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Review

Environmental Assessment of Pig Manure Treatment Systems through Life Cycle Assessment: A Mini-Review

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Abstract: The primary aim of this research was to evaluate and compare the environmental impacts, throughout the life cycle, of the main treatment systems employed by the industry, as well as to identify the processes that contribute most to these environmental impacts. To achieve this, a bibliographical search was conducted using the Web of Science Core Collection database platform, utilizing the keywords "life cycle assessment", "pig", "treatment", and "manure" or "slurry". The search was restricted to publications from the last five years (2019–2023), resulting in a total of 66 publications that were then analyzed according to the functional unit (FU) adopted. For the 10 publications whose FUs were expressed in tons or cubic meters of treated manure, a descriptive and quantitative analysis was carried out. It was found that anaerobic digestion has been the most widely used treatment technology for pig manure over the past five years, according to the LCA methodology. These systems, configured as biogas and biofertilizer production facilities, have proven to be environmentally friendly and could play a crucial role in the energy transition and decarbonization of the energy matrix.

Keywords: life cycle assessment; LCA; pig manure; waste treatment

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1. Introduction

According to the Planning, Policy, and General Administration Office (GPP), pig farming is economically important in the European Union (EU). Over the years, pig production has steadily increased, with a record production value of 23,407.79 tons achieved by 2021. As a result, exports also experienced growth, amounting to 67 million euros in 2019. In 2021, this figure increased by 22.8% compared with 2019 and by 13.2% compared with 2020 [1]. Similarly, in Portugal, pig farming contributes significantly to the economic and social development of the areas where it is conducted, as well as to the balance of the country's trade balance and food supply.

The expansion of the livestock industry has led to an increase in waste, particularly that of pig manure. Improper management of this waste can have significant consequences on the environment, human and animal health, and climate change. Livestock is a major contributor to greenhouse gas emissions, accounting for approximately 66% of all agricultural emissions [2]. Additionally, handling pig manure can result in terrestrial acidification and eutrophication in freshwater systems, and releasing gases during storage and transport can exacerbate these environmental issues [3].

Economic and social growth must be aligned to minimize environmental consequences. It is crucial to alter our approach to managing pig production waste, specifically manure.

This waste can be incorporated into reusable and recyclable options through sustainable management, thus moving closer to a circular economy [4]. To achieve this, it is necessary to identify the most environmentally efficient pig manure treatment technique currently available.

Life cycle assessment (LCA) is a technique, as defined by ISO 14040/44 [5,6] standards, that measures and compares the potential environmental impacts of a product throughout its entire life cycle, from the extraction of raw materials for its manufacture to its end-of-life treatment. LCA presents its findings in a structured manner from a holistic perspective of the product or process, ensuring a comprehensive assessment and quantification of environmental impacts [7].

The primary objective of this review was to evaluate and compare the major environmental impacts from a life cycle perspective of pig manure treatment technologies, which have been published in reputable scientific journals within the last five years. Another aim of this study was to determine which processes contribute the most to these environmental impacts, thus providing a comprehensive view of sustainable waste management in pig farming.

2. Methodology

2.1. Bibliographic Research

Bibliographic research was conducted using the Web of Science Core Collection database platform, as it provides an effective means of identifying influential researchers, institutions, journals, and articles in various fields of study. The study concentrated on the findings derived from the search for the topics "life cycle assessment", and "pig", and "treatment", and "manure", or "slurry".

The following specific criteria were employed to ensure the scientific validity of the analyzed studies:

- Studies published within the last five years (2019–2023);
- Studies that adhere to the ISO 14040/44:2006 method for LCA;
- Studies that present original research findings, excluding results from cited literature, and avoiding duplication;
- Studies with emphasis on environmental analysis and the impact of pig manure management;
- Studies that provide a descriptive LCA analysis.

From the LCA studies obtained through this research, those with functional units (FU) expressed in weight (tons) or volume (cubic meters) of pig manure were selected for further examination.

The FU constraint was established to focus on examining exclusively those research endeavors directed towards the management of a specific quantity of swine waste, such as LCA investigations typically conducted with an emphasis on input materials as opposed to treatment outcomes. Given the frequent updates of LCA software and databases such as Ecoinvent, prolonging the search beyond a span of 5 years could potentially exacerbate the complexity of interpreting the results.

2.2. Descriptive Analysis

The analysis began with a review of LCA studies that met the specified criteria, including publication title, authors, country, year, journal of publication, and the primary objective. The studies were then assessed based on the type of treatment, description, and ultimate use of the products or by-products produced. Additionally, the studies were evaluated in terms of the functional unit (FU), system limits, impact categories, life cycle impact assessment (LCIA) method, database, and software used.

2.3. Quantitative Analysis

A quantitative analysis was then conducted for the LCA studies, considering only the results obtained for the impact categories deemed most relevant for pig manure treatment, as determined by the descriptive analysis.

3. Results

3.1. Descriptive Analysis of the Life Cycle Assessment of the Pig Manure Treatment Systems

3.1.1. Basic Study Characteristics

The descriptive analysis of the LCA of pig manure treatment systems revealed 66 studies in the Web of Science database, based on the topics "life cycle assessment", "pig", "treatment", and "manure", or "slurry" for the last five years. Of these, only ten studies reported the functional unit in terms of weight (tons) or volume (cubic meters) of treated pig manure (Table 1).

Table 1. General description of the publications selected for the study.

St. N°.	Publication Title	Authors	Year	Country	LCA Approach/Goal	Reference
1	A life cycle assessment of an enterprise's low-carbon emissions model: The Xinjiang Shihezi pig farm fecal treatment biogas project as a case study	Wang et al.	2022	China	Attributional and substitution approaches to evaluate the environmental impacts of swine waste management on electricity and biomethane production.	[8]
2	Life cycle assessment on the environmental impacts of different pig manure management techniques	Dong et al.	2022	China	Attributional and substitution approach to evaluate the environmental impacts of swine waste management for electricity or biomethane production.	[9]
3	Life cycle assessment of waste management from the Brazilian pig chain residues in two perspectives: Electricity and biomethane production.	Hollas et al.	2022	Brazil	Attributional and substitution approaches to evaluate and compare the potential environmental impacts of swine waste management on electricity and biomethane production.	[10]
4	Life cycle assessment of anaerobic digestion of pig manure coupled with different digestate treatment technologies.	Duan et al.	2020	China	Attributional and substitution approach to evaluate the environmental impacts of swine waste management for electricity or biomethane production.	[11]
5	Environmental assessment of energy production from anaerobic digestion of pig manure at medium-scale using life cycle assessment.	Ramírez-Islas et al.	2020	Mexico	Attributional and substitution approach to evaluate the environmental impacts of swine waste management for electricity or biomethane production.	[12]
6	Holistic life cycle assessment of a biogas-based electricity generation plant in a pig farm considering co-digestion and an additive.	Freitas et al.	2022	Brazil	Consequential LCA to produce biogas for electricity generation from co-digestion with different substrates and additives.	[13]

Table 1. *Cont.*

St. N°.	Publication Title	Authors	Year	Country	LCA Approach/Goal	Reference
7	Effects of swine manure storage time on solid–liquid separation and biogas production: A life-cycle assessment approach	Hollas et al.	2021	Brazil	Attributional and substitution approaches were used to evaluate the environmental impacts associated with swine manure storage time and energy use by anaerobic digestion.	[14]
8	Swine manure treatment technologies as drivers for circular economy in agribusiness: A techno-economic and life cycle assessment approach.	Hollas et al.	2023	Brazil	Attributional and substitution approach to evaluate the environmental impacts of swine waste management for electricity or biomethane production.	[15]
9	Environmental impact and optimization suggestions of pig manure and wastewater treatment systems from a life cycle perspective.	Liu et al.	2023	China	Attributional LCA is used to evaluate the environmental impacts of pig manure treatment and disposal routes and provide insights for optimizing future technical improvements.	[16]
10	Consequential Life Cycle Assessment of Swine Manure Management within a Thermal Gasification Scenario.	Sharara et al.	2019	USA	Consequential LCA to evaluate the environmental impacts of swine waste management for electricity or biomethane production.	[17]

Most studies were conducted in China and Brazil, with four studies each, while Mexico and the USA had one study each. China's prominence in these studies can be attributed to its position as the world's largest pig producer, producing approximately 450 million pigs in 2021, nearly half the world's pig production [2]. Despite being the world's second-largest producer and largest exporter of pork and pork products, the European Union is experiencing a decline in pork production and exports, resulting in a 20% reduction in exports in the first half of 2023. This indicates that pork prices are less competitive than in the world market [18].

Regarding the year of publication, most studies were published in 2022, with a total of four studies, followed by 2020 and 2023, with two studies each, while 2019 and 2021 had one study each.

The objectives of these studies mainly focused on the evaluation and environmental comparison of various treatments or routes of pig manure treatment. There are also a significant number of studies with objectives related to the production and use of biogas from pig manure.

A brief summary of the type of treatment, scenario/description, and final use of products/co-products generated in the system of each study is presented in Table 2. Anaerobic digestion is the primary treatment found in the selected studies and is present in all but one publication, which used gasification as its treatment. In most of these studies, biogas was utilized to generate electrical or thermal energy, thereby avoiding the production of fossil fuels. Studies 1 and 2 used the term anaerobic fermentation, rather than anaerobic digestion. Anaerobic fermentation is a broader term encompassing various anaerobic processes, while anaerobic digestion specifically refers to the controlled breakdown of organic waste to produce biogas.

Table 2. Type of treatment, scenario/description, and end use of products/coproducts of each work.

St. N°.	Treatment	Scenario/Description	Use of Products/By-Products
1	Anaerobic fermentation	Sce I—Long chain fermentation system (LC) (underground anaerobic); Sce II—automatic integration fermentation system (AI).	1—Return of dry manure and biogas residue to the field; 2—use of gas/biogas for heating.
2	Aerobic composting and anaerobic fermentation	Sce I—Traditional composting system; Sce II—biogas production system.	Biogas waste and biogas slurry were used comprehensively.
3	Anaerobic digestion (AD)	Sce I—Storage in stabilization open lagoon; Sce II and Sce V—AD based on covered lagoon biodigester (CLB); Sce III and Sce IV—solid–liquid separation of effluent; Sce VI—A power generation unit.	Generation of electricity and vehicular fuel from biogas.
4	Anaerobic digestion (AD)	Sce I—Direct use of digestates in agriculture; Sce II—composting of the solid fraction and pretreatment of the liquid fraction; Sce III—composting the solid fraction and diluting the liquid fraction with water; Sce IV—composting of the solid fraction and production of powdered biofertilizers.	2—Power generation, replacement of natural cooking gas; 3—conditioning of the soil by the solid fraction; 4—production of liquid medium for the production of microalgae.
5	Anaerobic digestion (AD)	Sce I—With partial energy production; Sce II—with total energy production; Sce III—with the burning of biogas; Sce IV—traditional management.	Power generation from biogas.
6	Anaerobic digestion (AD)	Sce I—Traditional anaerobic digestion; Sce II—co-digestion with elephant grass silage; Sce III—co-digestion with corn silage; Sce IV—biochar as an additive.	Power generation from biogas.
7	Anaerobic digestion (AD)	Sce I—Storage and stabilization open lagoon; Sce II—Storage and AD; Sce III—Solid–liquid separation and AD.	1—Generation of energy from biogas; 2—application of the digestate as a soil fertilizer.
8	Anaerobic digestion (AD)	Sce I—Traditional management; Sce II—digestion in continuous stirred-tank reactor (CSTR) and CLB; Sce III—digestion in CSTR; Sce IV—digestion in CSTR and anaerobic sludge blanket; Sce V—digestion in CSTR and system sludge composting.	1—Generation of energy from biogas; 2—application of the digestate as a soil fertilizer.
9	Biological wastewater treatment; anaerobic digestion; composting	Sce I—Buffering and direct use on the ground; Sce II—black-film anaerobic digestion and composting; Sce III—buffering and composting.	Use of manure and sludge as soil fertilizers.
10	Gasification for manure solids	The gasification system produces gas, heat, and biofertilizer.	1—Use of gas as a fuel and as a substitute for natural gas; 2—use of heat in drying; 3—application of biochar in the soil as fertilizer.

Anaerobic digestion has gained widespread recognition as the most environmentally friendly waste treatment method because of its ability to mitigate the negative effects of eutrophication and soil acidification caused by CH_4 and NH_4 emissions from poor manure management. In addition, it produces bioenergy and biofertilizers [16]. Developed countries such as the United States, the United Kingdom, Italy, and Germany have increasingly adopted the anaerobic digestion of livestock manure for biogas and energy production [19].

The selected publications also examined complementary treatments such as composting, biological water treatment, and gasification. Additionally, some co-products are used for energy production, as previously mentioned, and others are used as agricultural fertilizers or as a liquid medium for the production of microalgae.

3.1.2. Functional Unit (FU), Methods/Software and Database

Table 3 presents the functional units, system limits, methods/software, and databases used in the selected studies. Eight of the ten studies analyzed used the mass (tons) of pig manure to be treated as the most representative functional unit. Only two studies used volume as the functional unit. In work No. 1, the functional unit is expressed as the amount (tons) of manure produced by 1000 pigs during the three summer months, equivalent to 7.4 tons of pig manure (2.2 tons of solids and 5.2 tons of liquid).

Table 3. Functional unit, methods/software, and database used in the selected works.

St. N°.	FU	LCIA Method/Software	Database
1	7.4 t	-	-
2	1 t	-	-
3	1 t	Midpoint ReCipe 2016/SimaPro 9.1.1.1	Ecoinvent 3.7.1
4	1 t	IMPACT2002+ (Endpoint)	Ecoinvent V3.3
5	1 t	CML-IA 2013/SimaPro 8.1.1.16	Ecoinvent 3
6	1 t	CML2 baseline 2000, V3.01/SimaPro 8.0	-
7	1 m^3	OpenLCA 1.10.2/OpenLCA 1.10.2	Ecoinvent 3.6
8	1 m^3	ReCiPe Midpoint/SimaPro 9.2.0.1	Ecoinvent 3.8
9	1 t	Recipe Midpoint 1.04/SimaPro 9.1	Ecoinvent 3.5
10	1 t	IMPACT World+ (Midpoint)/SimaPro 8.5.2	Ecoinvent V3.4

Although many studies have typically reported the functional unit in terms of mass, it is important to note that there can be significant variations in the type of pig manure, which can make it difficult to compare the results of these studies. In terms of life cycle impact assessment (LCIA) methods, software, and databases, the analyzed studies used diverse methods, as shown in Table 3. All studies except for one presented the impact categories at the intermediate level, and the most used method was the ReCipe Midpoint method, followed by the CML and IMPACT methods. Study 7 used a free method (OpenLCA), whereas Studies 1 and 2 used models for the impact categories available in the literature. SimaPro software was the most used software in the analyzed studies. In terms of generic databases, 70% of the studies used the Ecoinvent database, whereas the remaining 30% did not mention the databases used.

It is important to acknowledge that certain studies have employed similar methodologies, software, or databases; however, the versions used may vary, which may pose challenges when attempting to draw comparisons between the outcomes achieved.

3.1.3. System Boundaries

The system boundaries of pig waste management presented in these studies can be divided into three stages, as presented in Table 4: pig farming, manure treatment, and end use. The following processes were included in pig farming: facility construction (FC), pig management (PM), and manure collection (MC). Manure treatment consisted of the following processes: transport of manure to treatment (TT), construction of the treatment plant (CT), manure treatment (MT), and manure storage (MS). End use included the transport of treated manure for use (TU), use of the product or by-product in the field (UF), and use of the product or by-product (biogas) (UB).

As shown in Table 4, manure collection (MC) served as the starting point for the system boundary in approximately 70% of the studies, while transport of manure for treatment (TT) was the starting point in 20% of the cases. Study 9 initiated its system boundary with manure treatment (MT).

It is important to note that all the analyzed studies concentrated solely on the treatment of pig manure and disregarded the construction of facilities for pig production or manure treatment. Understanding the processes that constitute the system boundaries of each study is crucial for comparing the obtained results.

Table 4. Stages and processes within the system boundaries of the selected works.

St. N°.	Pig Farming			Manure Treatment				End-Use		
	FC	PM	MC	TT	CT	MT	MS	TU	UF	UB
1			x	x		x	x	x	x	x
2			x			x	x			x
3			x	x		x	x	x		x
4				x		x	x	x	x	x
5				x		x	x		x	x
6			x			x	x			x
7			x	x		x	x	x	x	x
8			x	x		x	x	x	x	x
9						x	x		x	x
10			x	x		x	x	x	x	x

x: process included in the system boundary; FC: facility construction; PM: pig management; MC: manure collection; TT: transport of manure for treatment; CT: construction of the treatment plant; MT: manure treatment; MS: manure storage; TU: transport of treated manure for use; UF: use of the product or by-product in the field; UB: use of the product or by-product (biogas).

3.1.4. Impact Categories

Table 5 presents the impact categories used in two or more studies. The most frequently addressed impact categories were global warming potential (GWP), terrestrial acidification (TA), and freshwater eutrophication (EUF), which collectively appeared in seven out of ten publications. Consequently, these impact categories were considered to be the most relevant in LCA studies of pig manure treatment systems, as stated by McAuliffe et al. [20].

Table 5. Impact categories at the midpoint level used in the selected studies.

St. N°.	FEc	TEc	GWP	OD	AC	EU	OF	HT	HCT	SFR	SMR
1			x		x	x				x	
2			x		x	x	x				
3		x	x		x	x	x				
4											
5					x	x				x	x
6			x	x	x	x					x
7	x		x		x	x		x	x		
8		x	x	x	x	x	x				
9	x	x	x	x	x	x	x	x	x	x	x
10			x			x				x	

x: impact category included in the system boundary; FEc: freshwater ecotoxicity; TEc: terrestrial ecotoxicity; GWP: global warming potential; OD: ozone depletion; AC: acidification; EU: eutrophication; OF: ozone formation; HT: non-carcinogenic human toxicity; HCT: human carcinogenic toxicity; SFR: scarcity of fossil resources; SMR: scarcity of mineral resources.

Study 4 provided the impact categories at the endpoint level, categorized into four categories: human health, ecosystem quality, climate change, and resources.

3.2. Quantitative Analysis of the Global Warming Potential, Acidification, and Eutrophication Results for the Pig Manure Treatment

Table 6 presents a quantitative analysis of the results obtained from the analyzed studies on the treatment of pig manure, both solid and liquid, and disposal routes, solely for the impact categories deemed most relevant, namely global warming potential (GWP), acidification, and eutrophication.

Table 6. Results found for global warming potential, acidification, and eutrophication in the selected studies per FU.

St. N°./Scenario		Global Warming Potential (GWP)		Acidification (AC)		Eutrophication (EU)	
		Value	Unit	Value	Unit	Value	Unit
1	Sce I	319.77	kg CO_2 eq. $(7.4\ t)^{-1}$	9.16	kg SO_2 eq. $(7.4\ t)^{-1}$	2.35	kg PO_4 eq $(7.4\ t)^{-1}$
	Sce II	2354.33		20.09		4.22	
2	Sce I	107.38	kg CO_2 eq.t^{-1}	6.17	kg SO_2 eq.t^{-1}	1.10	kg PO_4 eq.t^{-1}
	Sce II	143.14		0.02		1.34×10^{-3}	
3	Sce I	119.25	kg CO_2 eq.t^{-1}	2.04	kg SO_2 eq.t^{-1}	9.60×10^{-4}	kg P eq.t^{-1}
	Sce II (a)	31.54		0.37		3.69×10^{-4}	
	(b)	30.53		0.34		3.72×10^{-3}	
	Sce III (a)	6.90		1.40		4.99×10^{-3}	
	(b)	2.31		1.40		5.14×10^{-3}	
	Sce IV (a)	6.75		1.41		5.01×10^{-3}	
	(b)	4.83		1.41		5.05×10^{-3}	
	Sce V (a)	2.92		1.35		2.08×10^{-3}	
	(b)	−17.04		1.31		2.57×10^{-3}	
	Sce VI (a)	−0.08		1.34		2.21×10^{-3}	
	(b)	−16.73		1.31		2.65×10^{-3}	
4	Sce I	−11	kg CO_2 eq.t^{-1}	-		-	
	Sce II	64.7		-		-	
	Sce III	35.5		-		-	
	Sce IV	45		-		-	
5	Sce I	272	kg CO_2 eq.t^{-1}	10.1	kg SO_2 eq.t^{-1}	2.25	kg PO_4 eq.t^{-1}
	Sce II	359		9.8		2.21	
	Sce III	356		11.06		2.33	
	Sce IV	402		6.36		5.97	
6	Sce I	18 *	kg CO_2 eq.t^{-1}	−0.19 *	kg SO_2 eq.t^{-1}	−0.035 *	kg PO_4 eq.t^{-1}
	Sce II	71 *		−0.1 *		−0.08 *	
	Sce III	118 *		0.4 *		0.06 *	
	Sce IV	22 *		−0.19 *		−0.035 *	
7	Sce I	175 *	kg CO_2 eq.m^{-3}	3.4×10^{-6} *	kg SO_2 eq.m^{-3}	4.55×10^{-2} *	kg PO_4 eq.m^{-3}
	Sce II	90 *		3.2×10^{-6} *		4.55×10^{-2} *	
	Sce III	80 *		3.2×10^{-6} *		4.55×10^{-2} *	
8	Sce I	221	kg CO_2 eq.m^{-3}	1.32	kg SO_2 eq.m^{-3}	-1.99×10^{-3}	kg P eq.m^{-3}
	Sce II	21.6		2.04×10^{-1}		1×10^{-2}	
	Sce III	31.6		1.13		3.85×10^{-3}	
	Sce IV	27.7		5.91×10^{-1}		7.21×10^{-3}	
	Sce V	38.9		2.48		1.37×10^{-3}	
9	Sce I	652	kg CO_2 eq.t^{-1}	1.4	kg SO_2 eq.t^{-1}	0.3	kg P eq.t^{-1}
	Sce II	1300		4.1		0.2	
	Sce III	909		2.1		0.3	
10	Sce I	166	kg CO_2 eq.t^{-1}	-		0.551	kg PO_4 eq.t^{-1}

(a) from the perspective of electricity generation; (b) from the perspective of biomethane generation; * approximate value (obtained from the graph).

The first study presented two options for processing pig manure in the form of sludge, which mainly differ in the pretreatment and final treatment stages of the biogas sludge. Both options included the following stages: pre-treatment, characterized in Scenario I

(Sce I) by dried nightsoil and temporarily stored dry feces, and characterized in Scenario II (Sce II) by water nightsoil, where biogas slurry backwash and dung are stored in deep pits; anaerobic fermentation, in Sce I, characterized by underground pipe insulation and biogas heating in winter, as well as solid–liquid separation, and in Sce II, characterized by solar pipe network insulation and biogas heating in winter; outdoor storage, in Sce I, characterized by compost storage and open composting of dry manure and biogas residue, and in Sce II, characterized by open storage, with biogas slurry and residue (mixed) stored in the open air; return of fertilizer, in Sce I, characterized by (1) the return of dry dung and biogas residue to the field, and (2) biogas slurry filtration and drip irrigation, and in Sce II, characterized by the return of biogas slurry and residue (mixed) to the field; and biogas power generation, in both scenarios, which avoids the production of electricity in the national grid, which is often generated from coal. The return of fertilizers for agricultural purposes avoids the use of chemical fertilizers. The primary distinction between these two scenarios lies in the utilization of solar energy for heating the fermentation process in AI, as opposed to the use of biogas to heat the process in the LC.

From Table 6, it is evident that Scenario I was preferable to Scenario II for all impact categories considered. In Scenario I, the global warming potential was notably lower, at approximately 7.4 times less, and outdoor storage was the process that makes the most significant contribution, accounting for 63% of the impact. By avoiding the production of chemical fertilizers and energy, there was a considerable reduction of 38% in this environmental impact. With regard to acidification, the reduction was approximately 60%, with the process of returning fertilizer being the primary contributor, accounting for 56% of the impact, followed by pretreatment at 28%. The avoided production of chemical fertilizer allowed for a slight reduction in this impact category of approximately 13%. In terms of eutrophication, the process of returning fertilizer was the primary contributor, accounting for 64% of the impact, followed by pre-treatment at 12%. The avoided production of chemical fertilizers resulted in a slight reduction of 10% in this impact category.

In Study 2, two contrasting strategies for pig manure management were assessed. Scenario I entailed the combination of waste with straw and its application in aerobic composting. Conversely, Scenario II involved mixing manure with washing water and subjecting it to anaerobic fermentation. In both scenarios, the solid fraction was transformed into organic compost, and Scenario II produced biogas that was utilized for electricity generation.

Examining the data presented in Table 6, Scenario I proved to be a more favorable option with regard to global warming. In contrast, Scenario II exhibited a significantly more favorable impact on acidification and eutrophication. However, it should be noted that this study did not delve into the individual contributions of these scenarios to various impact categories.

In Study 3, six alternative approaches for managing pig manure were comparatively evaluated. Except for the base scenario (Scenario I), all other scenarios presented two possibilities for the treatment of the gaseous fraction (biogas). Option A involved converting biogas into electricity, thereby replacing the electricity produced by the national grid. Option B, on the other hand, involved purifying the biogas (biomethane) and utilizing it to replace the national diesel oil production (with a 12% biodiesel component) in Scenarios II, III, V, and VI, and replacing gasoline consumption in vehicles in Scenario IV.

Scenario I served as the base scenario, characterized by the stabilization of pig manure in an open pond for 100 days, followed by its transportation to the field for application in the soil, avoiding the production of chemical fertilizers.

Scenario II involved pig manure passing through the biodigester of the covered lagoon, before being stored in the open lagoon (stabilization lagoon) for an additional 100 days, with the intention of applying it to the soil and avoiding the production of chemical fertilizers.

After anaerobic digestion of manure in a covered pond, solid–liquid separation occurred, with the solid fraction composted and the liquid stored in an open tank for 60 days before being applied to the soil, thus avoiding the production of chemical fertilizers. This process was similar in Sce III and Sce IV, with the latter utilizing biomethane to replace the national production of vehicular gasoline.

In Sce V, pig manure from 40 facilities in the region was transported by truck to the treatment plant, where it underwent anaerobic digestion in a covered lagoon. The resulting product was stored in an open lagoon for 60 days before being applied to the soil to avoid the production of chemical fertilizers.

In Sce VI, pig manure from 17 regional facilities was sent to a covered lagoon (biodigester) for anaerobic digestion. The resulting digestate was then sent to a stabilization pond for 60 days before being applied to the soil to avoid the production of chemical fertilizers. The gaseous fraction of the 17 units was then sent through a pipeline to the energy recovery unit.

From a global warming perspective, it was preferable to use biogas to produce diesel fuel or vehicular gasoline rather than electricity. Sce V had the most favorable result in this regard, with a reduction of -17.04 kg CO_2 eq/ton in global warming potential. In this scenario, the process that contributed the most to this impact category was the purification of biogas (17.44 kg CO_2 eq), followed by unintentional emissions in anaerobic digestion (7.02 kg CO_2 eq). The emissions avoided in diesel burning represented the highest negative impact value (-34.65 kg CO_2 eq).

The acidification resulted in the lowest value of 0.34 kg SO_2 eq. for Sce II, which utilized biogas to produce biomethane as fuel. Emissions from the storage pond were the primary contributors to this impact category, accounting for 84.17% of the total. However, the application of digestate from the digester to the soil had a residual impact on reducing acidification.

Eutrophication had the lowest value in Sce I (base scenario), with a total of 9.60×10^{-4} kg P eq. Fertigation negatively impacted eutrophication the most, whereas fertilization (solid) was the most positive contributor.

Study 4 compared four scenarios for PM treatment of pig manure. Sce I (base scenario) involved the direct use of the digestate from anaerobic digestion in agriculture, thereby avoiding the production of chemical fertilizers. An internal combustion engine used part of the biogas to produce electricity for the anaerobic digestion process, whereas the rest was used for biomethane, which was injected into the natural gas network to avoid natural gas extraction.

Sce II included the composting of the solid fraction of the digestate, pre-treatment of the liquid fraction with integrated flocculation, oxidation of biological contact, and the use of the resulting medium for the cultivation of microalgae, which were then sent for anaerobic digestion. Compost and solid fractions of flocculation were used in agriculture to avoid the production of chemical fertilizers. Part of the biogas generated electricity and heat in a cogeneration plant for internal consumption, whereas the other produced biomethane, which was injected into the natural gas network to avoid extracting natural gas.

The following text describes two scenarios for the management of digestate, a byproduct of anaerobic digestion. In Scenario III, the solid part of the digestate was sent for composting, and the liquid part was used as a medium for the cultivation of microalgae, which were then sent for anaerobic digestion. The compost and solid fractions from the centrifuge and settling tank were used in agriculture to reduce the need for chemical fertilizers. The biogas produced was used in a cogeneration plant to generate electricity and heat for internal consumption, with the surplus used to produce biomethane and sold to the grid.

In Scenario IV, a solid fraction of the digestate was composted and powdered biofertilizers were produced through struvite precipitation with ammonia removal. Compost and biofertilizers were used in agriculture to reduce the need for chemical fertilizers. The biogas produced was used in a cogeneration plant to generate electricity and heat for domestic use, with the surplus used as a substitute for electricity from the grid and natural gas.

In this study, inventory data were aggregated into four categories of damage: human health, ecosystem quality, climate change, and resources. The results for climate change are presented in Table 6 and indicate that Scenario I (base scenario) was the most sustainable option, with the process that avoided the production of chemical fertilizers having the most positive impact, and the storage of the digestate having the most negative impact.

In terms of the impact on human health and ecosystem quality, Scenario III was preferred because the digestate storage process was the most negative contributor. Processes that avoided the production of chemical fertilizers and natural gas contributed the most positively. In terms of the impact on resources, Scenario IV was preferred, as the anaerobic digestion process was the most negative contributor, and processes that avoided the production of chemical fertilizers and natural gas contributed the most positively.

Study 5 compared four scenarios for pig manure management. Scenario I (partial energy production) was the current scenario, in which 59% of the liquid fraction was treated through anaerobic digestion in a covered pond, and 41% of the solid fraction was treated through composting. It was considered that 10% of the biogas produced was transformed into electricity for internal consumption, thereby avoiding the consumption of electricity from the national electricity grid and burning the rest. The compost and solid fractions of the digestate were utilized in agriculture to avoid the production of chemical fertilizers.

Scenario II (total energy production) was a simulated scenario in which all manure energy was produced through anaerobic digestion, both liquid and solid fractions. The electricity produced was used for domestic consumption, and any excess was sent to the national grid to avoid the production of electricity. The solid fraction of anaerobic digestion was used in agriculture to avoid the production of chemical fertilizers.

Scenario III (biogas burning) was a simulated scenario identical to Scenario I, except that all the biogas produced was burned without energy use, and the electricity used in the system comes from the national electricity grid.

Sce IV (conventional management) represented a scenario that simulates manure management without any treatment, adhering to conventional practices. In this scenario, all dried manure was utilized directly as an organic fertilizer in agricultural settings, thereby avoiding the production of chemical fertilizers. Half of the liquid manure was discharged directly into waterways, while the remaining portion was stored in uncovered ponds for half a year before being utilized as an organic fertilizer in agriculture, again avoiding the production of chemical fertilizers.

In terms of global warming, Sce I was the preferred scenario, with a total value of 272 kg CO_2 eq. This represented a reduction of 130 kg CO_2 eq compared to Sce IV, which was less favorable. In Sce I, digestate discharge represented 46% of the total GWP, while unintentional releases represented 23%. The process that contributed the most to reducing global warming potential was avoiding electricity production in the national grid (82%).

For acidification, Sce IV achieved the best result (6.36 kg SO_2 eq), primarily due to the greater replacement of chemical fertilizers. The waste storage process (liquid and solid) was the primary contributor (79%) to this impact category, because of the NH_3 emissions while the avoided production of chemical fertilizers contributed the most (21%) to the reduction in the total value.

The scenario with the lowest eutrophication impact was Sce II (2.21 kg PO_4 eq), due to the lower compost production and subsequent reduction in NH_3 emissions. In this scenario, the waste storage process (liquid and solid) was the primary contributor (50%) to the total value, mainly due to NH_3 emission. Conversely, avoiding the production of chemical fertilizers contributed in a residual manner to reducing the environmental impact.

Study 6 examined four scenarios for pig manure treatment. All scenarios generated biogas for the co-generation of heat and electricity and the production of biofertilizers for use in agriculture, thereby eliminating the production of chemical fertilizers. In Scenario I, the amount of electricity consumed internally was greater than the amount produced in the system. In Scenarios II and III, the amount of electricity produced exceeded the amount consumed. In Scenario IV, the amount of electricity produced was equal to the amount consumed. Any unused energy in the system avoided the production of electricity in the national electrical grid and propane in the gas grid.

Scenario I (base scenario) involved the anaerobic digestion of both the solid and liquid fractions of pig manure. In Scenario II, the pig manure substrate was co-digested with elephant grass silage. Scenario III involved the co-digestion of pig manure substrate with corn silage. Scenario IV utilized biochar as an additive for the treatment of a pig manure substrate.

Regarding global warming, Scenario I (base) was the most favorable, emitting approximately 18 kg CO_2 eq/ton. Scenario III was the least favorable, emitting 117.81 kg CO_2 eq/ton. Fugitive methane emissions from indoor lagoon digesters were the primary contributors to this impact category.

For acidification, Scenarios I and IV, with emissions of approximately −0.19 kg SO_2 eq/ton, were preferable. Scenario III, with emissions of approximately 0.4 kg SO_2 eq/ton, was the least favorable. The use of biofertilizers in agriculture was the primary contributor to this impact category, whereas the avoided production of electricity in the grid was the primary contributor to its reduction.

To mitigate eutrophication, it was preferable to opt for Sce II, which emitted approximately −0.08 kg PO_4 eq/ton. Conversely, Sce III, with an emission rate of 0.2082 kg PO_4 eq/ton, was the least favorable option. The processes that had the most significant impact on reducing this effect were avoiding electricity production in the grid and the substitution of chemical fertilizers.

As previously mentioned, Sce III ranked lowest among the three categories of impact, despite the positive effects of avoided grid electricity production and the substitution of chemical fertilizers with organic fertilizers, due to the strong negative environmental impact of using fossil fuels in planting, harvesting, and silage production.

Study 7, which involved laboratory experiments on treating pig manure (both solid and liquid), consisted of three scenarios.

Sce I was the base scenario, in which the waste was stored in facilities for 8 days before being stabilized in an open storage tank for 120 days, transported to the field, and applied as fertilizer.

Sce II included the storage of manure in facilities for 8 days, followed by the degradation of organic matter via anaerobic digestion for 30 days, and the storage of the digestate in an open tank for 60 days. This digestate was subsequently applied as fertilizer to the soil, and the gaseous fraction (biogas) could be utilized in a cogeneration plant for heat and electricity production.

Sce III reduced waste storage in facilities by three days, after which the solid fraction was separated from the liquid in a separator. The biological process then occurred in separate reactors due to the concentration of solids in the waste. As in the previous scenario, digestate was utilized as fertilizer for the soil, and the gaseous fraction (biogas) could be harnessed for heat and electricity production in a cogeneration plant.

Treatment systems could be classified into various phases, including storage, transport and fertilization, infrastructure and operation, electricity avoided, heat avoided, and fertilizer (NPK) avoided. Sce III generally presented the most favorable environmental outcomes in the three impact categories examined, while the base scenario (Sce I) tended to produce the least favorable results.

With regard to global warming, Sce III emitted approximately 80 kg CO_2 eq/ton, whereas Sce I emitted approximately 175 kg CO_2 eq/ton. These emissions were primarily attributed to the storage phase (approximately 200 kg CO_2 eq/ton), and the avoided fertilizer phase contributed to their reduction by approximately 25 kg CO_2 eq/ton.

For acidification, the three scenarios produced extremely similar results (about 3.4×10^{-6} kg SO_2 eq/ton). The transport and fertilization phases contributed the most to this environmental impact (approximately 3.5×10^{-6} kg SO_2 eq/ton), followed by storage (approximately 0.5×10^{-6} kg SO_2 eq/ton). The avoided fertilizer phase contributed to its reduction by about 0.6×10^{-6} kg SO_2 eq/ton.

Regarding eutrophication, the scenarios yielded comparable results, with emissions of approximately 4.6×10^{-2} kg PO_4/ton, with the transport and fertilization phases being the primary contributors to this environmental impact.

Study 8 evaluated five different scenarios of pig manure treatment. All scenarios, apart from the base scenario, produced biogas that was utilized in a combined heat and power plant and digestate that was used as a biofertilizer in the soil, thereby avoiding the production of chemical fertilizers. The electricity generated would replace the electricity that would otherwise be obtained from the grid, and the heat produced would replace the heat that would otherwise be derived from fossil fuels.

Scenario I was the baseline scenario, which involved the conventional management of pig manure. This involved storing the manure in a deep hole for approximately 80 days before applying it to the soil while avoiding the production of chemical fertilizers.

Scenario II consisted of three modules: biogas generation and organic load reduction (bio module), nitrogen removal (N module), and phosphorus removal and recovery (P module).

Scenario III focused on removing nitrogen and ensuring an adequate supply of carbon for denitrification.

Scenario IV replaced the covered lagoon bio-digester with four up flow anaerobic sludge blankets.

Scenario V aimed to produce fertilizer at the end of the process by composting the sludge of the system, which could be exported from the production area.

From a global warming and acidification perspective, Scenario II was preferred, with total emissions of 21.6 kg CO_2 eq/m^3 and 0.204 kg SO_2 eq/m^3, respectively. The fertilization process was the most significant contributor to global warming, accounting for 39% of the total value, followed by emissions in the storage pond (15%). Acidification was almost entirely due to emissions during fertilization.

For the assessment of eutrophication, the base scenario (Sce I) yielded the most favorable outcome, with a reduction of 1.99×10^{-3} kg Peq/m^3. The process that had the most detrimental effect on this category was fertilization, with approximately 2.45 kg P eq/m^3, while the most positive contribution came from avoided phosphorus production (about -2.6×10^{-3} kg P eq/m^3), followed by avoided nitrogen production (-1.8×10^{-3} kg P eq/m^3).

Study 9 presented three treatment scenarios and disposal routes, each with a pretreatment step for separating the solid and liquid fractions. Sce I and III shared similar wastewater treatment processes, including buffering, biochemical treatment, coagulation, sedimentation, and disinfection. In contrast, Sce II featured anaerobic digestion by a black film, biochemical treatment, coagulation/sedimentation, and disinfection. The primary distinction between these treatments lay in the utilization of digestate. In Sce I, the sludge and manure from the treatment were directly applied to the ground, while in Sce II, the sludge and manure were composted separately and utilized as fertilizers in the soil. In Sce III, silt and manure were mixed, composted, and used as fertilizers in the soil.

Regarding global warming (GWP) and acidification (TA), Sce I was the preferred option, with CO_2 emissions of 652 kg CO_2 eq/ton and SO_2 emissions of 1.4 kg SO_2 eq, respectively. Composting of the solid fraction of manure was the process that made the most significant contribution to GWP (approximately 65%), while emissions from electricity and chemicals consumed in the system accounted for 15.56% of the total GWP value. In terms of GWP, Sce III represented the worst-case scenario, with CO_2 emissions of 1300 kg CO_2 eq/ton. Acidification was primarily due to emissions from the use of the solid fraction (manure) in soil (approximately 67%) and wastewater treatment (approximately 24%).

For the mitigation of eutrophication, the utilization of manure, both in solid and liquid form, in the soil was the most significant contributor (89%) to this impact category, with a preference for the emission of 0.2 kg Peq. Avoided fertilizer production contributed to reducing the overall impact by approximately 10%.

The objective of Study 10 was to evaluate the effects of managing pig manure using gasification technology, resulting in the production of three byproducts: syngas, heat, and biochar. Syngas that was not utilized within the system was considered as a substitute for natural gas. In soil, biochar was utilized as a substitute for chemical fertilizers. The treatment process included the following stages: swine house, pre-separation tank, pumping/stirring, separation, post-separation storage, drying, gasification boiler, transport, mixing/spreading, and land application.

For global warming, the system had a net emission of 166 kg CO_2 eq/ton. Emissions from the sludge storage processes under slatted floors in the swine house and external storage (pre-separation tank) made the most significant contribution to the total value, representing 42.1% and 35.1%, respectively. Nitrous oxide (N_2O) and methane (CH_4) were the substances that contributed most significantly to this impact category. The post-separation storage process contributed 22.4% of this impact category. Natural gas avoided by the production of syngas in the gasification boiler process and chemical fertilizer avoided by the application of sludge and biochar in the land (land application process) contributed to a reduction in global warming potential (GWP) by (−3.54%) and (−3.57%), respectively.

Eutrophication was primarily caused by the application of slurry biochar to the soil, accounting for almost all (98.5%) of the phosphorus contained in the compost being leached.

4. Discussion

The presence of distinct goals and scope, system boundaries, functional units, impact assessment methods and model assumptions pose challenges to achieving precise comparisons among LCA investigations. The same was emphasized in a preceding review [20]. Nonetheless, by classifying inquiries under the three categories delineated in this manuscript, extensive comparisons emerged as more viable, as demonstrated in Table 7. The optimal scenario was presented for each study's relevant impact categories to facilitate comprehension.

Anaerobic digestion emerged as the predominant treatment method utilized for pig manure management in various studies examined in this manuscript, with the exception of Study 10, where solid manure gasification was employed, devoid of comparative analysis with other treatment modalities.

Utilization of composting has been observed in several studies (Studies 2 and 9). In Study 2, a blend of manure and straw preceded composting, juxtaposed with anaerobic digestion of the manure, and wash water amalgam. Meanwhile, Study 9 entailed co-composting and mono-composting of sludge and manure, in contrast to the direct application of wastewater biological treatment on soil containing manure and sludge.

The composting of pig manure along with straw to generate organic compost has exhibited superiority over mixing manure with wash water for anaerobic digestion for global warming, albeit inferiority in terms of acidification and eutrophication. Both mono-composting and co-composting of manure/sludge alongside land utilization have shown adverse effects on global warming and acidification, compared to the direct application of manure and sludge from wastewater biological treatment onto the soil. This contention was also supported by Lopez-Ridaura et al. [21], who indicated that spreading had a lesser impact than aerobic treatment, with mono-composting emerging as the optimal choice for addressing eutrophication concerns.

Subsequent studies have focused on anaerobic digestion as the primary treatment modality, with comparisons drawn among various scenarios. Study 1 particularly highlighted distinctions between the two scenarios, emphasizing the pretreatment and final treatment stages of biogas sludge. The scenario characterized by dried nightsoil and temporarily stored dry feces, coupled with biogas residue managed through compost storage and open composting, proved preferable in terms of global warming, acidification, and eutrophication.

Studies 3, 5, 7, and 8 delineated a baseline scenario in which manure management proceeded without treatment. While Study 5 involved direct manure application onto soil, Study 3 entailed stabilization in an open pond for 100 days, Study 7 in an open storage tank for 120 days, and Study 8 in a deep hole for approximately 80 days.

Table 7. Treatment, system boundary, functional unit, and GWP, AC, and EU for the best pig manure treatment systems found in the selected studies.

St. Nº	Treatment	Scope	FU	GWP	AC	EU
1	Sce I—Long chain fermentation	Pre-treatment to biogas power generation	7.4 t	319.77 kg CO_2 eq. $(7.4\ t)^{-1}$	9.16 kg SO_2 eq. $(7.4\ t)^{-1}$	2.35 kg PO_4 eq $(7.4\ t)^{-1}$
2	Sce I—Aerobic composting Sce II—Anaerobic fermentation	Collection of pig waste and transfer to the treatment area until solid waste is formed during composting.	1 t	107.38 kg CO_2 eq/ton	0.02 kg SO_2 eq/ton	1.34×10^{-3} kg PO_4 eq/ton
3	Sce 1—(baseline) application the manure to the soil as a source of fertilizer Sce II (b)—Solid–liquid separation and AD based on covered lagoon biodigester—Biomethane generation Sce V (b)—AD based on covered lagoon biodigester—Biomethane generation	Manure storage; stabilization of organic matter followed by field application and/or production of biogas for electricity or biomethane; followed by storage of the digested AD and application as fertilizer.	1 t	−17.04 kg CO_2 eq.t^{-1}	0.34 kg SO_2 eq/ton—(Terrestrial AC)	9.60×10^{-4} kg PO eq/ton—(Freshwater EU)
4	Sce I—AD—Direct use of digestates in agriculture;	Transport of pig manure, storage, treatment and use of digestate in agricultural processes, production and use of biogas to generate heat/energy, and replacement of biogas or biofertilizers with equivalents from fossil resources.	1 t	−11 kg CO_2 eq.t^{-1}	-	-
5	Sce I—AD with partial energy production Sce II—AD with total energy production Sce IV—AD with Traditional management	Treatment and handling of liquid and solid manure generated on the farm until the production of inputs of biogas/electricity, compost, and treated water for irrigation	1 t	272 kg CO_2 eq.t^{-1}	6.36 kg SO_2 eq.t^{-1}	2.21 kg PO_4 eq.t^{-1}
6 *	Sce I—Traditional AD Sce II—AD with Co-digestion with elephant grass silage Sce IV—AD with Biochar as an additive	Collection of manure for the production of biochar for the use of biogas and biofertilizer and the production of biogas for heat/electricity cogeneration.	1 t	18 kg CO_2 eq.t^{-1}	−0.19 kg SO_2 eq.t^{-1}	−0.08 kg PO_4 eq.t^{-1}
7 *	Sce III—Solid–liquid separation and AD	Production and storage of manure, stabilization of organic matter in manure, and application in the field and/or production of biogas for electricity/heat cogeneration, storage of digestate, and application as fertilizer.	1 m^3	80 kg CO_2 eq.m^{-3}	3.2×10^{-6} kg SO_2 eq.m^{-3} (Freshwater AC)	4.55×10^{-2} kg PO_4 eq.m^{-3} (Marine EU)
8	Sce II—AD with continuous stirred-tank reactor and covered lagoon biodigester Sce V—AD with continuous stirred-tank reactor and system sludge composting	AD process, solid–liquid separation, N and P removal, water reuse, sludge storage and/or composting, application as biofertilizer, replacement of synthetic fertilizers, production and use of biogas for electricity/heat cogeneration, and replacement of the energy generated.	1 m^3	21.6 kg CO_2 eq.m^{-3}	2.04×10^{-1} kg SO_2 eq.m^{-3} (Terrestrial AC)	1.37×10^{-3} kg P eq.m^{-3} (Freshwater EU)
9	Sce I—Buffering and direct use on the ground; Sce II—black-film anaerobic digestion and composting;	The pre-treatment process and manure/sludge treatment process until the digestate is used in the field.	1 t	652 kg CO_2 eq.t^{-1}	1.4 kg SO_2 eq.t^{-1} (Terrestrial AC)	0.2 kg P eq.t^{-1} (Freshwater EU)
10	Sce I—Gasification for manure solids	Waste management activities up to the application of the liquid fraction (slurry) and the solid fraction of the digestate to the land.	1 t	166 kg CO_2 eq.t^{-1}	-	0.551 kg PO_4 eq.t^{-1}(Marine EU)

(b) from the perspective of biomethane generation. * study with approximate value.

The traditional approach to pig manure management (without any form of treatment) resulted in the least favorable outcomes in terms of global warming, acidification, and eutrophication in the laboratory experiments conducted in Study 7. Conversely, it showed a preference for eutrophication in Studies 3 and 8, which was attributed to the reduction in phosphorus and nitrogen production. The management method also demonstrated a preference for acidification in Study 5, primarily due to the increased substitution of chemical fertilizers. The separated liquid fraction from pig manure displayed a decrease in greenhouse gas emissions compared with the unseparated fraction, which can be linked to lower levels of carbon and nitrogen concentrations, as evidenced by Dennehy et al. [22].

The SISTRATES® system (Portuguese abbreviation for swine effluent treatment system) used in Study 8 efficiently eliminated nitrogen from pig farm wastewater, thus reducing eutrophication risks, as supported by the findings of Huang et al. [23]. Additionally, the energy and nitrogen removal (N module) and phosphorus removal and recovery (P module) techniques employed, together with the reduction in greenhouse gas emissions, contribute to the sustainability of the pig production chain.

Anaerobic digestion was consistently favored over the traditional management of pig manure, as it minimizes its impact on global warming. Furthermore, utilizing biogas for the production of diesel fuel or vehicular gasoline was preferred to electricity generation, mainly because of the emission reduction in diesel combustion, as indicated in Study 3. However, to minimize acidification, producing biomethane fuel using biogas was preferable.

The studies analyzed in this work also specify which stages of the pig waste management process produce the greatest environmental impacts, as shown below.

The processes of manure storage, composting, and fertilization were the ones that were most cited in studies as the processes that produced the most environmental impacts, each being cited in four studies.

Studies 1, 5, 6, and 10 identified manure storage as one of the main processes that negatively impacted the environment in their research. According to Im et al. [24], significant amounts of methane are emitted by manure storage tanks, which are important for maintaining the greenhouse effect.

The composting process was cited in Studies 2, 5, 8, and 9 as responsible for the greatest environmental impacts. According to Kim et al. [25], the aerobic composting stage of pig manure can release harmful substances into the environment, which can affect air, soil, and water quality, thus significantly contributing to environmental acidification and eutrophication.

Fertilization and agricultural processes were cited in Studies 3, 6, 7, and 8 as the worst in environmental terms. Although fertilizers derived from pig manure are considered environmentally better than synthetic fertilizers, they can still have varied environmental impacts [26] and their excessive use can intensify greenhouse gas emissions [27].

Other processes were also considered important for the production of environmental impacts, such as the anaerobic digestion process (cited in Studies 2 and 4), drying of manure or digestate (cited by Studies 5 and 10), wastewater treatment (cited by Study 1), transport (cited by Study 7), and disposal of manure in water bodies that occur in the conventional management system (cited by Study 5).

5. Conclusions

This study demonstrated the significant challenges encountered when attempting to compare the findings of the different LCA researches examined, as they lack a standardized methodological framework. Subsequent conclusions are outlined below.

Pig manure mishandling poses significant environmental impacts, emphasizing the importance of proper waste management practices. Anaerobic digestion is a commonly favored method for pig manure management, due to its benefits in reducing environmental impacts, which is in line with the article review made by Dennehy et al. [22] (European practices in particular). Different scenarios and treatment modalities have varying effects on global warming, acidification, and eutrophication, with some methods proving preferable in terms of environmental sustainability. Utilizing biogas to produce diesel fuel or vehicular gasoline was preferred over electricity generation to reduce emissions, while producing biomethane fuel using biogas was preferable for minimizing acidification. Optimization of storage time, solid–liquid separation, and anaerobic digestion processes are crucial for environmental sustainability in swine farms.

To realize improved comparisons between LCA studies in the pig manure sector, a methodical approach regarding the harmonization of system boundaries, functional units, considered processes, and allocation assumption is recommended for future research.

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