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Review

A Review on Anaerobic Digestate as a Biofertilizer: Characteristics, Production, and Environmental Impacts from a Life Cycle Assessment Perspective

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Featured Application

This review supports the application of digestate as a sustainable biofertilizer in agriculture, highlighting its potential to replace synthetic fertilizers and improve soil health. By analyzing Life Cycle Assessment studies, the work identifies key processing and post-treatment strategies—such as composting and solid–liquid separation—that enhance digestate's agronomic performance and environmental profile. The findings offer practical guidance for stakeholders aiming to implement digestate-based fertilization within circular economy models, while addressing regulatory and technical barriers to its wider adoption.

Abstract

Digestate valorization is essential for sustainable waste management and circular economy strategies, yet large-scale adoption faces technical, economic, and environmental challenges. Beyond waste-to-energy conversion, digestate is a valuable soil amendment, enhancing soil structure and reducing reliance on synthetic fertilizers. However, its agronomic benefits depend on feedstock characteristics, treatment processes, and application methods. This study reviews digestate composition, treatment technologies, regulatory frameworks, and environmental impact assessment through Life Cycle Assessment. It analyzes the influence of functional unit selection and system boundary definitions on Life Cycle Assessment outcomes and the effects of feedstock selection, pretreatment, and post-processing on its environmental footprint and fertilization efficiency. A review of 28 JCR-indexed articles (2018–present) analyzed LCA studies on digestate, focusing on methodologies, system boundaries, and impact categories. The findings indicate that Life Cycle Assessment methodologies vary widely, complicating direct comparisons. Transportation distances, nutrient stability, and post-processing strategies significantly impact greenhouse gas emissions and nutrient retention efficiency. Techniques like solid–liquid separation and composting enhance digestate stability and agronomic performance. Digestate remains a promising alternative to synthetic fertilizers despite market uncertainty and regulatory inconsistencies. Standardized Life Cycle Assessment methodologies and policy incentives are needed to promote its adoption as a sustainable soil amendment within circular economy frameworks.

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1. Introduction

Organic waste generation has been inherent to human activity since its beginnings. As the world's population grows, so does the amount of organic waste it creates daily. In this context, and to ensure correct management and disposal, the European Commission has designed an organic waste management hierarchy [1] based on prevention, reuse, recycling, and recovery, only allowing disposal as a last resort. Among recovery strategies, anaerobic digestion (AD) has emerged as a widely adopted solution enabling waste reduction and energy generation.

AD is a microbial-driven process in which a diverse community of microorganisms collaborates to break down complex organic substances [2] without oxygen, generating an energy-rich gas composed mainly of methane and carbon dioxide [3]. This renewable energy source, widely known as biogas, can be directly used as fuel or further upgraded into biomethane, which has a higher energy density after removing residual gases from the digester. Due to its organic nature, biogas and its derivatives are considered sustainable fuels with versatile applications. Moreover, it has been demonstrated that replacing conventional energy sources with biogas in electricity generation, natural gas substitution, and transportation fuels leads to a reduction in global warming potential (GWP) [4,5]. Given its role in the energy transition, AD emerges as a key waste-to-energy (WTE) system, facilitating the imperative shift towards sustainable energy generation.

In addition to biogas, AD generates digestate, the residual output composed of solid and liquid organic matter that is not decomposed in the anaerobic fermentation process [6]. Digestate is rich in organic matter (OM) and essential nutrients such as nitrogen, phosphorus, and potassium, as well as other trace elements, which depend significantly on the feedstock type and the specific conditions of the anaerobic digester [7–9]. Depending on the feedstock used in AD, digestate can be classified into four broad categories [10]: municipal sludge digestate, food waste (FW) digestate, municipal solid waste (MSW) digestate, and agricultural digestate (comprising both plant-based and livestock manure feedstocks). Digestate composition varies significantly within these categories. For instance, study [11] classifies FW digestate as having the lowest nitrogen content while being richer in phosphorus compared to digestates from different feedstocks, such as sewage sludge. Furthermore, digestate composition can vary within the same feedstock category, as total nitrogen (N) content and the carbon-to-nitrogen (C:N) ratio may fluctuate even among similar substrates [12].

Digestate flows out of the digester in a solid–liquid state and is typically subjected to a separation process before any further treatment [13]. This separation reduces the total volume for easier transportation and disposal [14], with the liquid fraction (LF) retaining most of the dry matter (DM), phosphorus, and ammonia, while the solid fraction (SF) presents higher concentrations of total organic carbon (TOC), total solids (TS), and volatile solids (VS) [15,16]. Initially, digestate separation served primarily as a waste disposal method to minimize landfill and incineration inputs. However, as research on digestate composition advanced, its perception shifted from a mere waste byproduct to a valuable resource [17]. A better understanding of its composition has revealed that digestate, rich in nutrients and OM, holds agronomic value as a fertilizer and supports various applications depending on its specific properties [18].

One of the most promising applications of digestate is its use as a fertilizer. Its high nitrogen availability for plants and lower environmental impact than synthetic fertilizers [19] make it an efficient and cost-effective option for organic waste management [10]. Additionally, digestate has demonstrated potential for soil fertilization and remediation, especially in degraded and polluted lands, where its high OM content and biostability contribute to enhancing soil structure, combating erosion, promoting microbial activity, and restoring nutrient cycles [20,21]. For both fertilization and soil remediation, digestate can be applied directly to soil or undergo further processing, such as composting or pelletization of its SF [6].

Beyond agriculture, digestate is also emerging as a key player in nutrient recovery and circular economy models. Recent advancements highlight the potential of digestate in recovering ammonia and phosphorus, yielding high-value byproducts [22]. Digestate's rich organic carbon content makes it a promising feedstock for biochar production [23], which has been shown to enhance carbon sequestration and adsorption properties [24]. Another innovative method is insect transformation, where larvae digestate to synthesize proteins and fats, enriching the remaining material [25]. Moreover, research has explored the use of digestate for animal feed, either as a direct supplement for pig feed [26] or as a nutrient medium for microalgae cultivation, which can then be used as plant-based protein feed [27,28]. In this context, Table 1 compiles information from various studies on digestate valorization, highlighting its origin, analyzed fraction, and potential applications. The study compiles data on locations, methodologies, feedstock types, and digestate uses (fertilization, nutrient recovery, and biochar). It highlights trends and opportunities in circular economy management.

In light of this analysis, it is evident that digestate plays a crucial role in waste valorization and resource recovery. This review explores digestate's applications as a biofertilizer, soil conditioner, and feedstock for bio-based products, with a focus on its composition, treatment technologies, and regulatory considerations. Life Cycle Assessment (LCA) is examined as a critical tool for evaluating digestate's environmental performance in terms of emissions, energy use, and nutrient recovery, while also addressing the practical challenges and opportunities associated with its utilization. A systematic literature search was conducted in Google Scholar for JCR-indexed studies published since 2018, initially targeting those with "Life Cycle Analysis" and "digestate" in the title, and later expanded to include relevant articles referencing these terms in their abstracts or keywords. A total of 28 studies were selected for in-depth analysis.

Accordingly, the aim of this review is to provide a comprehensive evaluation of digestate valorization strategies and their environmental implications through LCA, identifying key factors that influence sustainability outcomes and supporting the advancement of circular economy models.

Table 1. Summary of studies on digestate valorization, including study location, methodology, digestate fraction analyzed, feedstock type, and potential applications.

Reference	Location	Digestate Production			Digestate Uses					
		AD Process	Digestate Fraction	Feedstock Supply	Fertilizer	Soil Conditioning	Animal Feed	Nutrient/Mineral Recovery	Biochar Preparation	Insect Transformation
[29]	China		LF	WWS				X	X	
[30]	China	M	SF	PM				X		
[19]	Italy	M	LF	PM	X					
[31]	Italy	M	SF, LF	PM, Ps, CM, MS, OW	X					
[32]	China		LF	WWS	X					
[33]	China		SF, LF	FW	X	X				
[34]	China		SF, LF	FW		X			X	
[35]	Italy	M	SF	CM, pM, OW, MS		X				
[36]	Lithuania			CM, PM, pM	X					
[37]	Lithuania		SF, LF	CM, PM, pM	X					
[38]	Italy		SF, LF	AM	X					
[39]	Poland	M	SF, LF	MS, CM, FW	X					
[40]	Italy	M	SF, LF	WWS	X	X				
[41]	Austria	T	LF	OMSW		X				
[42]	France	T	SF, LF	OMSW		X				
[6]	Poland		SF	WWS, cM, CM, PM, MS, FW	X	X			X	
[43]	China			MS		X				
[44]	Ireland		LF	DS		X				
[45]	Italy	T	SF, LF	FW	X	X				
[46]	Colombia	M	SF, LF	FW	X					
[25]	Italy		SF	FW						X

Table 1. *Cont.*

Reference	Location	Digestate Production			Digestate Uses					
		AD Process	Digestate Fraction	Feedstock Supply	Fertilizer	Soil Conditioning	Animal Feed	Nutrient/Mineral Recovery	Biochar Preparation	Insect Transformation
[47]	China	M	SF, LF	FW						X
[48]	China	T	SF, LF	OW					X	
[49]	Poland	M, T	SF	OW					X	
[28]	Belgium	T	LF	FW			X			
[27]	UK		SF, LF	FW, OW			X			

Abbreviations: M—Mesophilic; T—Thermophilic. LF—Liquid Fraction; SF—Solid Fraction. AM—Animal Manure; CM—Cattle Manure; cM—Composted Manure; DS—Distillery Sludge; FW—Food Waste; MS—Maize Silage; OMSW—Organic Municipal Solid Waste; OW—Organic Waste; PM—Pig Manure; pM—Poultry Manure; Ps—Paper Sludge; WWS—Wastewater Sludge.

2. Digestate as Fertilizer

2.1. Use of Digestate as a Fertilizer

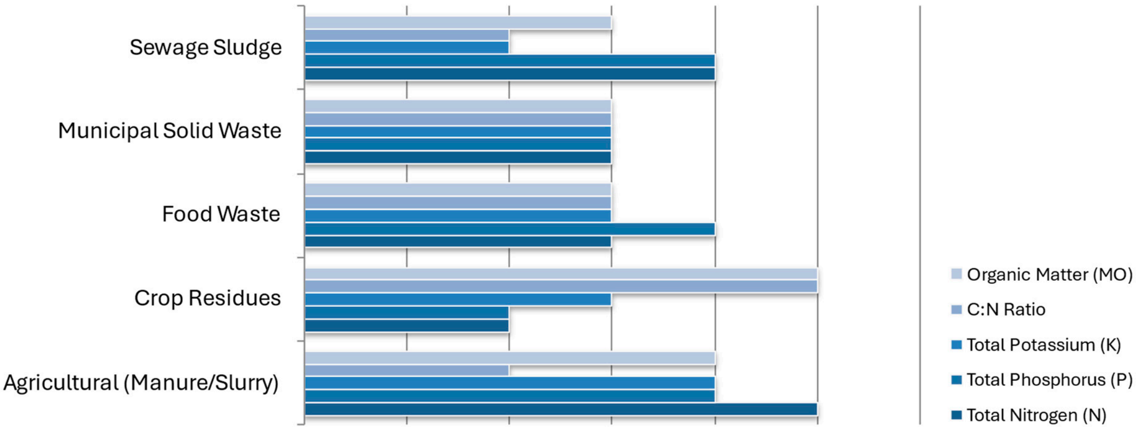
Soil fertilization remains the most widely used method for raw digestate management, requiring minimal processing [6]. While this practice has been in place for years, recent studies have focused on the role of digestate-derived fertilizers in soil amendment. However, their effectiveness varies significantly depending on feedstock composition, which influences chemical properties and fertilization efficiency [18,50]. Although research has primarily examined agricultural feedstocks due to their relevance in sustainable farming, further studies are needed to assess the specific effects of individual feedstocks on digestion and fertilization.

Nutrient availability plays a key role in digestate fertilization potential. Agricultural manure and slurry digestates typically contain higher nitrogen, phosphorus, and potassium levels than crop-based digestates. In contrast, crop digestates, though lower in nutrient content, are richer in organic carbon, with higher carbon-to-nitrogen ratios, promoting soil organic matter enrichment [12,51,52]. Organic fractions of solid waste digestates have intermediate nutrient levels—higher than crop digestates but lower than manure digestates—reducing the risk of nutrient overload and ammonia volatilization [18,53].

Soil pH and salinity regulation are particularly relevant for manure and slurry digestates, which help neutralize acidic soils [54–56]. In contrast, food waste and organic fraction of municipal waste digestates are generally neutral or slightly alkaline, making them suitable for agricultural use by preventing soil pH fluctuations and heavy metal mobilization [18].

Microbial activity and stability further influence fertilizer quality. Digestates with high microbial activity, such as those derived from manure and slurry, accelerate organic matter decomposition, enhance nutrient release, and improve stability—reducing volatilization, leaching, and pathogen release while minimizing overall environmental impact [12]. Chemical composition and fertilizing properties vary between digestate types and within digestates from the same category. The results shown in [57] demonstrated that digestates from cattle manure and slurry exhibit significant differences in composition and stability depending on co-digestion materials and process conditions. More biodegradable feedstocks, such as slurry, tend to result in nitrogen loss due to immobilization, reducing fertilization potential. In contrast, manure-derived digestates retain ammonium, leading to better short-term nutrient availability.

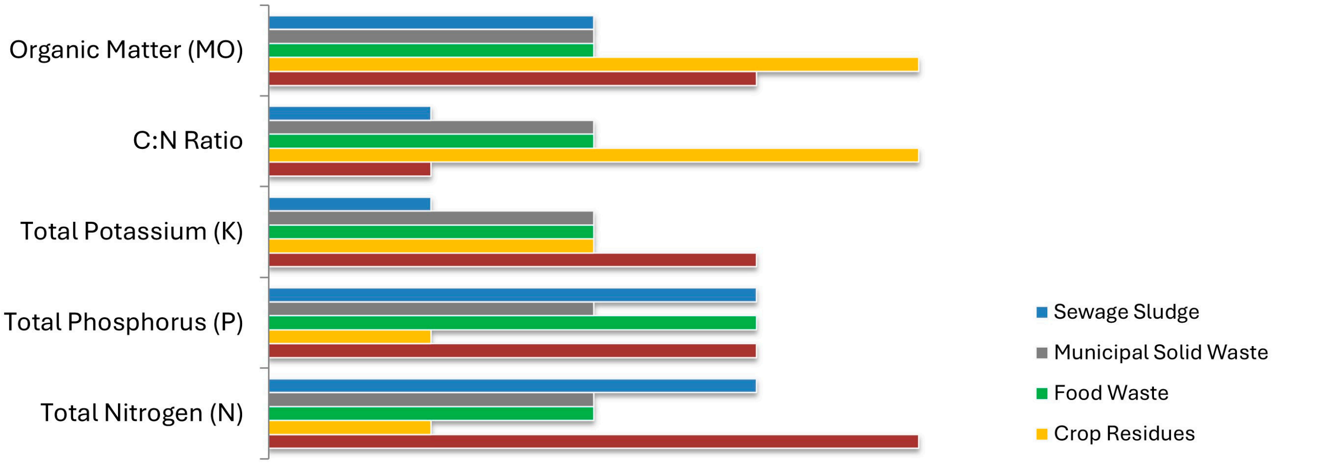
To complement the qualitative description above, Figure 1 summarizes the relative nutrient content of digestate derived from different feedstocks. These visual and tabular comparisons provide a clearer overview of how nitrogen, phosphorus, potassium, the C:N ratio, and organic matter content vary depending on the source material and underline the importance of substrate-specific digestate management.



	Agricultural (Manure/Slurry)	Crop Residues	Food Waste	Municipal Solid Waste	Sewage Sludge
Organic Matter (MO)	4	5	3	3	3
C:N Ratio	2	5	3	3	2
Total Potassium (K)	4	3	3	3	2
Total Phosphorus (P)	4	2	4	3	4
Total Nitrogen (N)	5	2	3	3	4

Level (1 = very low, 5 = very high)

(**a**)



	Total Nitrogen (N)	Total Phosphorus (P)	Total Potassium (K)	C:N Ratio	Organic Matter (MO)
Sewage Sludge	3	3	1	1	2
Municipal Solid Waste	2	2	2	2	2
Food Waste	2	3	2	2	2
Crop Residues	1	1	2	4	4
Agricultural (Manure/Slurry)	4	3	3	1	3

Level (1 = very low, 5 = very high)

(**b**)

Figure 1. Relative nutrient content of digestates derived from different feedstocks. (**a**) Parameter-based comparison. (**b**) Feedstock-based comparison. To optimize fertilizing properties, various post-processing methods may be required [6]. Mechanical separation of liquid and solid fractions enhances digestate usability [38,44]. Dehydration and drying increase nutrient concentration, while composting stabilizes digestate and reduces phytotoxicity [34,42,45,58]. Pelletization and briquetting modify environmental impact and application behavior [6,59].

The study in [60] assessed the fertilization potential of cattle manure digestate after mechanical separation, finding that the liquid fraction had a higher nitrogen fertilizer replacement value due to its ammonium-rich composition, leading to improved immediate crop performance. Conversely, with a higher carbon-to-nitrogen ratio, the solid fraction promoted long-term soil structure enhancement and organic matter build-up [61].

Composting is a promising post-treatment method to enhance digestate fertilization potential. Despite being cost-effective and widely applicable [62], it has received less attention than mechanical methods [63]. Rather than replacing other post-treatment techniques, composting is often applied after mechanical separation, as it is most effective for solid fractions [64]. During composting, microbial activity converts biogas residues into CO_2, biomass, thermal energy, and a stable, humus-like material [61]. This controlled, self-heating process enhances soil properties, reduces potassium leaching, and mitigates phytotoxicity by converting ammonia into nitrates, improving fertilization potential [65]. Studies indicate that composted digestate application significantly increases crop yields compared to inorganic fertilizers [66–68]. The results in [63] showed 40% and 100% higher sunflower yields with composted digestate than inorganic nitrogen and untreated digest, respectively, highlighting its potential as a cost-effective alternative to synthetic fertilizers.

Overall, the use of digestate as a fertilizer offers multiple agronomic and environmental advantages. It supplies essential nutrients such as nitrogen, phosphorus, and potassium, enhances soil structure, and improves water retention. Additionally, digestate can replace synthetic fertilizers, lowering greenhouse gas emissions linked to industrial fertilizer production. However, certain challenges limit its broad adoption. These include the potential presence of heavy metals, pathogens, or persistent organic pollutants—especially when the digestate is insufficiently treated. Nutrient imbalances and ammonia volatilization may also reduce fertilization efficiency and increase environmental risks. Consequently, proper management and, in many cases, additional post-treatment are essential to ensure the digestate's safety, stability, and agronomic performance.

2.2. Challenges of Digestate as Fertilizer

Despite its potential as a sustainable fertilizer, digestate faces several environmental, economic, and logistical challenges that hinder its widespread adoption.

One of the main concerns is the risk of soil, air, and water pollution. The organic nature of digestate means it may contain pathogens and heavy metals, depending on the feedstock and anaerobic digestion conditions. Pathogen contamination is a critical issue, as food waste, sludges, and contaminated plant materials may introduce microorganisms that persist through digestion and transfer to soils [69]. While certain bacteria and fungi contribute to soil health by fixing nitrogen and solubilizing phosphates [70,71], others may pose health risks if not properly managed [72]. Further research is needed to refine treatment conditions and post-processing methods to neutralize pathogens.

Heavy metal (HM) accumulation in soils is another concern, as these elements do not degrade during digestion and may transfer from feedstock to digestate, eventually contaminating crops and ecosystems [73,74]. The highest HM concentrations are typically found in animal slurries and manures, as HMs are commonly added to livestock feed to promote growth and microbial resistance [74,75]. Repeated applications of HM-containing digestate can lead to long-term soil accumulation, requiring careful feedstock selection and post-treatment strategies to reduce toxicity and bioavailability [76,77].

Nutrient runoff and volatilization also pose environmental risks, affecting both soil fertility and water quality. Nutrients such as phosphorus and nitrogen can leach from fertilized soils into water bodies, leading to eutrophication—a process that depletes oxygen levels and disrupts aquatic ecosystems [78]. Nitrates, due to their high solubility, are particularly prone to leaching [75]. Factors such as soil type, rainfall, and application method influence runoff potential, requiring optimized fertilization strategies [58,75,79].

Ammonia volatilization is another challenge, as anaerobic digestion increases the concentration of soluble inorganic nitrogen, primarily in the form of ammonium (NH_4^+). Under alkaline conditions, ammonium is converted into ammonia (NH_3) [80], which is released into the atmosphere, contributing to soil acidification and phytotoxicity [75,81–83]. This volatilization not only reduces the fertilizing efficiency of digestate but also exacerbates environmental degradation.

Beyond environmental concerns, digestate adoption is hindered by economic and logistical barriers. Its viability as an alternative to chemical fertilizers depends on overcoming feedstock variability, storage challenges, and market uncertainty. Unlike synthetic fertilizers, digestate composition is influenced by feedstock type, seasonality, and livestock diet [51,83]. This variability affects nutrient content and fertilization performance, making it difficult to standardize digestate as a reliable agricultural input.

Storage and co-digestion strategies have been proposed to mitigate seasonal and supply-chain fluctuations. Proper storage provides a buffer against supply inconsistencies, while the co-digestion of multiple feedstocks can improve digestate uniformity and enhance biogas production [6,84]. However, digestate storage and handling present additional logistical challenges, particularly due to its high-water content, which increases transport costs and risks of leakage [6,73]. Current approaches to address these issues include moisture reduction through physical and biological post-treatments, although further optimization is needed to improve cost-effectiveness.

The economic value of digestate remains uncertain, limiting its commercial potential. Pricing is influenced by nutrient content, regional demand, and competing synthetic fertilizers [84,85]. Unlike synthetic fertilizers with predictable pricing and standardized formulations, digestate lacks a consolidated market, making its widespread adoption less attractive to farmers. Clear economic models and policy incentives are necessary to enhance its competitiveness as a sustainable alternative.

3. LCA as a Tool in Digestate Use

3.1. LCA as a Tool to Measure Environmental Footprint

Life Cycle Assessment (LCA) is a widely recognized and standardized methodology for assessing the environmental impacts associated with all life cycle stages of a product, process, or service. From raw material extraction to final disposal, LCA allows a comprehensive view of material and energy flows, emissions, and waste. This methodology is particularly valuable because it provides a scientific basis for identifying environmental improvement opportunities, making informed decisions, and comparing options transparently. The use of LCA is supported by international bodies and regulatory frameworks, such as the International Organisation for Standardization Standards [86,87] and the Product Environmental Footprint (PEF) methodology promoted by the European Union. These guidelines ensure consistency and comparability of results, reinforcing their global acceptance as a key tool in environmental impact assessment.

LCA studies typically follow four main steps: (1) goal and scope, which defines the system boundaries and establishes the functional unit for the assessment; (2) inventory analysis, whereby inputs and outputs are measured and documented; (3) impact assessment, which transforms inventory data into potential environmental impacts; and (4) interpretation, whereby the results are analyzed to support informed decision-making. This systematic approach encourages transparency and easier comparisons among various products or systems.

3.2. LCA Applied to Digestate Production and Uses—A Survey of Recent Studies

For this review, we conducted a detailed search in Google Scholar for scientific articles published in journals indexed in the Journal Citation Reports (JCRs) since 2018 that included "life cycle analysis" plus "digestate" in their titles. Subsequently, with the aim of including more recent and relevant research, the search was expanded to identify articles that mentioned these words in the abstract or the article's keywords. After an exhaustive search, 28 articles were finally selected for analysis and inclusion in the review. All these studies indicate that they have followed the ISO 14040 and 14044 standards for LCA. Table 2 shows the most relevant information from the selected articles, including the functional unit, starting raw material, objectives, system boundaries, outputs, impact assessment method, software tool used, etc. The table also indicates whether a sensitivity analysis and an economic study have been conducted.

The structure of Table 2 has been constructed by considering, firstly, the functional unit (FU) and, secondly, the year of publication. In this way, the works with the same type of functional unit are grouped and ordered from the most recent to the oldest. Figure 2 provides a graphical overview of the distribution of functional units, geographic locations, system boundaries, and LCIA methods used in the studies included in Table 2.

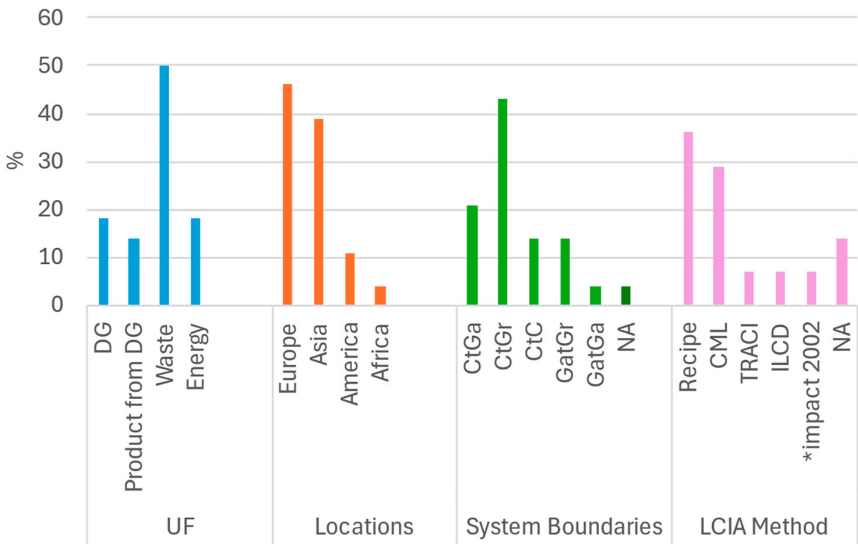


Figure 2. Distribution of articles included in Table 2, categorized by functional unit, system boundaries, geographical location, and LCIA method.

As shown in the first five studies, from study A to study E, the FU is the amount of digestate expressed in mass or volume, and these works are mainly focused on comparing different treatments applied to digestate for its use as biofertilizer and soil amendment, including its application in soil. In the next four papers, from F to I, the FU is the product obtained by treating the digestate, which can be a soil conditioner, compost, struvite, or used to fertilize a given area. In several of these studies, the production of these products is compared with conventional methods to assess their efficiency and environmental benefits. Studies ranging from position M to T of the table take the amount of waste used, measured in mass, as the functional unit. These studies cover all process stages, from waste collection to treatment in AD plants, including the generation and use of biogas and digestate. Biogas is used for energy to generate electricity, heat or converted into biomethane, while digestate is used in agricultural applications. The last five papers in the table (positions X to AB) use functional units based on biogas quantity or energy. These articles are mainly focused on biogas production for energy generation as well as biomethane production. These studies consider both biogas and digestate production within their limits.

Table 2. Overview of selected Life Cycle Assessment (LCA) studies on digestate as production and utilization, detailing study objectives, methodology, functional unit, system boundaries, feedstock type, environmental impact assessment methods, and whether sensitivity and economic analyses were conducted.

	Ref	Goal/Results	Methodology										Feedstock									Post LCA Studies	
			Location	LCA Software	FU	System Boundaries					End Product	LCIA Method	Plant Biomass				Livestock		Waste			Sensitivity Analysis	Economic Study
						CtGa	CtGr	CtC	GatGr	GatGa			RS	GS	CW	TW	CM	PS/M	FW	IW	OW		
A	[88]	Evaluate and compare treatments of DG for agricultural use.	Colombia	SimaPro 9.3	1 m^3 treated DG		X				DG, compost	ReCiPe 2016-midpoint (H), IPCC 2021					X			X			X
B	[89]	Evaluate and compare 3 DG treatment scenarios for use as a biofertilizer.	France	SimaPro 7.3.3	1 kg dry matter raw DG				X		Biofertilizer	ReCiPe at midpoint (H)						X	X				
C	[59]	Evaluate and compare DG treatment scenarios for its use as a biofertilizer.	China	Open LCA	1 ton raw DG				X		Biofertilizer, compost	CML 2001	X					X				X	
D	[90]	Evaluate and compare two types of DG treatment for soil application.	Italy	SimaPro 8.3	1 ton treated DG					X	Soil improvers	ReCiPe H midpoint, endpoint									X		
E	[91]	Comparison between direct use of DG and use of fertilizers derived from DG.	Sweden		1 m^3 DG				X		Biofertilizer	CLM-baseline							X				
F	[92]	Evaluate impacts of an industrial plant combining AD with vermicomposting.	Italy	SimaPro 9.4	1 t packaged soil aconditionator	X					BG, soil conditioner	ReCiPe 2016									X	X	

Table 2. *Cont.*

	Ref	Goal/Results	Methodology										Feedstock									Post LCA Studies	
			Location	LCA Software	FU	System Boundaries					End Product	LCIA Method	Plant Biomass				Livestock		Waste			Sensitivity Analysis	Economic Study
						CtGa	CtGr	CtC	GatGr	GatGa			RS	GS	CW	TW	CM	PS/M	FW	IW	OW		
G	[93]	Evaluate and compare the use direct biocompost and biocompost from DG.	Italy		1 mg compost used		X				Compost	ReCiPE 2016-midpoint									X		
H	[94]	Evaluate and compare the production and use of recovered and mineral fertilizers.	Italy	SimaPro 9.1.1.	Fertilization of 1 ha of maize		X				Two types of biofertilizers and BG	ReCiPe 2016 midpoint, end point									X	Monte Carlo	
I	[95]	Evaluate the environmental impacts of struvite recovery from LF of DG.	USA	SimaPro 8.5.2	1 kg LF DG & 1 kg of struvite.						Struvite and BG	TRACI 2.1, BEES (water footprint)						X				X	
J	[96]	Compare coupling AD hydrothermal carbonization vs. AD or composting alone. Best results: AD with hydrothermal carbonisation, followed by untreated AD.	China	SimaPro 9.4.0.1	1 ton FW		X				BG, DG and hydrochar	ReCiPe 2016							X			X	

Table 2. *Cont.*

	Ref	Goal/Results	Methodology										Feedstock									Post LCA Studies	
			Location	LCA Software	FU	System Boundaries					End Product	LCIA Method	Plant Biomass				Livestock		Waste			Sensitivity Analysis	Economic Study
						CtGa	CtGr	CtC	GatGr	GatGa			RS	GS	CW	TW	CM	PS/M	FW	IW	OW		
K	[97]	Evaluation of eco-industrial system integrating micro-scale AD and solid-state fermentation to produce RE and bioproducts.	Italy	SimaPro 9.1	1 ton wet weight of biowaste treated			X			Electricity heat, biofertilizer and compost	ReCipe 2016 midpoint, end point							X		X	X	X
L	[98]	Comparing pretreatment technologies (hydrothermal and ionic radiation) applied to the AD of FW.	China	Open LCA	1 ton FW	X					Electricity, Fertilizer treated water and biodiesel								X				
M	[99]	Evaluating impacts of liquid AD and solid-liquid mixed AD processes for FW	China	eBalance	10 ton FW		X				BG and DG	CML 2001							X			X	
N	[100]	Evaluating the impact of 3 solid DG management methods: incineration, composting, and landfill.	China		1 ton FW	X					BG for electricity and DG	CML 2001							X				

Table 2. *Cont.*

	Ref	Goal/Results	Methodology										Feedstock									Post LCA Studies	
			Location	LCA Software	FU	System Boundaries					End Product	LCIA Method	Plant Biomass				Livestock		Waste			Sensitivity Analysis	Economic Study
						CtGa	CtGr	CtC	GatGr	GatGa			RS	GS	CW	TW	CM	PS/M	FW	IW	OW		
O	[101]	Compare impacts of co-digesting PM and FW vs. impacts of existing management practices of PM and FW.	Ireland	SimaPro	PM 16 ktpa and FW 10 ktpa		X				BG for CHP and DG	CLM-IA, 2016						X	X			X	
P	[102]	Comparison of incineration and different AD configuration wtih different BG applications.	Singapore	Gabi 8.7	1 ton FW		X				BG and DG	ReCipe 2016							X			X	
Q	[103]	Evaluation of 3 PM management methods.	Ireland	SimaPro	PM: 15,070 m^3/yr and grass sillage: 1.3 ktpa		X				Heat, electricity, diesel, biofertilizer	CML-IA baseline		X				X				X	
R	[104]	Compare electricity generation with composting vs. BG flaring and conventional methods.	Mexico	SimaPro 8.1.1.6	1 ton of SM and LM				X		BG, electricity, DG and liquid effluents	CML-IA 2013						X				X	
S	[105]	Evaluate and compare environmental impact associated of two composting techniques.	Qatar	SimaPro 7.1.0	1 ton FW	X					BG and compost	CML-baseline 2000							X			X	

Table 2. *Cont.*

	Ref	Goal/Results	Methodology									Feedstock									Post LCA Studies	
			Location	LCA Software	FU	System Boundaries					End Product	LCIA Method	Plant Biomass				Livestock		Waste			Sensitivity Analysis	Economic Study
						CtGa	CtGr	CtC	GatGr	GatGa			RS	GS	CW	TW	CM	PS/M	FW	IW	OW		
T	[106]	Evaluate the impacts AD combined with different types of DG treatment for soil application.	China		1 ton PM		X				BG, compost, biofertilizer	Impact 2002 +						X				X	
U	[107]	Evaluate relationship between collection efficiency, legal restrictions on DG use, and performance of AD	Italy	SimaPro 9	1 mg biowaste			X			BG and fertilizers	Midpoint ILCD 2011+, Impact 2002+ for endpoint for HT									X		
V	[108]	Evaluate use of OFMSW to generate bioenergy and high-value products through biopulp-based biorefineries	Denmanrk	SimaPro 8.5	1 ton biopulp		X				BG and DG	Impact 2002+									X		
W	[109]	Evaluate environmental impacts of waste treatment through AD, composting, and AD plus composting.	China	Green delta	1 ton dairy manure		X				BG and compost	TRACI 2.1.			X	X	X						
X	[110]	Compare impacts of AD and electro-AD of various types of waste.	China	Open LCA	1 MJ bioCH4	X					bioCH4, biofertilizers						X		X			X	

Table 2. *Cont.*

	Ref	Goal/Results	Methodology										Feedstock									Post LCA Studies	
			Location	LCA Software	FU	System Boundaries					End Product	LCIA Method	Plant Biomass				Livestock		Waste			Sensitivity Analysis	Economic Study
						CtGa	CtGr	CtC	GatGr	GatGa			RS	GS	CW	TW	CM	PS/M	FW	IW	OW		
Y	[111]	Evaluate environmental impact of domestic BG digesters.	Egypt	SimaPro 9.1	1 m^3 BG		X				BG and DG as residue	ReCipe 2008 at midpoint, endpoint					X					X	
Z	[112]	Evaluate and compare 2 scenarios in partial and full substitution options of AD of Manure and MOW.	Europe		1 MJ LHV com-pressed bioCH4			X			BG and DG	EF 3.0					X				X	X	
AA	[113]	Evaluate emissions of complete AD process.	Finland	Semipros	MJ energy and kg N			X			BG and DG							X					
AB	[114]	Evaluate management of a BG plant from environmental, energy, and economic perspectives	Thailand	MilLCA	1 MJ bioCH4	X						Impact Assessment Endpoint							X			X	X

Abbreviations: CtC—Cradle to Cradle; CtGa—Cradle to Gate; CtGr—Cradle to Grave; GatGa—Gate to Gate; GatGr—Gate to Grave. CM—Cattle Manure; CW—Crop Waste; FW—Food Waste; GS—Grass Silage; IW—Industrial Waste; PM—Pig Manure; PS—Pig Slurry; RS—Residual Straw; TW—Tree Waste.

Regarding the locations where the evaluated studies were carried out, 46% were in Europe. Italy accounted for 21% of the total, 39% of the studies were conducted in Asia, and China was the main country, accounting for 29%. The Americas accounted for 11% of the studies, while Egypt accounted for one study. On the other hand, the most common software tool is Simapro in its different versions.

Considering the significant influence that the type of feedstock digested has on the quality of the digestate produced and the emissions produced, as pointed out by [73], the literature review reveals that some studies focus on the use of a single type of waste, while others incorporate mixtures of different types of waste. In the review of the articles, 19 use only one type of waste. Of these, eight focus exclusively on using food waste as the main material. The other eleven studies investigate the use of manure from different animals, bio waste, and organic municipal solid waste. As far as mixtures are concerned, combinations of some animal manure with other wastes, such as food, bio, and agricultural, predominate. Most of these studies only specify the amount of waste to be processed and its main composition (food waste, manure, OFMSW); however, in most of the reviewed studies (18 out of the 28 reviewed papers), the physicochemical characteristics of the substrates were not analyzed.

Most papers clearly indicate the system's boundaries, specifying the stages included and excluded from the study. However, as seen in the table, variations in the scope are considered, depending on its goal. The table clearly outlines the approach used for the life cycle analysis, categorizing it into the following groups: cradle to cradle (CtC), cradle to grave (CtGr), cradle to gate (CtGa), gate to grave (GatGr), and finally, gate to gate (GatGa). In thirteen of the reviewed papers, the system boundaries are defined from the cradle to the grave, which includes the stages of digestate production, processing, and agricultural use. In six studies, the scope is cradle to gate, which concludes once the product is finished, excluding distribution and usage. Four articles follow the gate to grave approach, excluding the prior production stages. For the other scopes, there are two gate to gate and one cradle to cradle.

The Life Cycle Impact Assessment (LCIA) utilizes Life Cycle Inventory (LCI) data to determine environmental impact indicators based on a functional unit. While ISO standards suggest impact categories, they do not prescribe a specific LCIA method, allowing for varied methodological choices that can significantly affect the analysis results. Key global LCIA methods like CML-IA [115], Recipe 2016 [116], IMPACT 2002+ [117], and ILCD [118] generally focus on mid-point impacts and differ in scope and detail. CML-IA, for example, offers two versions: a baseline with 11 impact categories and an extended version with 50 categories. The Recipe 2016 method encompasses 18 impact categories at the midpoint and 3 protection areas at the endpoints. The IMPACT 2002+ method [117] is damage-oriented and uses 15 impact categories at the midpoint level and 4 damage categories. The ILCD 2011 method uses 16 impact categories at the midpoint level. Out of all the reviewed papers, 10 of them use the ReCipe midpoint method and 3 of them also include the endpoints. Most used the 2016 version, except for one, which uses the 2008 version. Eight papers used the CLM-IA method in different versions. The following evaluation methods, Impact 2002+, TRACI, and ILCD, have each been used in two papers.

Table 2 also indicates whether the paper has conducted a sensitivity analysis and an economic study. In 17 of the reviewed articles, a sensitivity analysis is included to identify the variables that most significantly influence the study's outcomes. Meanwhile, only two of them conducted an economic evaluation.

The objectives of the reviewed studies vary based on the functional unit, system boundaries, raw materials, and products obtained, among other factors. Some studies seek to evaluate and compare the environmental impacts of applying different treatments to digestate for agricultural use, either as a soil conditioner or biofertilizer, including the use of vermifilters [88], phase separations, and treatments thereof [89], and the production of fertilizer in different physical forms [59]. In other cases, the direct use of digestate is compared with the use of biofertilizer derived from treated digestate [91], direct composting substrate versus composting digestate [93], and co-digestion with management methods [101,110]. Furthermore, other studies compare waste treatment by AD with other types of treatment, such as incineration, landfill composting, etc. [100,102]. Finally, some studies compare the products obtained from digestate treatment with the same products obtained by conventional methods [94]. Some of these works also evaluate the impacts of AD on waste, including pre-treatment to improve biogas production yield and, subsequently, treatment of the digestate for land application [96,98]. Despite the methodological richness of the selected studies, a direct comparison is hindered by significant inconsistencies in functional unit selection, impact assessment methods, and system boundaries. These differences reflect broader challenges in applying LCA to digestate systems, highlighting the need for standardized practices to reduce bias and improve comparability across studies.

Beyond these methodological differences, the reviewed studies show a series of converging results. Table 2 illustrates these findings, highlighting the impact of various treatments and valorization strategies on digestate sustainability. In general, significant environmental benefits are observed when implementing treatments that enhance the value of digestates. This improvement is also notable when comparing biofertilizers derived from digestate against the direct use of digestate or substrate and comparing AD and other management methods, such as incineration and landfilling. Additionally, it has been demonstrated that applying pretreatments to waste optimizes the efficiency of AD and the quality of the final products, with the co-digestion of various substrates being a key factor in enhancing these results.

4. System and Stages in Digestate Production

4.1. Digestate Production Systems

Digestate production systems, closely linked to biogas production, vary in design and scale depending on input materials and geography. These systems range from household digesters [111] to municipal-scale treatment plants [101,102]. Despite differences in specific processes, digestate production follows four main stages: feedstock storage and conditioning, biogas and digestate production, digestate separation, and post-treatment.

As shown in Figure 3, organic waste is collected—either onsite (manure for farm plants) or via transportation (20 km average for municipal and food waste plants). Upon arrival, feedstock undergoes storage and pretreatment, particularly in municipal solid waste facilities, where sorting, shredding, blending, and hydrothermal treatment optimize biogas yield [99]. Co-digestion enhances both biogas and digestate composition.

In the anaerobic digestion (AD) stage, biogas and digestate are produced, refined into biomethane, electricity, or heat. Raw digestate may be directly applied to land [113,114] or further processed into refined products [111].

Digestate separation is essential for product refinement. It involves gravity-based methods (settling ponds and decanters) [106], filtration techniques [88], ultrafiltration, and reverse osmosis. Mechanical separation (centrifugation and pressing) is most widely used due to its efficiency and cost-effectiveness. The separated solid fraction (SF) and liquid fraction (LF) can be managed as waste, fertilizers, or further processed.

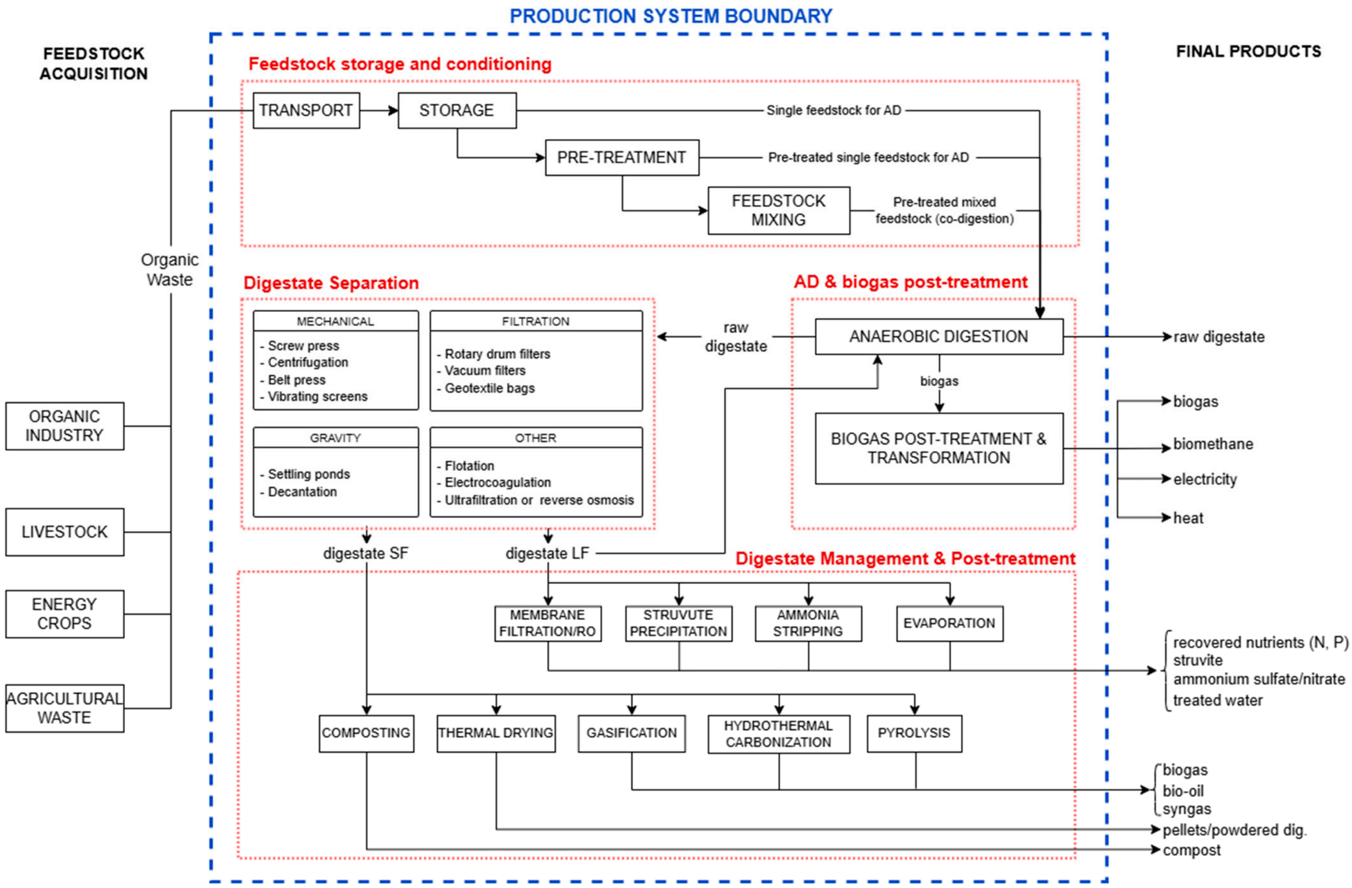


Figure 3. Diagram of digestate production systems.

Post-treatment methods for digestate depend on the fraction being processed and the intended final product. The solid fraction (SF) can undergo traditional vermicomposting or windrow composting, producing nutrient-rich organic fertilizers. Alternatively, it can be dried into powdered fertilizers or pellets for easier application. In less common cases, SF is converted into energy products such as biogas, bio-oil, or syngas through gasification, hydrothermal carbonization, or pyrolysis. The liquid fraction (LF) can either be reintroduced into the digester to regulate moisture levels or further processed to recover valuable nutrients, such as struvite and ammonia, or through membrane filtration. These treatments allow for safe water reuse in irrigation while maximizing resource efficiency.

4.2. Using LCA to Improve Digestate Production Systems

LCA is a key tool for optimizing digestate production by identifying environmental impacts, improving efficiency, and guiding the transition to a circular economy through sustainable waste management and high-value product generation. This text consolidates the remarks and possible improvements highlighted by the LCA methodology in the reviewed papers.

LCA identifies critical "hotspots" in the system, such as fugitive emissions during feedstock handling, digestate post-treatment, storage, land application, anaerobic digestion, and long-distance transport, which significantly contribute to energy consumption and greenhouse gas (GHG) emissions [33,93,101,104,106]. These emissions often go unaccounted for but considerably impact Global Warming Potential. LCA also quantifies resource consumption, acidification, eutrophication, and ecosystem toxicity, identifying unit processes with the highest contributions. Digestate-derived fertilizers tend to have high acidification and eutrophication impacts due to ammonia and nitrate volatilization and runoff during land application [52,99,119]. If not properly managed with efficient application and storage techniques, these impacts can surpass those of inorganic fertilizers [113]. Many studies highlight anaerobic digestion (AD) as key in reducing GWP and fossil fuel resource depletion, with biogas production providing positive environmental credit. Increasing biogas yield is the most direct way to reduce environmental impact [98,102,105,107,110,120], while fertilizer displacement also plays a role [89].

LCA facilitates comparisons between liquid digestate and solid fertilizers, assessing transport, handling, and fertilizing potential. A previous study [112] found that while manures reduce emissions in storage, municipal organic waste has greater fertilizing potential and displaces more inorganic fertilizers. Another study [89] found lower emissions when digestate is dried and separated before storage. The results in [96] showed that transforming digestate into hydrochar reduces GWP by storing carbon in the final product. The authors in [100] reported that burning digestate instead of using it as fertilizer can further lower GWP by reducing external energy demand. LCA identifies key environmental impacts and informs sustainable system improvements, fostering a circular economy through fertilizer and bioproduct valorization.

Electricity consumption is a major contributor to digestate production's environmental footprint, accounting for 50–80% of the total impact [90]. Adopting renewable energy sources and biofilters can mitigate this burden [93]. Storage and land application are primary GHG emissions, acidification, and eutrophication sources. Storage alone contributes up to 65% of direct GHG emissions [103], while land application is responsible for 99% of eutrophication potential due to nitrogen runoff [89]. Improved sealing of digestate storage can reduce fugitive methane emissions by up to 165% [106].

Transportation distance plays a crucial role in digestate feasibility. When exceeding 10–15 km, drying and transport emissions can outweigh economic benefits [96]. The maximum break-even distance for achieving GWP neutrality is 211 km [92]. Composting helps mitigate ammonia volatilization and nitrate leaching by stabilizing organic matter [88]. Digestate's total solid (TS) content influences emissions, with higher TS reducing ammonia losses but increasing ozone depletion [99].

Phase separation is crucial for digestate management. Mechanical separation methods, such as centrifugation and pressing, are widely used due to their efficiency and lower [97]. Filtration techniques, like reverse osmosis, reduce GWP by 9% but require higher energy input [97]. Anaerobic digestion provides fossil fuel substitution credits, lowering overall environmental impact [107]. Electro-digestion improves energy efficiency by 35.9% but increases initial energy demand [110]. Composting reduces ammonia volatilization and nitrate leaching, significantly lowering eutrophication and acidification potential [88]. Hydrothermal carbonization (HTC) and pyrolysis convert digestate into hydrochar, biochar, or syngas, offering additional energy recovery [105]. Hydrochar has been identified as the most effective process for GWP reduction due to its carbon storage potential [96].

By optimizing post-treatment strategies and increasing biogas yields, digestate systems can maximize environmental benefits while supporting a circular economy. The integration of LCA ensures that digestate management continues evolving toward lower emissions, improved nutrient recovery, and enhanced sustainability.

5. Discussion

Although all the LCA studies reviewed for this work follow the structure and guidelines established in ISO 14040 and ISO 14044, the different choices of goal, scope, functional units, allocation, and boundaries make a direct comparison and analysis through the information conveyed in Table 2 impossible. However, the shared final product of the studied works allows the identification of elements and processes that have clear influence on the results of the LCA across the different studies.

5.1. Choice of Functional Unit and System Boundaries

According to ISO guidelines, selecting a functional unit aligned with the study's goal is crucial [95]. Depending on the focus, studies use different units: digestate applications use m^3, kg, or tonnes of digestate (solid or liquid), compost studies use kg of compost or soil conditioner, and energy recovery studies use MJ or m^3 of biogas/biomethane. Waste treatment studies rely on kg of processed waste (manure, organic, or food waste). The functional unit determines environmental credit allocation when a product displaces another, but limits quantitative comparison across studies.

System boundaries define which lifecycle stages are included in LCA assessments and vary based on study goals. For energy recovery studies, boundaries typically end at biogas or biomethane production [110,111], excluding digestate post-treatment. In contrast, studies on digestate-based fertilizer substitution require boundaries covering the full value chain [88,94].

Clear inclusion/exclusion of system processes is essential, as it impacts study conclusions. Considering upstream waste generation enables a full assessment of total system impact, whereas excluding it limits the study to waste treatment and disposal. Transportation of feedstock and digestate significantly affects energy consumption and GHG emissions, especially for long distances [92,96]. Furthermore, including infrastructure construction (digesters, storage, and transport) influences cumulative LCA impacts, particularly in long-term or technology comparison studies [88]. Thus, clearly defining system boundaries is key for accurate LCA interpretation and reproducibility.

5.2. Feedstock Choice and Handling Before AD

Feedstock selection is critical for LCA accuracy, as it determines biofertilizer quality, including nutrient content (N, P, and K), organic matter, and contaminants [97,120]. From collection to digestion, feedstock handling significantly influences energy use, emissions, and resource consumption [92,96,106].

Transport distances impact GWP, especially for high-water-content feedstocks, which require moving large liquid volumes with low fertilizing and energy content [59,105,109]. Storage emissions from organic feedstocks (manures and slurries) can lead to methane (CH_4) and ammonia (NH_3) leaks, increasing GWP and acidification potential (AP) while reducing biogas yield [93,104,110].

Pretreatment techniques enhance digestibility but impact energy demand. Thermal or hydrolytic pretreatments boost biogas yield but require more energy [98,110]. Sorting and shredding remove contaminants, improving degradability but increasing total system energy consumption [99]. Pretreatment strategies must balance energy demand and yield, adapting to the specific feedstock composition.

5.3. Digestate Post-Treatment and Handling After AD

Digestate post-treatment significantly impacts LCA results by influencing system emissions and the efficiency of mineral fertilizer substitution. Various post-treatment technologies alter material stability, nutrient composition, water content, and agricultural suitability, ultimately affecting system sustainability. The first stage of post-treatment involves separating the solid fraction (SF) and liquid fraction (LF), primarily through mechanical methods, which reduce volume and humidity, facilitating transport and land application while maintaining a lower GWP compared to more energy-intensive filtering or drying processes [59,89].

Further processing of digestate depends on its intended final use. Composting stabilizes organic matter, reduces pathogens, and improves digestate quality as an organic fertilizer, requiring minimal energy input while enhancing nutrient retention. This leads to a higher-quality product capable of substituting a greater quantity of synthetic fertilizers [89]. Additionally, increasing total solids (TS) in compost reduces ammonia volatilization and nitrate leaching, significantly lowering eutrophication and acidification potential.

The final stage of digestate handling, land application, is often the primary contributor to emissions in acidification and eutrophication impact categories [99,101,106]. To mitigate these environmental impacts, it is recommended to prevent excessive digestate application on land and to implement specific application techniques such as soil injection, which reduces nutrient losses and associated emissions [94].

5.4. Impact Allocation and Product Displacement or Substitution

The results of an LCA depend heavily on allocation and substitution choices. Feedstock is often classified as waste with no environmental burden. Still, it can also be considered a resource for biogas production, in which upstream impacts like cultivation, processing, and transport are accounted for, increasing the environmental footprint [113,121]. System product classification also affects results: if digestate and biogas are co-products, their impacts are allocated based on mass, energy, or economic criteria, while if only one is classified as a product, it bears the entire environmental burden.

Product displacement and substitution play a crucial role in LCA outcomes. Anaerobic digestion (AD) generates co-products that replace market alternatives, assigning them environmental credits based on avoided impacts [104]. Biogas, a carbon-neutral energy source, can replace fossil fuels, significantly reducing GWP and resource depletion [62,105,109]. Studies highlight that increasing AD energy yield is the most effective way to lower overall emissions [101,107,110].

Digestate can replace synthetic fertilizers, reducing the environmental burden of their production. The extent of substitution credits depends on the digestate form (SF, LF, compost, and pellets) and its efficiency in fertilizing land. A direct substitution approach considers digestate's nutrient content (N, P, and K) as a replacement for synthetic N, P_2O_5, and K_2O [59,88,90,107,109]. Some studies adjust credits based on nutrient absorption rates [94], while others incorporate digestate into fertilizer production processes [97].

5.5. Policy and Market Barriers to Digestate Utilization

The legal status of digestate plays a crucial role in determining its permitted uses, the regulatory procedures required for its commercialization, and its classification as either waste or a valuable resource. As anaerobic digestion gains prominence within the European Union's circular bioeconomy strategies, a clear understanding of the legal framework governing digestate is increasingly relevant. This section provides an overview of the regulatory context applicable to digestate in the EU, complemented by an examination of its implementation in Spain as a representative Member State. By analyzing both EU-level and national legislation, this review aims to clarify the current legal status of digestate as a fertilizing product and identify key challenges in the application of existing laws.

5.5.1. Legal Complexity in the Classification of Digestate

The focus lies on the legal framework related to the use of digestate as a fertilizing product, and it is important to acknowledge that any legal assessment must also consider the nature and origin of the input materials fed into the anaerobic digestion process. The legal acceptability of digestate for specific uses may be constrained by the classification of these inputs. However, a detailed evaluation of feedstock admissibility is beyond the scope of this work. Instead, the following sections focus on the regulatory pathways governing the commercialization and agricultural application of digestate, assuming compliance with relevant quality and safety standards.

A central legal challenge is the classification of digestate. Depending on its origin, treatment process, and intended use, digestate can be legally defined as a product, by-product, waste, or as a material that has achieved "end-of-waste" status. This classification significantly affects how digestate can be stored, transported, applied to land, and marketed. In practice, the legal status of digestate is often determined on a case-by-case basis, considering both feedstock characteristics and processing conditions.

At the EU level, digestate is generally considered waste unless it satisfies the conditions set forth in Article 6 of the Waste Framework Directive [122] to be classified as having reached end-of-waste status. According to this directive, a material ceases to be waste after undergoing a recovery operation and meeting specific criteria, such as being commonly used for specific purposes, having a market demand, and posing no adverse environmental or human health impacts. Additionally, the material must comply with all relevant legislation. However, the absence of harmonized EU-wide end-of-waste criteria for digestate results in divergent interpretations and implementations across Member States.

In Spain, digestate is legally defined by Article 3 (e) of Royal Decree 1051/2022 [123] as "organic material obtained through anaerobic digestion in accordance with the requirements of Component Material Categories 4 and 5 (CMC4 and CMC5) of Annex II of Regulation (EU) 2019/1009" [124]. The decree further clarifies that digestate may be regarded as a product recovered from waste treatment—i.e., a recovered product—provided it complies with end-of-waste criteria established in the Spanish Waste Law 7/2022 [125] and associated regulations. Consequently, under Spanish law, digestate can exit the waste regulatory framework and be treated as a product, subject to quality, traceability, and usage conditions. This status enables its commercialization and use as a fertilizing material, albeit often requiring case-specific evaluations and administrative approvals.

5.5.2. Legal and Commercial Feasibility of Digestate as Fertilizer

The regulation of digestate as a fertilizing product is governed both at the European Union level and by individual Member States. Digestate can be marketed under EU harmonized rules or according to national legislation, each with distinct requirements and implications.

Regulation (EU) 2019/1009 [124] governs the placing of fertilizing products on the EU internal market and establishes a harmonized approval and labeling system. Within this regulation, digestate is addressed under specific Component Material Categories (CMCs): CMC4: Digestate derived from fresh crop materials (excluding food and feed waste); and CMC5: Digestate derived from non-food/non-feed biodegradable waste.

To qualify under these categories, digestate must meet stringent input material restrictions, processing conditions (e.g., sanitization), and contaminant limits. The final product must correspond to a Product Function Category (PFC), such as fertilizer, soil improver, or growing medium, and comply with associated quality and safety criteria.

Upon meeting these requirements, digestate products obtain CE marking through conformity assessment, enabling free marketing across the EU without additional national authorizations. This facilitates cross-border trade and regulatory harmonization. Nonetheless, manufacturers may elect to operate under national regulations if EU criteria are unmet or inapplicable.

In Spain, the commercialization and use of digestate as a fertilizer are primarily governed by Royal Decree 506/2013 [126] on fertilizing products and Law 7/2022 [125] on waste and contaminated soils, which regulate conditions for end-of-waste status. Digestate can be marketed in Spain either as a finished fertilizer, complying with specifications in Royal Decree 506/2013 [126] annexes, or as a raw material for compound fertilizer formulation, subject to prior evaluation and approval.

If derived from waste, digestate must have undergone an end-of-waste assessment ensuring quality, environmental safety, and traceability. Royal Decree 1051/2022 [123] aligns with Regulation (EU) 2019/1009 [124] in recognizing digestate conforming to CMC4 or CMC5 as a recovered material suitable for fertilizer use. Additionally, operators marketing digestate-based fertilizing products must register with the National Register of Fertilizer Manufacturers and Importers and comply with relevant reporting and traceability obligations.

It is important to note that obtaining fertilizer status—either at an EU or national level—does not automatically authorize land application. Use in agriculture must comply with national and regional environmental regulations, including restrictions related to nitrate vulnerable zones, application methods, and nutrient limits.

5.5.3. Challenges and Uncertainties in the Legal Framework for Digestate

Despite the existence of both harmonized EU regulations—such as Regulation (EU) 2019/1009 [124]—and national legislative frameworks like the Spanish law, the legal status of digestate remains complex and often ambiguous. Its classification as a product, by-product, waste, or end-of-waste material varies across jurisdictions, creating uncertainty for producers, regulators, and market actors. The coexistence of multiple regulatory pathways, along with regional restrictions and variability in feedstock inputs, complicates the commercialization and application of digestate—particularly for smaller operators. While some successful cases exist, they remain limited, underscoring the pressing need for clearer, more consistent guidance and regulatory harmonization. Addressing these challenges is essential to unlocking digestate's potential as a sustainable fertilizer and advancing its role in circular economy strategies and climate-resilient agriculture.

In conclusion, the environmental performance of digestate is shaped by a combination of technical, methodological, and regulatory factors. Variables such as feedstock selection, system boundaries, functional units, post-treatment strategies, and allocation methods significantly influence the outcomes of Life Cycle Assessment studies. Although methodological heterogeneity limits direct comparability, it also underscores the importance of standardized approaches and context-specific interpretation. Additionally, regulatory complexity and market barriers remain critical obstacles to the large-scale adoption of digestate-based solutions. A more harmonized legal framework, coupled with policy incentives and continued technological innovation, will be essential to unlock the full environmental and agronomic potential of digestate within circular economy strategies.

6. Conclusions

Digestate represents a key resource within the circular bioeconomy, standing out as a valuable biofertilizer capable of enhancing soil fertility and reducing dependence on synthetic fertilizers. However, its efficient utilization requires appropriate treatment and application strategies to maximize agronomic benefits while minimizing adverse environmental impacts.

LCA studies reveal significant variability in results due to differences in functional unit selection and system boundaries. Feedstock type, pretreatment methods, and post-processing strategies influence nutrient retention, fertilization potential, and digestate-associated emissions.

Implementing post-treatment strategies, such as solid–liquid separation and composting, has proven effective in improving digestate stability and optimizing agronomic properties. Proper soil application can mitigate eutrophication risks, enhance soil structure, and reduce greenhouse gas emissions, particularly ammonia and nitrogen oxide losses.

However, digestate's economic and environmental feasibility depends on transportation distances and application methods. Studies indicate that when transport exceeds 15 km, the environmental benefits may be offset by increased emissions and energy use. Additionally, direct soil injection has been identified as an effective strategy to minimize NH_3 volatilization and reduce nitrate leaching.

The selection of digestate valorization processes also involves important environmental trade-offs. Converting digestate into hydrochar enables significant carbon sequestration (15–30%), reducing long-term global warming potential. While composting extends processing time, it stabilizes nutrients and enhances fertilizer efficiency. In contrast, direct application of liquid digestate poses a higher risk of nitrate leaching and water contamination.

Anaerobic digestion remains the most effective strategy for obtaining carbon credits, primarily due to its role in replacing fossil fuels. Increasing anaerobic digestion efficiency through technologies such as electro-digestion can reduce system-wide emissions by up to 35.9%, although it entails higher initial energy consumption.

Finally, LCA studies demonstrate that the choice of the functional unit and the scope of the analysis significantly impact results, limiting direct comparability between studies. Research focusing on biogas production (MJ or m^3 of methane) and those prioritizing fertilizer substitution (kg of digestate, NPK content) reach different conclusions regarding digestate sustainability. Similarly, system boundaries, including infrastructure and transportation, greatly influence the final environmental impact values.

To promote digestate valorization and consolidate its role within the circular economy, it is crucial to implement policy incentives and standardize LCA methodologies. These measures will facilitate its optimal utilization, enhance its competitiveness against conventional alternatives, and ensure sustainable organic waste management. Furthermore, developing robust markets for digestate-derived products will drive their large-scale adoption.

To conclude, the following action points summarize key recommendations for stakeholders and decision-makers:

- Promote the development and adoption of standardized LCA methodologies to improve comparability and transparency.
- Incentivize digestate post-treatment strategies (e.g., composting, separation) to enhance agronomic quality and environmental safety.
- Establish clear policy frameworks and end-of-waste criteria to enable digestate commercialization.
- Support research on digestate behavior under diverse agronomic and climatic conditions.
- Strengthen regional digestate markets through public procurement, farmer training, and quality certification schemes.

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Abbreviations

The following abbreviations are used in this manuscript:

AD	Anaerobic Digestion
AM	Animal Manure
BG	Biogas
CM	Cattle Manure
cM	Composted Manure
CHN	Calcium Hydrolysis Neutralization
CHP	Combined Heat and Power
CtC	Cradle to Cradle
CtGa	Cradle to Gate
CtGr	Cradle to Grave
CW	Crop Waste
DG	Digestate
DM	Dry Matter
DS	Distillery Sludge
FU	Functional Unit
FW	Food Waste
GatGa	Gate to Gate
GatGr	Gate to Grave
GHG	Greenhouse Gases
GS	Grass Silage
GWP	Global Warming Potential
HM	Heavy Metal
HTC	Hydrothermal Carbonization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
IW	Industrial Waste
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LF	Liquid Fraction
M	Mesophilic
MS	Maize Silage
MSW	Municipal Solid Waste
OM	Organic Matter
OMSW	Organic Municipal Solid Waste
OW	Organic Waste
PEF	Product Environmental Footprint
PM	Pig Manure
pM	Poultry Manure
PS	Pig Slurry
Ps	Paper Sludge
RS	Residual Straw
SF	Solid Fraction
SM	Sheep Manure
SP	Slaughterhouse Processing Waste
T	Thermophilic
TOC	Total Organic Carbon

TS	Total Solids
TW	Tree Waste
VS	Volatile Solids
WWS	Wastewater Sludge

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