This digester, which had a volume of 150 m^3 and a hydraulic retention time (HRT) of 40 days, was operated under mesophilic conditions (35 °C) and treated the swine manure.

A bibliographical study was conducted to perform the LCI for each stage. *Supplementary Information Section B* has a list of references used for the LCI.

1.4. LCA analysis

The software used for the LCA calculations was SIMAPRO version 9.5.0.1, based on Environmental Footprint 3.1, a method developed and recommended by the European Commission (European Commission, 2022; Jungbluth, 2023). This methodology evaluates the following categories of impacts: acidification, climate change, ecotoxicity (freshwater), particulate matter, eutrophication (marine, freshwater and terrestrial), human toxicity (cancer and non-cancer), ionising radiation, land use, ozone depletion, photochemical ozone formation, resource use (fossils, minerals and metals) and water use. *Supplementary Information Section A* provides a comprehensive explanation of these categories. The soil-carbon changes are highly complex and warrants a comprehensive review and analysis of its own, which lies well beyond the scope of this study (Walling and Vaneeckhaute, 2020).

1.5. Montecarlo simulation

Montecarlo Simulation (MCS) has been performed to evaluate the robustness of the results from LCA. An MCS consisting of 1000 runs was applied to the input of the model using the probability distribution of the parameters obtained in the laboratory, using three samples per month during a year, with a total of 36 samples. The variables selected in this simulation are listed in Table 2, with the mean and deviation values.

2. Results and discussion

2.1. Mass and energy balance

This section explains the inputs and outputs of mass and energy necessary for obtaining biogas in each scenario. A comprehensive flow of mass and energy can be found in the *Supplementary Information Section B*. Fig. 2(a) depicts the amount of consumed and produced mass and Fig. 2(b) shows the consumed and produced energy per 1000 swine heads (functional unit) per day. As depicted in Fig. 2(a) for all Scenarios, the amount of matter consumed remained constant and corresponded to the amount of manure generated per 1000 swine heads on a daily basis (4680 kg). The quantity of fertiliser generated was calculated as manure stored or digestated produced. For Scenarios 1 and 2 the fertiliser produced was 4870 kg/day and for Scenarios 3, 4 and 5 the fertiliser generated is 4626 kg/day. The slight difference is due to the biogas production during the anaerobic digestion process.

In case of energy balance, electricity and heat consumption were taken into account (Fig. 2 b). In case of energy produced there was considered the energy content of biogas. Scenario 5 was characterized by the highest energy consumption and production. This scenario used solar energy not only for electricity, with an average daily energy production of 8.64 kWh, while a consumption of 7.16 kWh, a surplus of 0.534 kWh will be exported to the grid over the course of the day, but also for heating, in contrast than Scenario 4 only use solar energy for electricity production with an average value during a day of 8.64 kWh, and there are only consumed 7.16 kWh, so 0.534 kWh will be sold to the grid considering all day. Subsequently, an extra production of biogas of

Table 2
Variables of MCS.

Variable	Mean	Deviation value
Manure density (kg/m^3)	1040	16.4
Dry matter (g/kg)	45.3	12.5
Organic matter (g SV/kg)	33.3	15
Biogas production (m^3/kg SV)	0.5	0.125
Content of nitrogen in manure (g/L)	3.3	1.3
Content of mineral nitrogen in manure (%)	63.5	4.6
Content of nitrogen in digestate (g/L)	3.06	0.77
Content of mineral nitrogen in digestate (%)	71.69	2.69
Content of methane in biogas (%)	64.3	5

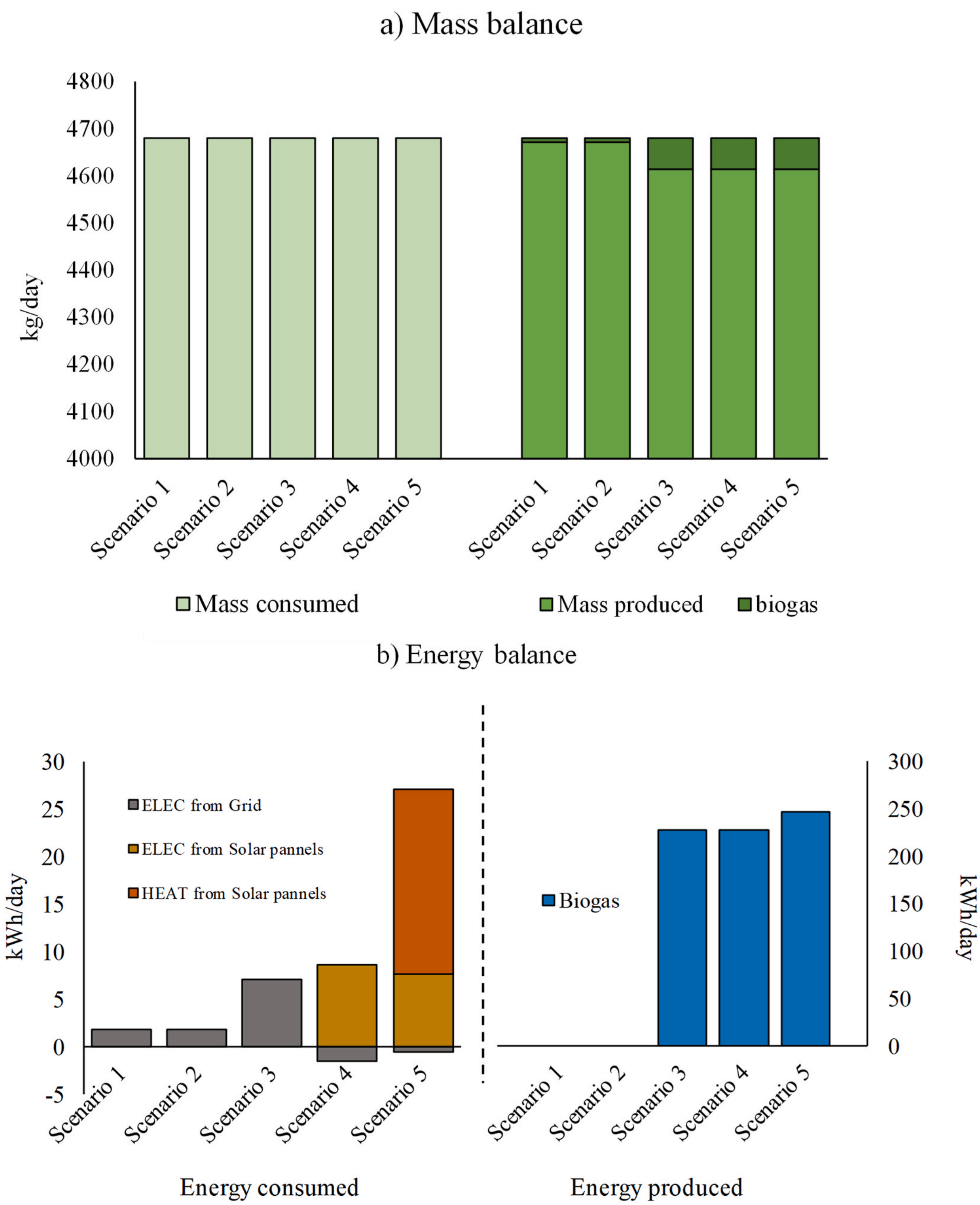

Fig. 2. (a): Mass consumed and produced. Fig. 2(b): Energy consumed and produced in each scenario.

19 kWh/day was obtaining reaching a final value of 227 and 246 kWh/day was produced for scenario 4 and 5, compared to Scenarios. On the other hand, Scenarios 1 and 2 have no energy production since there is no recovery of methane or electricity.

2.2. LCA analysis

The results of this study are listed in Table 3. Three main situations were analysed: conventional manure management (Scenario 1), conventional management with covered storage pit (Scenario 2), biogas production with anaerobic digestion (Scenario 3), use of solar panels for electricity production (Scenario 4) and for simultaneous heat and electricity generation (Scenario 5).

The production of biogas (Scenarios 3, 4, and 5) has a clear advantage in the impact categories of climate change, eutrophication marine, human toxicity, land use, and photochemical ozone formation opposite to manure storage and land application alternatives of Scenarios 1 and 2.

For most of the impacts, covering the pit (Scenario 2) resulted in a reduction of impacts compared to the conventional technique of Scenario 1. In case of climate change a reduction of 19.7 % was found in Scenario 2 compared to 1, evidencing the strong impact of methane emssions during storage. In the case of acidification, similar values were detected in both cases (covered and uncovered pit) since this category rather depends on the fertilization stage. In this sense, slightly improvements were found in the categories of ecotoxicity in freshwater, particle matter and terrestrial eutrophication with reductions of 3.17 %, 3.35 % and 3.32 %, since they are mainly impacted by application of manure into soil. On the other hand, reductions of 19.31 % and 16.23 % were found in non-cancer and photochemical ozone formation, since these categories are impacted by methane emissions from manure storage stage. For the rest of the categories: marine eutrophication, freshwater eutrophication, cancer human toxicity, ionising radiation,

Table 3
Results of Life Cycle Assessment for the different categories of impacts in each scenario. The green colour indicates lower impact values, while the red colour indicates higher impact values, according to the mean value plus or minus a 10 % of the mean value.

Impact category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Acidification	mol H^+ eq	0.489	0.475	0.489	0.484	0.493
Climate change	kg CO_2 eq	183.33	147.11	41.90	40.86	41.40
Ecotoxicity, freshwater	CTUe	813.18	787.37	813.24	812.09	825.56
Particulate matter	disease inc.	1.17E-04	1.13E-04	1.18E-04	1.18E-04	1.18E-04
Eutrophication, marine	kg N eq	1.306	1.288	0.998	0.997	0.998
Eutrophication, freshwater	kg P eq	1.98E-03	1.98E-03	1.95E-03	1.89E-03	2.56E-03
Eutrophication, terrestrial	mol N eq	19.34	18.70	19.45	19.44	19.45
Human toxicity, cancer	CTUh	1.33E-07	1.33E-07	1.20E-07	1.19E-07	1.32E-07
Human toxicity, non-cancer	CTUh	5.22E-07	4.21E-07	2.96E-07	2.89E-07	3.41E-07
Ionising radiation	kBq U-235 eq	0.666	0.666	1.656	-0.075	0.209
Land use	Pt	112.67	112.67	105.37	96.59	103.40
Ozone depletion	kg CFC11 eq	1.07E-07	1.07E-07	1.12E-07	1.14E-07	1.23E-07
Photochemical ozone formation	kg NMVOC eq	1.28E-01	1.07E-01	7.59E-02	7.25E-02	7.63E-02
Resource use, fossils	MJ	121.29	121.29	136.34	92.78	108.79
Resource use, minerals and metals	kg Sb eq	7.22E-05	7.22E-05	8.30E-05	8.38E-05	1.48E-04
Water use	m^3 depriv.	1.391	1.391	2.142	1.085	1.439

land use, ozone depletion, resource use, fossils, minerals and metals, and water use, there were no differences between covering or not covering the pit, also due to the main source of these impacts take place during the fertilization stage, specifically in the use of the fertilization truck. In none of the categories analysed, an increase was obtained as consequence of the application of the proposed technologies; nevertheless, it is worth mentioning that N_2O emissions were 150 % higher covering the pit because this results in more oxidised forms of nitrogen and a higher potential for nitrification and denitrification (Hatfield et al., 2006). However, this fact presents low impact in the studied categories because N_2O emissions is two orders of magnitude lower than those of ammonia or methane emissions. These results are in accordance with previous works of Hou et al. (2015).

Biogas production considerable reduced the environmental impact in several categories: an average decrease of 77 % in climate change was found comparing scenario 1 with scenarios 3, 4 and 5, since producing and consuming biogas intensely dismish methane emissions. Lowest climate change impact was detected in Scenario 4, with a slight reductions of 2.49 % and 1.19 %, compared to 3 and 5 respectively. In case of acidification the conventional techniques (Scenarios 1 and 2) and the biogas production techniques (Scenarios 3, 4, and 5) presented a similar levels, with a small influence of the digestion step. Although digestate storage produces more ammonia emissions than manure because the mineralization of organic nitrogen and volatile fatty acids take place during anaerobic digestion along with an increases in manure pH, very similar results were obtained in the acidification category due to the main contribution of the fertilization stage (Holly et al., 2017).

Biogas production (Scenario 3) resulted in lower impacts for marine eutrophication, with a reduction of 23.57 %, since digestate produces less leaching than manure in the stage of land application. Toxicity was also dismissed, especially in cancer category with a total reduction of 43.24 %, while a decrease of 9.40 % was obtained in case of non-cancer. A strong reduction in photochemical ozone formation accounted with a value 40.45 %. These reductions are due to the lower level of truck utilization for fertilization, as consequence of lower volume that must be transported in case of digestate. Similary, land use, is also lower with a 6.48 % less impact. Other impacts categories were not improved, such as ecotoxicity, particulate matter and eutrophication freshwater and terrestrial. Finally, categories depending on electricity consumption presented an increase level compared with Scenario 1, especially in ionising radiation with 148.68 % increase in Scenario 3. In the same manner, ozone depletion increase was accounted in 5.07 % and resource use, fossils and minerals, and metals with 12.41 % and 14.9 %, respectively. Similary a strong impact was detected in case of water use with a value of 53.98 %.

Scenarios 4 and 5 are very similar to Scenario 3 since all of them involve biogas production, but the energy sources are different; therefore, the differences in these scenarios are due to electricity and heat production. Scenario 3 used the Spanish energy mix obtained from Ecoinvent version 3.10, Scenario 4 used solar panels in slanted-roof to produce electricity, and Scenario 5 used hybrid solar panels slanted-roof to produce heat and electricity. A significant reductions of the ionising radiation, of 104.55 % and 87.39 % were obtained in Scenarios 4 and 5, respectively compared to Scenario 3 as consequence of the electricity production. In the same manner, land use impact achieved a 8.33 % reduction with the use of solar panels (both scenarios 4 and 5). Fossil resource use obtained a decrease in 31.95 % in Scenario 4 and 20.21 % in Scenario 5. Finally water use was notably reduced in Scenario 4 (49.35 %) and Scenario 5 (32.85 %).

For some impacts, there was a reduction in Scenario 4 compared to Scenario 3 but an increase in Scenario 5 compared to Scenario 3: freshwater eutrophication with a reduction of 3.13 % in Scenario 4 and an increase of 31.12 % in Scenario 5, human toxicity cancer and non-cancer Scenario 4 obtained similar results but an increase of 9.97 % and 14.96 % were detected in Scenario 5, respectively. This is attributable to the increased materials complexity of the solar hybrid panels and their installation compared to photovoltaic (PV) panels.

There were only two impacts higher for Scenarios 4 and 5 (with solar installation) compared to Scenario 3 (only energy from the grid), in the categories of ozone depletion, where Scenario 4 has a little increase and Scenario 5 has 9.64 % of increase; and mineral and metal resource use Scenario 4 has similar results and 78.18 % increase in Scenario 5. Finally, for the rest of the impact categories, freshwater ecotoxicity particulate matter, marine eutrophication, terrestrial eutrophication and photochemical ozone formation there were no significant differences between Scenarios 3, 4, and 5. The results show that there is no category in which is better in Scenario 5 than in Scenario 4 (except for land use); in other words, solar panels are more environmentally friendly than hybrid panels. However, it is worth mentioning that in Scenario 5, the production of biogas was 8.3 % higher, resulting in enhanced energy availability for consumption.

2.2.1. Methane and ammonia flows

As explained in Introduction, methane and ammonia emissions are the principal ones to be considered in the agricultural sector. Therefore, they will be studied in detail, and Figure D.1 from *Supplementary Information Section D* provides information on the emissions produced at each process stage.

Methane emissions showed a clear decrease in each scenario comparing with the base case. Covering the pit (Scenario 2) produces a reduction of 38.61 % in the entire process while producing biogas (Scenario 3) generates an 83.59 % reduction, as compared with conventional techniques (Scenario 1). In the case of biogas production, using solar energy for electricity (Scenario 4) and for heat (Scenario 5), instead of electricity from the grid and heat from biogas combustion (Scenario 3) produce similar emissions of methane. Methane emissions were significantly higher in the storage stage, being on the order of magnitude of kilograms. For biodigestion and for transport, the methane emissions were in the order of grams. Finally, in electricity production the methane emissions are in the order of magnitude of milligrams.

As mentioned, the main stage in which methane emissions are produced is during the storage of the manure and digestate. According to the IPCC Guidelines, methane emissions depend on the storage time (Gavrilova et al., 2019). In Scenario 1, manure storage produced 4.972 kg of methane which represented 93.7 % of the total emissions. Covering the pit (Scenario 2) reduced methane emissions to 2.928 kg, a significant reduction of 41.20 %. For these scenarios, methane emissions during the field application of 0.297 kg were observed in both scenarios. For Scenario 3, where biogas production is considered, the emissions from digestate storage are 0.278 kg which represent 31.6 % of the total emissions. The reduction in emissions from manure and digestate storage was 94.5 % in Scenario 2. These results are consistent with those reported by Zhang et al. (2021) who reported a 94.20 % reduction in methane emissions between manure and digestate.

In scenarios with biogas production (Scenarios 3, 4, and 5), fugitive emissions occurred during the anaerobic digestion stage: 1 % of the total methane in the biogas in the biodigester and 0.50 % of the total methane in the biogas in the heater (De Vries et al., 2012). In the case of digestate field applications, no methane emissions were observed. These results are also consistent with those reported by Zhang et al. (2021), who obtained fugitive emissions of methane in biodigester and no emissions during field application of digestate.

In contrast, ammonia emissions are very similar in biogas production (Scenarios 3, 4, and 5) compared with conventional techniques (Scenario 1) and covering the pit (Scenario 2). In Scenario 1 there are produced 5.57 kg of ammonia, Scenario 2 produced 5.38 kg, Scenarios 3 and 4 reached a value of 5.55 kg and in Scenario 5 5.60 kg were produced. The stages with most ammonia emissions are storage and field applications. The rest of the activities are orders of magnitude smaller: the biodigestion process, electricity and transport are in the order of milligrams. Scenarios 4 and 5 had similar emissions to Scenario 3 because electricity consumption and biodigestion did not have significant emissions. In conventional techniques (Scenario 1), storage represents 27.97 % of the total ammonia emissions, with 1.558 kg emitted. These results are similar to Hou et al. (2015). Scenario 2 had a reduction of 12 % because the pit is covered (Hansen et al., 2006). In the case of digestate storage, ammonia emissions increased by 23.67 %, with a total of 1.926 kg of ammonia emissions in this stage. These results are consistent with those reported by Zhang et al. (2021) based on the digestate storage produced more ammonia than manure. Field application represents the main ammonia emissions. For conventional techniques (Scenario 1), it represents 72 %, with 4 kg of ammonia emitted. Scenario 2 showed the same emissions because, in this scenario, manure is also used for field application. In Scenarios 3, 4, and 5, 3.68 kg was emitted by digestate field application, a reduction of 8.21 % compared with manure. Based on a study by Nicholson et al. (2017), the ammonia emissions produced per kilogram of manure or digestate in field applications are similar. Therefore the reduction herein found suggested a higher performance of digestate fertilization compared with manure since less digestate is required per land (Càndido et al., 2022; Doyeni et al., 2021).

2.3. Montecarlo simulation

An MCS was conducted to understand how the impacts varied depending on the different analytical parameters of the swine manure and digestate, as explained in Section 2.5. These results provide information on the estimator of the mean, median, 2.5th percentile, and 97.5th percentile. Additionally, the values for the standard deviation and coefficient of variation (CV) can be found in Supplementary Information Section E. This analysis was performed for all impact categories. In LCA studies, the MCS is commonly used to measure uncertainty in the LCA (Ross and Cheah, 2019; Sheikholeslami et al., 2023). In this study, the lowest variation was observed in acidification, climate change, ecotoxicity, marine and terrestrial eutrophication, and particulate matter, where the CV was approximately 35 % in Scenarios 1 and 2 and approximately 25 % in Scenarios 3, 4, and 5. On the other hand, the highest deviations, with CV values of over 1000 %, were human toxicity non-cancer, and water use.

The complete MCS results are detailed in *Supplementary Information Section E* in Tables E.1 to E.16. In this section, we summarise the results and show the MCS for climate change and acidification in Fig. 3. Climate change and acidification were chosen as focal points since methane primarily contributes to climate change, while ammonia primarily causes acidification.

For acidification and climate change, the uncertainty is higher in Scenarios 1 and 2 than in Scenarios 3, 4, and 5 because the emissions produced in Scenarios 1 and 2 depend only on the manure composition. In Scenarios 3, 4, and 5, there are other parameters such as fugitive emissions that do not depend on manure or digestate parameters.

In the case of the 2.5th percentile of climate change (Fig. 3 a), there is a reduction in all scenarios compared to Scenario 1 because in Scenario 1 there is higher uncertainty. However, for acidification, there is a reduction in the 2.5th percentile in Scenario 2 but there is an increase in Scenarios 3, 4, and 5 because the uncertainty is lower than Scenario 1 as explained in the previous paragraph. In the case of the 97.5th percentile for climate change, there was a significant reduction in Scenarios 2, 3, 4, and 5 compared to Scenario 1 due to the higher uncertainty and higher

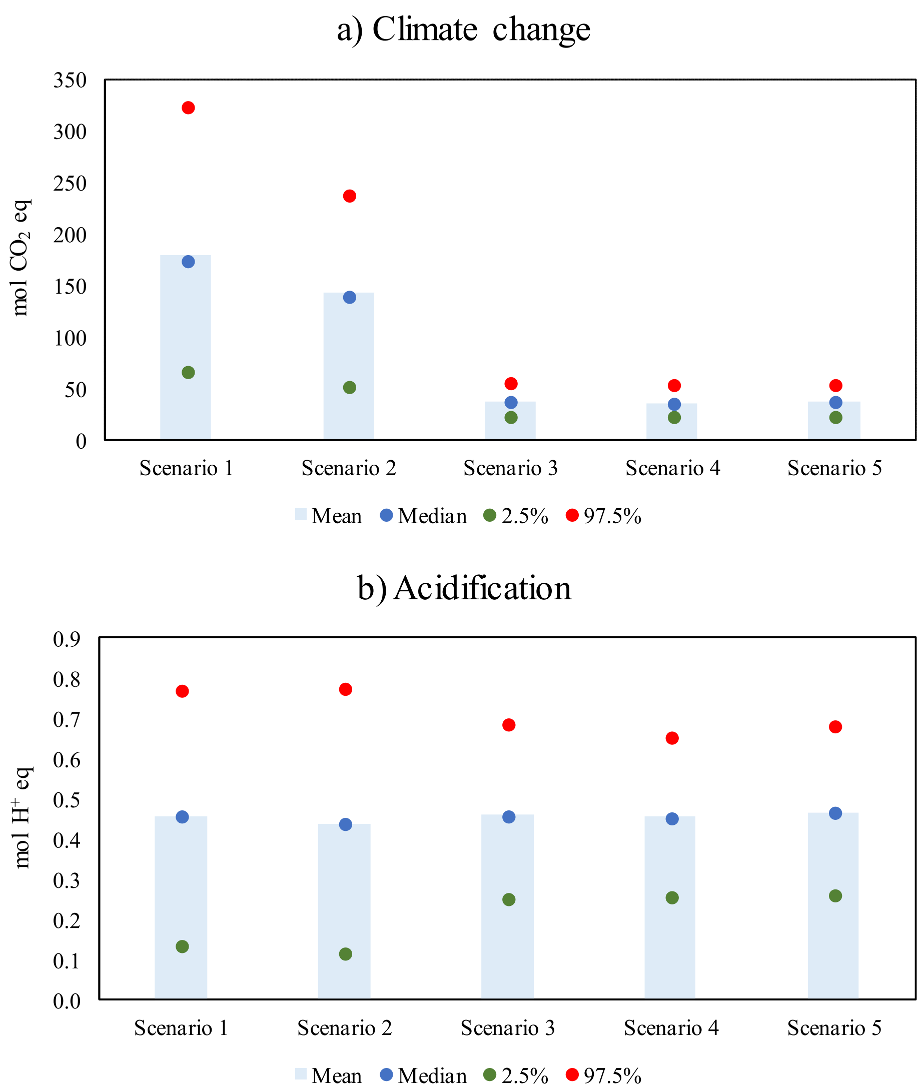

Fig. 3. Montecarlo Simulation results for a) climate change and b) acidification in the five proposed scenarios.

emissions produced in Scenario 1. With regard to acidification (Fig. 3 b) the variation between scenarios is minimal because ammonia emissions are directly dependent on nitrogen content in manure or digestate, and according to the laboratory analytical results explained in Section 2.3, the uncertainty of nitrogen content in manure is 60 % higher than the uncertainty of nitrogen content in digestate. Furthermore, previous studies measuring ammonia emissions of manure and digestate have shown inconsistent results (Holly et al., 2017). The variability in these results underscores the importance of conducting additional research to explore the effect of ammonia emissions.

3. Conclusions

The comparisons of five types of pig farming systems concerning the swine manure management are addressed. The base case (Scenario 1) is based on conventional techniques of managing swine manure by converting it into organic fertilizer and directly applying to the soil. Scenario 2 involves adding a cover material to the slurry storage to prevent direct contact between the liquid and air. In Scenario 3, the swine manure effluent is transferred to an anaerobic digester, generating both biogas and digestate. Scenarios 4 and 5 build upon Scenario 3 by incorporating solar installations - photovoltaic (PV) in Scenario 4 and a hybrid system (PV and thermal) in Scenario 5. The significant conclusions of this work are summarized:

(i) LCA and MCS reveal that methane emissions and the climate change impact category is reduced by covering the storage tank of but this reduction is considerably higher when biogas is produced, achieving until 80 %.
(ii) LCA results demonstrate a consistent pattern in ammonia emissions across the five scenarios. The principal sources of these emissions are the storage of slurry and digestate and the fertilisation stage. Although the storage of digestate results in higher ammonia emissions compared to the storage of swine manure, this increase is offset during the fertilization.
(iii) For the acidification and climate change impact categories, the uncertainty is greater in cases where biogas is not produced. The introduction of the digester mitigates the effect of composition variability.
(iv) The biogas production scenario combining with PV solar panels exhibit clear advantages in impact categories such as climate change, human toxicity, land use, water use or fossils resource use, among others, when compared to the other scenarios.
(v) Positive energy balances are achieved in scenarios considering biogas production with a value of 227 kWh/day without solar energy production and maximum of 246 kWh/day when hybrid solar panels are used.
(vi) Although they provide the highest energy production, the use of hybrid solar panels increase impacts related to human toxicity

and freshwaster eutrophication due to the higher material demand of these sytems, when compared to simple photovoltaic panels.

CRediT authorship contribution statement

Alfonso García Alvaro: Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **María-Pilar Martínez-Hernando:** Software, Methodology, Investigation, Conceptualization. **María-Jesús García-Martínez:** Writing – review & editing, Supervision, Investigation. **César Ruiz Palomar:** Validation, Methodology. **María del Carmen Suárez Rodríguez:** Validation, Methodology. **Daphne Hermosilla:** Supervision, Funding acquisition. **Marcelo F. Ortega:** Project administration, Funding acquisition. **Ignacio de Godos Crespo:** Supervision, Funding acquisition, 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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.145368.

Data availability

No data was used for the research described in the article.

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