Bioresource Technology 409 (2024) 131252

Contents lists available at ScienceDirect

Bioresource Technology

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

Comprehensive review of technologies for separate digestate treatment and agricultural valorisation within circular and green economy

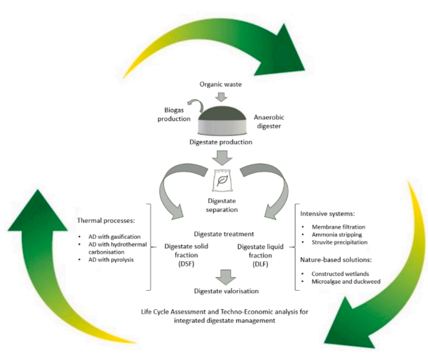
Giuseppe Mancuso [a], Sanae Habchi [b], Mirko Maraldi [a], Francesca Valenti [a,*], Hassan El Bari [b]

[a] *Alma Mater Studiorum - University of Bologna, Department of Agricultural and Food Sciences, viale Giuseppe Fanin 50, Bologna 40127, Italy*
[b] *Laboratory of Electronic Systems, Information Processing, Mechanics and Energetics, Faculty of Sciences, Ibn Tofail University, Kenitra, Morocco*

HIGHLIGHTS

- AD reduces environmental risks, achieving energy conversion efficiencies up to 50%.
- Digestate hydrothermal processes can increase electric biogas plant output by 42%.
- Intensive treatment of digestate liquid fraction can cost up to €13/m^3.
- Optimised nature-based solutions can achieve about 90% of pollutant removal.
- LCA and TEA aid sustainable IDM decisions, boosting economic viability.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Integrated digestate management
Liquid fraction
Solid fraction
Sustainable resource management
Organic waste recycling

ABSTRACT

Anaerobic digestion (AD) has the potential to catalyse the shift from a linear to a circular economy. However, effective treatment and management of both solid (DSF) and liquid (DLF) digestate fraction treatment and management require adopting sustainable technologies to recover valuable by-products like energy, biofuels, biochar, and nutrients. This study reviews state-of-the-art advanced technologies for DSF and DLF treatment and valorisation, using life cycle assessment (LCA) and techno-economic analysis (TEA) in integrated digestate management (IDM). Key findings highlight these technologies' potential in mitigating environmental impacts from digestate management, but there's a need to improve process efficiency, especially at larger scales. Future research should prioritize cost-effective and eco-friendly IDM technologies. This review emphasizes how LCA and TEA can guide decision-making and promote sustainable agricultural practices. Ultimately, sustainable IDM technologies can boost resource recovery and advance circular economy principles, enhancing the environmental and economic sustainability of AD processes.

1. Introduction

Organic waste from agriculture, agro-food, municipal sectors, and household wastewater sludge is extensive globally but often mismanaged, posing significant environmental risks (Valenti et al., 2020b, 2020a). Inadequate treatment leads to pollution and greenhouse gas

* Corresponding author.
E-mail address: francesca.valenti9@unibo.it (F. Valenti).

https://doi.org/10.1016/j.biortech.2024.131252
Received 4 May 2024; Received in revised form 6 August 2024; Accepted 7 August 2024
Available online 8 August 2024

emissions (Hosseini et al., 2013). Livestock manure, particularly from intensive industries, contains high levels of organic matter, nutrients, and emerging contaminants, threatening both health and the environment if improperly managed (Zhou et al., 2021). Additionally, crop, fruit, and vegetable residues exacerbate waste management challenges (Selvaggi and Valenti, 2021). Addressing the treatment of these waste types is crucial, especially in municipalities with inadequate waste management, to prevent uncontrolled decay, disease spread, and pollution (Chatterjee and Mazumder, 2020). AD often generates more energy than it needs, making it an energy-positive process and highlighting its growing (El Gnaoui et al., 2022). Recovering and recycling organic wastes add nutrients to the soil, making AD essential for a circular economy (Borrello et al., 2016). AD addresses waste, energy, and nutrient recycling in a sustainable and circular manner by closing the loops on previously linear processes. To achieve circular economy goals, biogas plants must meet several requirements. AD not only preserves the environment and generates energy but also produces biogas, a viable alternative fuel source (Habchi et al., 2022). Consequently, AD reduces greenhouse gas emissions while treating and reducing the volume of waste (Silva et al., 2021). Despite the variability in waste composition (e.g., livestock manure, crop, fruit and vegetable residues), these wastes commonly contain readily biodegradable organic matter (about 75 %) and high moisture content (around 80 %) making them suitable for biological treatment and emphasizing AD as an efficient technology (Alvarado-Lassman et al., 2008). Achieving circular economy goals and establishing sustainable recycling of digestate require closing the loop in the AD process, which entails suitable treatment of both digestate fractions, the DSF and the DLF. The DSF is often used as a fertilizer or soil amendment without separating it into liquid and solid fractions, enriching the soil with macro-nutrients such as nitrogen, potassium and phosphorus. To enhance organic matter and nutrients content of digestate, AD can be conducted with a higher solids content (HSAD) (Costanzo et al., 2021). However, the feasibility of land application depends on economic factors and digestate composition, which may not always be suitable (Pappalardo et al., 2018). In such case, an alternative solution for DSF utilisation must be considered, such as combining AD with gasification (Antoniou et al., 2019), hydrothermal carbonisation (HTC) (Sharma et al., 2020), combustion (Kratzeisen et al., 2010), or pyrolysis (Monlau et al., 2016). The DLF has been used as a crop fertiliser due to its nutrient content, addressing environmental implications related to soil and water resources. Factors in DLF application include land capacity, storage, transportation, and application methods (Khoshnevisan et al., 2021). Technologies like membrane filtration, ammonia stripping, and struvite precipitation optimize DLF reuse, decreasing volume and boosting nutrient concentrations. Constructed wetlands (CWs) are sustainable technologies that reduce complex organic and inorganic substances in DLF, minimising environmental impact (Mancuso et al., 2024). CW vegetation can be harvested and converted into valuable compounds, promoting clean production and circular economy principles (Mancuso et al., 2023; Nan et al., 2023). DSF primarily undergoes thermo-chemical conversion processes (gasification, HTC, and pyrolysis), while DLF is mainly subjected to physico-chemical and biological processes (membrane filtration, stripping method, struvite precipitation, phytoremediation, and microalgae/duckweed cultivation). To the authors' knowledge, not all the above-mentioned treatment methods have been thoroughly explored or comprehensively investigated in previous review studies (Cesaro, 2021; Costanzo et al., 2021; Kapoor et al., 2020; Wang et al., 2023). This study investigates these technologies for treating and valorising DSF and DLF in agriculture within the circular and green economy framework. With this purpose, the paper aims to provide an up-to-date systematic literature review of methods commonly used for digestate treatment and valorisation, conducting a critical analysis of the associated challenges and opportunities. Additionally, it describes the application of LCA and TEA for IDM. Due to the multidimensional nature of digestate treatment and the recovery of valuable by-products from its solid and liquid fractions, these topics have not been thoroughly addressed in the majority of studies found in the literature. The novelty of this study lies in demonstrating how to treat and valorise digestate using suitable methods and applying LCA and TEA tailored to IDM.

2. Methodology

To thoroughly analyse the topic, the authors initially selected a set of keywords representative of relevant research areas. These keywords were carefully chosen to cover a wide range of practices and technologies for both DSF and DLF treatment and valorisation, as well as environmental and economic aspects related to IDM, specifically LCA and TEA (see supplementary material). The specific technologies (e.g., "gasification, HTC", "pyrolysis", "membrane filtration", "ammonia stripping", "struvite precipitation", "constructed wetlands", "microalgae and duckweed cultivation"), and the two indicators (e.g., "LCA" and "TEA") were combined with keywords related to the AD process (e.g., "liquid and solid fraction", "anaerobic digestion", "digestate", etc). The selected keywords were used to query two databases, Scopus and Web of Science (WoS), employing the specified search strings within the article title, abstract, and keywords domains (see supplementary material). This approach ensured the review's scientific rigor, as these databases are widely recognized for their comprehensive coverage of peer-reviewed journals. The search results from both databases were merged, maximising the identification of relevant contributions and ensuring a rigorous selection of papers for the review. The inclusion and exclusion criteria for the review were as follows: only peer-reviewed articles published in English between 2013 and 2023 were considered. The review was limited to review and research articles, excluding notes, short communications, book chapters, and conference proceedings. Overlaps between the two databases were resolved to avoid double-counting. A preliminary abstract-level screening identified articles relevant to the review's objectives based on their assessment methodologies. Articles meeting these criteria were further processed, with full texts acquired and thoroughly reviewed. This led to the selection of definitive studies, which were critically discussed and included in the review. References in the selected papers were also scanned to identify any additional suitable papers. Fig. 1 provides a schematic flow diagram outlining the process of identification, screening, eligibility assessment, and inclusion of papers, detailing the number of papers included and/or excluded at each stage of the review process. The authors selected 72 studies: 5 on AD with gasification, 6 on AD with, 8 on AD with pyrolysis; 3 on membrane filtration, 4 on ammonia stripping, 16 on struvite precipitation, 11 on CWs, and 5 on microalgae and duckweed; and 8 on LCA and 6 on TEA. The final selection included 19 studies on DSF, 39 on DLF, and 14 on IDM, ensuring that the review sample aligns with the objectives and provides a comprehensive overview of DSF and DLF treatment, agricultural valorisation, and management.

Building upon this selection, the review included 3 sections: Section 3.1 provides a comprehensive analysis of DSF practices and technologies, examining methodologies, findings, and limitations of various treatment methods. It evaluates the efficacy and feasibility of different valorisation processes for resource recovery and environmental sustainability; Section 3.2 delves into DLF practices and nutrient recovery methods, scrutinising the effectiveness of different treatment technologies in recovering valuable nutrients while minimising environmental impact. Section 3.3 critically synthesizes studies on LCA and TEA for IDM, examining methodological approaches, assumptions, boundary conditions, and key indicators used to assess the environmental and economic performance of IDM systems. For a comprehensive understanding of the selection methodology and rationale behind the inclusion of studies in both qualitative and quantitative synthesis, the authors developed a detailed outline of the identification, screening, and eligibility criteria used to select relevant studies. This outline specifies the inclusion and exclusion criteria applied (e.g., domain, time frame, article type, etc.) for each technology (DSF, DLF, IDM). It also provides

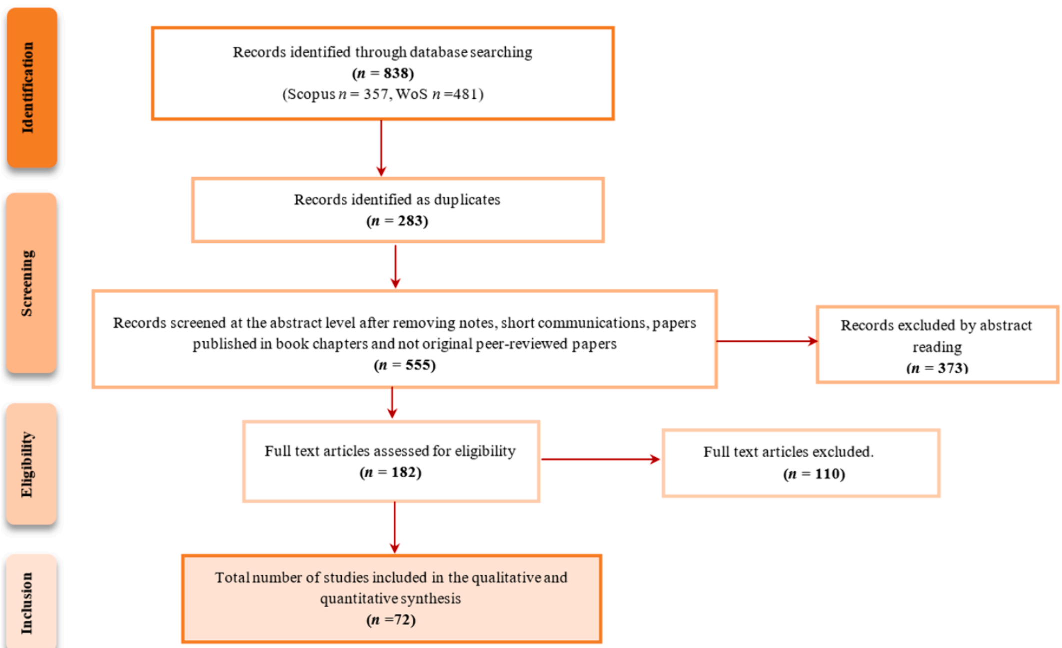


Fig. 1. Flowchart of the literature review performed in this paper.

the numbers of studies initially identified, screened, and ultimately included in the review (see supplementary materials). Fig. 2 shows the significant increase in the number of peer-reviewed publications indexed by Scopus and WoS databases on DSF, DLF, LCA and TEA. Specifically, the number of articles of interest for this review doubled in 2020 compared to 2014, with a continued slight increase observed from 2020 to 2023. This trend indicates an increasing focus on waste management and sustainable practices, highlighting the pivotal role that digestate treatment and valorisation play in addressing environmental challenges and promoting resource efficiency.

3. Solid and liquid phases separation

During the processing of livestock manure, crop residues, and food waste, solid–liquid separation typically occurs in the pre-treatment phase. This involves fractionating the digestate after AD, a cost-effective method that enables further treatment of the two resulting fractions. DLF serves as a potential source of nutrients for e.g., microalgae and duckweed cultivation or for extracting struvite and ammonium phosphate. In contrast, DSF can produce carbon products such as biochar, bio-oil, and ethanol (Sfetsas et al., 2022). Separating digestate into DSF and DLF simplifies its management, including storage, transformation, and final use. During separation, DLF typically accounts for approximately 80 % of the total volume compared to DSF (Orduña-Gaytán et al., 2022). Physical methods, mainly including gravity-driven sedimentation, are primarily used for this separation. Coagulants can enhance settling performance, but their high cost and ability to alter contaminant concentrations limit their use. Mechanical separation methods include sieving, pressure filtration, and centrifugal separation.

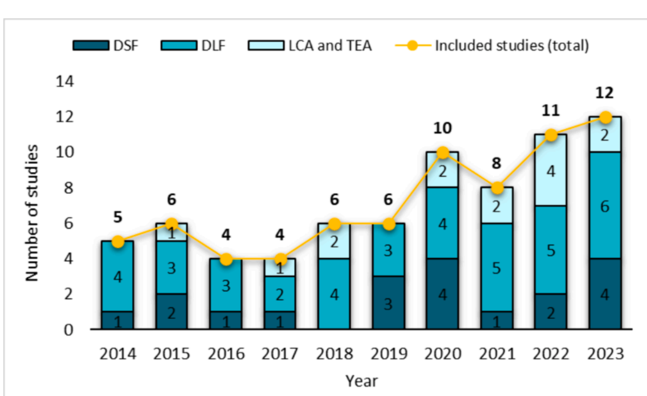


Fig. 2. Increase in the number of peer-reviewed publications selected from the databases of Scopus and WoS from 2014 to 2023 for DSF, DLF and IDM (LCA and TEA).

3.1. Solid phase practices and technologies

Organic materials from municipal, industrial, and agricultural waste can be used as feedstock for solid-state AD. Solid waste composition and characteristics greatly impact the performance of solid-state AD, including start-up time, retention time, biogas generation, and the conversion ratio of total and volatile solids (TS and VS) (Li et al., 2011). Managing municipal and industrial organic solid waste has become a critical environmental issue (Zabaniotou and Kamaterou, 2019). Current management strategies include incineration, composting, and landfilling, with incineration being the most prevalent for hazardous organic wastes. Fast pyrolysis, an eco-friendly and economically effective alternative, plays a significant role in the petrochemical and biomass valorisation industries. Traditionally, DSF has been used as a soil amendment to enhance soil quality. However, the increasing volume of DSF raises concerns regarding transportation costs, GHG emissions during storage, and high nitrogen content, limiting its application to land use only. This situation highlights the need for alternative valorisation methods to reduce environmental impacts and improve the economic viability of AD plants (Monlau et al., 2015b). One promising alternative is utilising solid digestate for energy production or converting it into biochar. Biochar, produced through the thermochemical transformation of biomass in oxygen-deprived conditions, offers several environmental benefits. It improves soil fertility, helps combat climate change, reduces nutrient runoff, aids in waste management, and can be used as an energy resource. Excessive application of DSF has led to problems such as land saturation, excessive nitrogen levels, extensive transportation distances, presence of harmful microorganisms, and increased greenhouse gas emissions. Therefore, effective DSF management is crucial. Various digestate management strategies have emerged, guided by environmental life cycle assessments. AD typically achieves energy conversion efficiencies ranging from 33 to 50 % (Monlau et al., 2015b). Digestate, retaining more than half its energy, emerges as a viable resource for biofuel production. Comprising a liquid portion (as residue after DSF and DLF separation) rich in nitrogen and a solid part abundant in lignin, it lends itself to thermochemical conversion processes, yielding heat, gas, and bio-oil. By-products like charcoal and ash find utility as soil fertilisers. The thermochemical conversion of DSF is outlined in Fig. 3 and will be examined in detail in the subsequent sections.

3.1.1. Anaerobic digestion integration with gasification

Gasification is a thermal process that converts carbonaceous material into gaseous substances using heat and a gasifying agent. This process typically occurs between 600 °C and 1000 °C, employing agents such as steam, air, CO_2, and H_2. The resulting gas is known as producer gas or syngas, depending on its composition. Factors such as raw material type, reaction temperature, gasification agent, and reactor design influence the composition and quantity of the gas produced. At lower temperatures, the gas primarily consists of CO_2, CO, H_2, CH_4, tar, N_2, H_2S, and other hydrocarbons (Peng et al., 2024). Gasification converts carbon-rich materials like coal, biomass, petroleum residue, or organic waste into synthesis gas (syngas), mainly composed of hydrogen (H_2) and carbon monoxide (CO). By-products of this process, influenced by the substrate and method used, can include tars and oils, ash, char, sulphur compounds, CO_2, water, and more. Gasification can also be applied to dried DSF, producing gaseous products (Chen et al., 2017). It is a promising method for handling large volumes of AD digestate, resulting in low-tar gaseous products and bio-fertilisers. Key factors affecting the quality of the digestate gasification process include Gas yield (Nm^3/kg) and Cold Gas Efficiency (CGE) (%). CGE (Eq. (1) is calculated by comparing the output power of the gas to the total thermal power inputs:

$$Coldgasefficiency = \frac{LHV_{gas} * gasyield}{LHV_{biomass} + \frac{P_{el}+P_t}{m}} \quad (1)$$

The term in the denominator, $\frac{P_{el}+P_t}{m}$, represents the ratio of the total power, including electrical and thermal inputs required to heat the reactor and produce steam, to the rate of biomass feeding. LHV denotes the low heating value. In literature only few research studies have combined AD and gasification to evaluate digestate gasification performance. This review includes 5 papers that met eligibility criteria. Table 1 summarises the main parameters and results from the DSF gasification process, including Gas yield, CGE, operating temperature, and gas composition As reported in Table 1, the gasification temperature ranged from 600 °C to 1000 °C, with the lowest value of 700 °C (Ermolaev et al., 2023). The highest gas yield of 2.2 Nm^3/kg was obtained using crop residue as the DSF for gasification process (Timofeeva et al., 2023), while the lowest one of 1.4 Nm^3/kg was found using Organic Fraction of Municipal Solid Waste (OFMSW) as a feedstock for gasification process (Freda et al., 2019). Notably, using the same feedstock, such as corn silage, resulted in different gas yields: 1.9 Nm^3/kg with CGE of 67 % at 800 °C (Chen et al., 2017), and 1.6 Nm^3/kg with CGE of 74 % at 745 °C (Baláš et al., 2022).

3.1.2. Anaerobic digestion integration hydrothermal carbonisation

HTC has the potential to enrich DSF by producing solid hydrochar and process water containing a high organic carbon content. There is a growing demand for exploring alternative markets for DSF and land reuse, focusing on technologies that add value to the entire digestion process (Wilk et al., 2019). Among these technologies, HTC is promising for enhancing DSF, although not all feedstocks exhibit energy densification. For example, sewage sludge typically yields bio-coal with low CV, whereas feedstocks with higher lignin content yield bio-coal with higher CV. Combining DSF with lignocellulosic biomass feedstocks can increase the CV of hydrochar and aid in treating resistant biomass for biogas production. HTC is known for producing solid minerals high in carbon content. The HTC process involves using wet feedstock or dry feedstock treated with water under critical conditions, with temperatures ranging from 180 to 250 °C and pressures from 2 to 6 MPa (Habchi et al., 2024). HTC generates liquid, hydrochar, and a small quantity of carbon-deficient gaseous molecules without emitting any GHGs. The aqueous phase used in HTC can be recycled (Kumar et al., 2020). Despite the growing interest in alternative technologies enhance digestate, research on HVT technology remains limited. This review selected 6 papers meeting eligibility criteria. Table 2 presents the main operational parameters of HTC for different types of DSF and the corresponding results in terms of High Heating Value (HHV). The highest HHV, 23.2 MJ/kg, was observed using agriculture residue digestate (cow dung) as a feedstock at 200 °C with a residence time of 270 min, while the lowest HHV values, 9.2 and 5.4 MJ/kg, were obtained using municipal solid waste as a feedstock (Pawlak-Kruczek et al., 2020). In conclusion, HTC improves DSF treatment and increases biogas yields through the AD of process fluids. However, the use of hydrochar derived from DSF as a solid fuel is discouraged due to concerns regarding its ash composition and the potential for slagging and fouling during combustion (Parmar and Ross, 2019).

3.1.3. Anaerobic digestion integration with pyrolysis

DSF pyrolysis has garnered significant attention due to its potential benefits. The products of DSF pyrolysis include biochar (often referred to

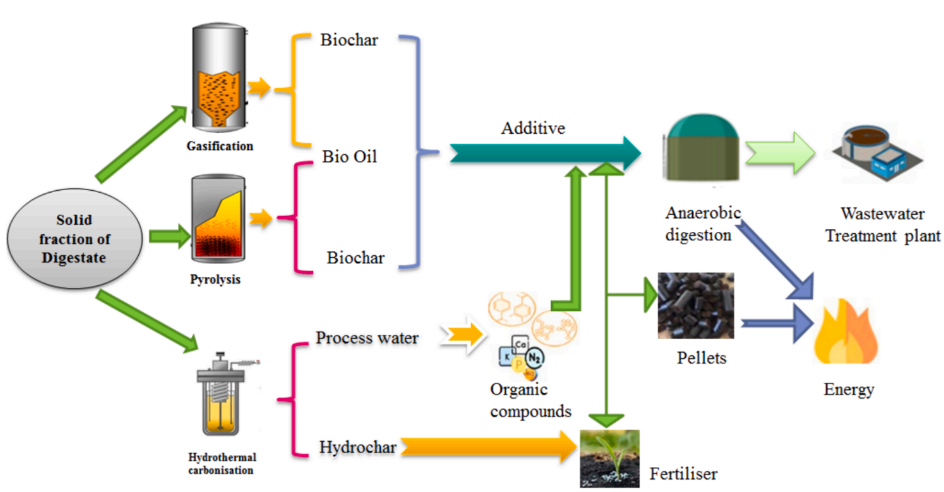


Fig. 3. Thermochemical conversion of solid fraction of digestate.

Table 1
Performance of DSF gasification.

Reference	Year	Article type	Digestate origin	Gasification temperature	Gas composition (vol %, dry basis)					Gas yield (Nm^3/kg)	CGE (%)
					H_2	CO	CO_2	CH_4	C_2H_6		
(Chen et al., 2017)	2017	Article	Corn silage	800 °C	21.5	19.9	43.5	11.2	< 3.78	1.9	67
(Freda et al., 2019)	2019	Article	OFMSW	820 °C	9.3	11.1	13.8	2.9	0.6	1.4	47
(Timofeeva et al., 2023)	2023	Article	Cow manure	1000 °C	54.2	34.5	–	–	–	1.8	–
(Timofeeva et al., 2023)	2023	Article	Agro-waste	1000 °C	54.6	40.4	–	–	–	1.6	–
(Timofeeva et al., 2023)	2023	Article	Crop residue	1000 °C	55.0	33.0	–	–	–	2.2	–
(Baláš et al., 2022)	2022	Article	Cattle manure and corn silage	745 °C	9.5	17.3	14.2	2.0	<0.1	1.6	74
(Ermolaev et al., 2023)	2023	Article	Cereals, bran, sunflower meal and rapeseed cake	700 °C	26.9	7.7	14.7	0.1	–	1.8	–

CGE: Cold Gas Efficiency (%), OFMSW: Organic fraction municipal solid waste.

Table 2
Operational parameters and main results for HTC of DSF.

Reference	Year	Article type	Digestate origin	Process conditions		Ultimate analysis (%)					Proximate analysis (%)				HHV (MJ/kg)
				T (°C)	RT (min)	C	H	N	S	O	M	Ash	VM	FC	
(Yan et al., 2023)	2023	Article	Food waste	260	60	35.3	4.2	1.6	0.3	6.3	1.1	52.4	41.4	5.0	15.4
(Aragon-Briceño et al., 2022)	2022	Article	MSW	200	120	20.7	2.4	1.2	–	11.9	–	–	–	–	9.2
(Aragón-Briceño et al., 2020)	2020	Article	Sewage digestate	250	30	34.4	4.4	2.8	1.2	8.7	1.9	48.5	41.2	8.4	16.5
(Parmar and Ross, 2019)	2019	Article	Silage and manure	150	60	44.2	4.8	3.1	0.0	27.5	–	20.4	62.2	17.5	17.9
(Pawlak-Kruczek et al., 2020)	2020	Article	Cow dung	200	270	55.1	5.8	3.6	0.3	–	51.3	9.7	53.9	–	23.2
(Pawlak-Kruczek et al., 2020)	2020	Article	MSW	200	270	19.3	1.9	0.6	0.3	–	26.8	53.7	26.2	–	5.4
(Belete et al., 2021)	2021	Article	Manure	240	–	41.0	4.0	2.6	0.7	8.2	–	43.5	–	–	19.3
(Yan et al., 2023)	2023	Article	Maize silage	220	–	56.4	5.6	1.9	0.1	31.4	–	4.7	70.3	25.0	22.9

MSW: Municipal solid waste; T: temperature; RT: Residence time; M: Moisture; VM: Volatile matter; FC: Fixed carbon; HHV: High heating value.

as pyrochar), bio-oil, aqueous pyrolysis liquid (APL), and syngas, with various utilisation pathways explored over the past decade (Tayibi et al., 2021). Biochar, especially when combined with untreated DSF, is a promising soil amendment (Pecchi and Baratieri, 2019). Additionally, recirculating biochar within the digestor (in-situ) has shown positive effects, including stabilising the AD process, enhancing microbial

Table 3
DSF Pyrolysis considering different feedstocks and operating conditions.

Reference	Year	Article Type	AD reactor scale	Biogas Plant Location	AD feedstock	Pyrolysis process
(Li et al., 2014)	2014	Article	Lab-scale	China	chicken manure and corn stover	• pyrolysis temperature:800°C • heating rate:50°C/min • residence time:3 h
(Monlau et al., 2015b)	2015	Review	/	/	/	/
(Monlau et al., 2015a)	2015	Article	Full-scale	Italy	chicken manure, groats, olive oil cake and triticale	• pyrolysis at 400°C, 500°C and 600°C • heating rate:20°C/min • residence time:10 min
(Neumann et al., 2016)	2016	Article	Full-scale	Germany	animal and plant waste	• pyrolysis temperature:400 –500°C • heating rate:1°C/s • residence time:5 min • post reforming temperature:500 –800°C
(Pecchi and Baratieri, 2019)	2019	Review	/	/	/	/
(Ting et al., 2020)	2020	Article	Lab-scale	China	corn stover	• alkaline pyrolysis with NaOH • pyrolysis temperature:300°C • heating rate:10°C/min
(Miliotti et al., 2020)	2020	Article	Full-scale	Italy	herbaceous biomass and agro-industrial residues	• pyrolysis temperature: 5 00°C • heating rate: reaching 500 °C in nearly 70 min • residence time:1 h
(Wystalska and Kwarciak-Kozłowska, 2023)	2023	Article	Full-scale	Poland	animal manure, straw, agri-food waste	• pyrolysis temperature:400 –900°C • heating rate: reaching max. temperature in 120 –180 min • residence time:1 h

growth, facilitating direct interspecies electron transfer (DIET), increasing methane yield, and absorbing undesired compounds such as carbon dioxide, hydrogen sulphide, ammonia, and siloxanes (Cavali et al., 2022). Bio-oil and syngas can be valorised to increase energy recovery from the biomass subjected to AD (Pecchi and Baratieri, 2019). However, promising valorisation pathways for APL are still under investigation (Tayibi et al., 2021). Despite AD and pyrolysis being well-established processes, their integration is still in the early stage of investigation (Tayibi et al., 2021). This review selected 8 papers meeting eligibility criteria, as summarised in Table 3. Monlau et al. (Monlau et al., 2015b) highlighted early contributions to the valorisation of agricultural DSF, including energy recovery from syngas and bio-oil through thermochemical processes or recirculation into the AD process. Furthermore, early investigations explored the use of pyrochar as a soil amender or a bio-adsorbent for environmental contaminants. Miliotti et al. (Miliotti et al., 2020) conducted lab-scale tests on DSF from the AD of herbaceous biomass and agro-industrial residues subjected to slow pyrolysis. The resulting pyrochar met international standards for biochar, although further investigations are needed to assess its viability as a soil amendment. Monlau et al. (Monlau et al., 2016) compared DSF and the derived pyrochar, finding both to have favourable properties as soil amendments. Moreover, they noted complementary beneficial properties, suggesting the most effective approach might involve using pyrochar in combination with untreated DSF. Pyrochar is enriched in phosphorus and potassium, has a greater water-holding capacity, and a more recalcitrant carbon structure, which can improve soil fertility (and, consequently, its productivity), reduce nutrient leaching and soil erosion, and capture carbon in the soil. Wystalska & Kwarciak-Kozlowska (Wystalska and Kwarciak-Kozłowska, 2023) explored the use of biochar for soil remediation, assessing its potential to sorb heavy metal cations through a methylene blue sorption experiment. Li et al. (Li et al., 2014) reported a first attempt to increase biogas plant energy yield through DSF pyrolysis. They determined the CV of the produced syngas, suggesting that DSF pyrolysis could offer additional energy recovery from biomass. Similarly, Neumann et al. (Neumann et al., 2016) investigated using bio-oil as a biofuel, subjecting DSF to a novel Thermo-Catalytic-Reforming process (TCR®) to obtain a liquid bio-oil with improved fuel properties. Monlau et al. (Monlau et al., 2015a) explored the combined use of syngas and bio-oil to enhance energy recovery from biomass, estimating a 42 % increase in electric output for the studied biogas plant. The energy required to dry the DSF for pyrolysis could be obtained from the heat produced during the AD process. Additionally, DSF can serve as a basis for hydrogen production. In the study by Ting et al. (Ting et al., 2020), DSF was subjected to alkaline pyrolysis with sodium hydroxide to produce hydrogen-rich syngas, with hydroxide suppressing carbon dioxide in the syngas by fixing it in the form of Na_2CO_3. In conclusion, DSF pyrolysis shows significant potential for enhancing the overall efficiency and sustainability of biogas plants, offering multiple pathways for energy recovery and soil improvement. Further research is needed to optimize these processes and fully realize their benefits.

3.2. Liquid phase practices and nutrient recovery methods

3.2.1. Membrane filtration

The utilisation of DLF remains challenging due to its high concentrations of suspended particles, phosphates, and ammonium nitrogen. Pressure membrane technology, including microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), offers a method for purifying DLF. Low-pressure techniques, such as MF and UF, effectively remove turbidity, suspended solids, bacteria and some viruses, colour, and large-molecular organic compounds from wastewater or other waste streams to a level suitable for effluent discharge into the environment. One challenge in using filtration for treating DLF is fouling caused by contaminants accumulating on the membrane's surface or in its pores. This results in decreased permeate flux, deterioration of permeate quality, increased filtering resistance, a shorter membrane life cycle, and even system failure. The accumulation of pollutants depends on flow conditions, membrane material, pore size, and the properties of the effluent being treated (Chuda and Ziemiński, 2023). Membrane filtration technologies are categorised into pressure-driven and non-pressure-driven methods. These technologies include filtration (micro, nano, ultra), and reverse osmosis. Non-pressure membranes can provide both a nutrient-rich medium and nutrient-free fluids when used together. Although manure cannot be directly used as a substrate for these technologies due to its high organic matter content and TS, pre-treatment is necessary. However, manure DLF or the DLF of animal slurries can be employed. Microfiltration and ultrafiltration using ceramic or polymeric membranes can separate phosphorus-rich solids from ammonium-rich liquids. The DLF can then be filtered by nanofiltration or reverse osmosis, resulting in a concentrated ammonium rich media of up to 10 g/L (Khoshnevisan and Bazgir, 2021). The typical processes for DLF processing via membrane filtration are illustrated in Fig. 4.

Table 4 presents the main results obtained for membrane filtration of DLF, including the operational conditions for the type of membranes used. Among literature on this topic, only 3 research articles met the eligibility criteria for this review.

3.2.2. Ammonia stripping

On one hand, numerous studies have focused on extracting, recovering, and reusing nutrients from DLF, on the other hand, only a few focused on the other organic compounds (Sheets et al., 2015). Only 4 research articles met the eligibility criteria for this section. Ammonia stripping proves to be a highly effective physicochemical technique for eliminating and recovering nitrogen. This method involves converting liquid samples containing NH_3 into gas upon contact with air or steam containing minimal or no NH_3. Key process parameters include pH, temperature, air/liquid ratio, and pressure. Among these factors, increased pH levels have the most significant impact on ammonia stripping, followed by air flow rate and temperature. In the study carried out by Guštin and Marinšek-Logar (Guštin and Marinšek-Logar, 2011), continuous ammonia stripping was conducted on DLF derived from pig slurry post-centrifugation, resulting in removal rates of 93 % for ammonia and 88 % for total nitrogen. Employing AD treating food waste alongside semi-continuous ammonia stripping columns, using biogas as the medium, led to a 48 % reduction in NH_4^+ content at temperatures exceeding 70 °C and a pH level of 10 (Serna-Maza et al., 2015). Bousek et al. (Bousek et al., 2016) investigated the elimination of ammonia from the liquid component of digestate post-sieving at 1 mm. The mixture comprised pig manure, maize silage, sugar, and forage. The introduction of oxygen in the air stripping process resulted in an 86 % decrease in NH_4^+ content within a 4-h period. Flue gas, which achieved a 45 % reduction in NH_4^+ after 4 h, emerged as a viable alternative to biogas, which achieved only a 16 % reduction. According to Bousek et al. (Bousek et al., 2016), the efficiency of stripping is inversely related to the levels of CO_2 in the stripping gas. In the study conducted by Li et al. (Li et al., 2016), it was observed that the addition of 12 g/L of $Ca(OH)_2$ at pH levels greater than 7 effectively removed 89.9 % of NH_4^+ from the DLF of pig manure. Additionally, the introduction of $Ca(OH)_2$ resulted in the precipitation of 97 % of soluble phosphorus. Table 4 presents the main results obtained for ammonia stripping of DLF, including the operational conditions for this method.

3.2.3. Struvite precipitation

DLF can contain high levels of NH_4^+ and PO_4^{3-}, making struvite precipitation a viable method for nutrient recovery, effectively capturing both nitrogen and phosphorus simultaneously (Orner et al., 2021). The crystalline struvite resulting from the struvite precipitation process ($MgNH_4PO_4{\cdot}6H_2O$) is a solid with high nutrient density, easy transportability, and can be used as slow-release fertiliser without additional processing (Escalante et al., 2018). It offers the advantage of containing

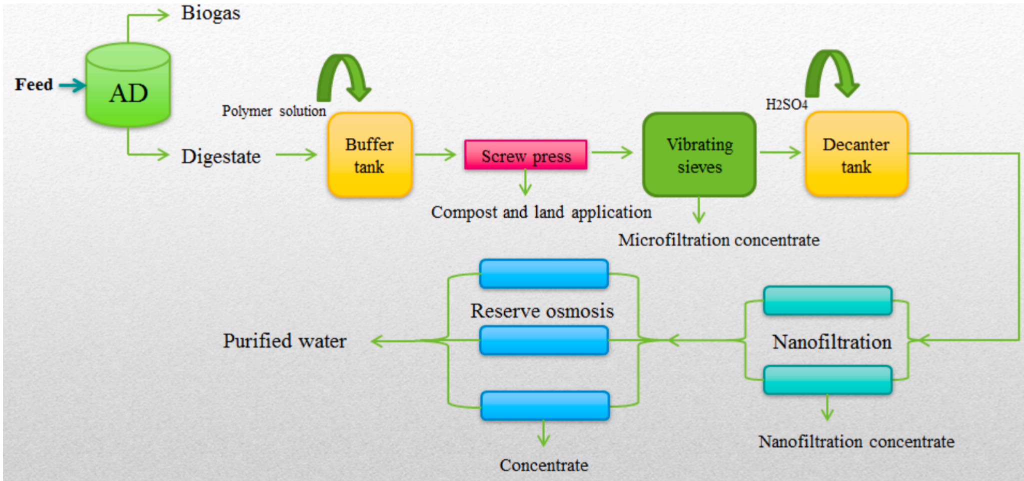


Fig. 4. Typical processes for DLF processing via membrane filtration.

Table 4
The properties and main results for DLF using membrane filtration and ammonia stripping processes.

Reference	Year	Article Type	Source of DLF	Operational conditions	Main results
Membrane filtration process					
(Zielińska et al., 2022)	2022	Article	Agricultural biogas plant	Membrane installation: batch mode. Pore size of MF: 0.45 μmthe cut-off of UF: 150 kDathe cut-off of fine-UF: 5 kDa	Production of permeate for the cultivation of Chlorella vulgaris.
(Chuda and Ziemiński, 2023)	2023	Article	Sugar beet pulp digestate	cut-off of fiber membranes: 150 kDa pore diameter: 0.04 μm	Permeate flux: 22.33 $dm^3/m^2/h$ membrane resistance: $5.32 \cdot 10^{11}$ m^{-1}
(Khoshnevisan and Bazgir, 2021)	2021	Article	Livestock manure	The membrane used: ceramic or polymeric membranes	energy demand of membrane filtration: 4–6 kWh/m^3 operation cost: 4–13 €/m^3
Ammonia stripping processes					
(Sheets et al., 2015)	2015	Article	Pig slurry	Continuous ammonia stripping process	Ammonia stripping/absorption has successfully produced nitrogen and phosphate fertilizers from the liquid fraction at pilot- and full-scale. Ammonia stripping/absorption has significant energy demands; thus, the success of this technologies will be dependent on the scale of operation and cost of energy.
(Serna-Maza et al., 2015)	2015	Article	Fresh source-segregated domestic food waste digestate	Stripping agent: biogas Batch experiments at 35, 55 and 70 °CGas flow rates: 0.125 and 0.250 L_{biogas} / min $L_{digestate}$	Biogas stripping reduced ammonia concentrations. Ammonia stripping was most effective at 70 °C and pH 10
(Bousek et al., 2016)	2016	Article	Pig manure and maize silage	Solution for stripping: Ammonia bicarbonate (99.0 % pure) Volume of stripper: 1 l round bottom flask (0.5 l volume used)	Experiments with different stripping gases demonstrated a considerable spike in loss of stripping performance at increased CO_2 concentrations.
(Li et al., 2016)	2016	Article	Pig breeding farm	Solution for stripping: Calcium hydroxide ($Ca(OH)_2$) (Solubility: 1.77 g/L, 15 °C)	Ammonia stripping and vacuum evaporation can be utilized as alternate nutrient recovery processes, which should be chosen based on the potential varied applications of liquid digestate.

nutrients with low water solubility, ensuring their gradual release into the soil (Kovačić et al., 2022). Struvite precipitation occurs when the concentration of NH_4^+, Mg^{2+}, and PO_4^3 ions exceeds the struvite solubility product under alkaline conditions (Martín-Hernández et al., 2018). However, the formation of struvite crystals requires the addition of $MgCl_2$ (Eq. (2).

$$Mg^{2+} + NH_4^+ + HnPO_4^{3-n} + 6H_2O \leftrightarrow MgNH_4PO_4{\cdot}6H_2O + nH^+ \quad (2)$$

For effective struvite precipitation, all three components (PO_4^3, Mg^{2+}, NH_4^+) must be present simultaneously in a stoichiometric molecular ratio of 1:1:1, with a pH level above 7.5 (Estevez et al., 2014a). However, some studies have shown a non-linear relationship between pH and struvite precipitation, with struvite production peaking at pH 9.5. Additionally, the pH was observed to be influenced by the origin of the DLF (Persson and Rueda-Ayala, 2022). AD with a higher solids content (HSAD) can enhance the nutrient content of digestate (Di Costanzo et al., 2023). Moreover, higher $Mg{:}PO_4$ ratios have a positive impact on nutrient recovery, with optimal results achieved at ratios up to 4:1 (Macura et al., 2019). The presence of additional ions such as calcium or carbonates may result in the formation of amorphous precipitates, inhibiting the struvite formation process. Impurities like suspended solids can also interfere with struvite formation (Estevez et al., 2014a). In the case of DLF, potassium can lead to the formation of potassium struvite or K-Struvite (Eq. 3), in which the ammonia cation is substituted by the potassium cation:

$$K^+ + Mg^{2+} + HnPO_4^{3\text{-}n} + 6H_2O \leftrightarrow KMgPO_4{\cdot}6H_2O + nH^+ \quad (3)$$

However, since the formation of struvite is preferred over K-Struvite, it is estimated that only 15 % of the potassium in DLF participates in the reaction to produce K-Struvite (Martín-Hernández et al., 2018). To achieve simultaneous recovery of ammonia and phosphates from DLF through struvite precipitation, significant quantities of magnesium salt and phosphate must be added (Yang et al., 2022). The main limiting factor for the implementation of this method is the cost of magnesium salts and alkalis added for pH control, making the process too expensive to be economically attractive (Rizzioli et al., 2023). Another challenge arises from operational difficulties associated with magnesium oxide, as its lower solubility requires either prolonged contact time or an additional solubilisation step (Moyo et al., 2023). To address these challenges, low-cost reagents have been proposed in the literature. For example, Siciliano and De Rosa (Siciliano and De Rosa, 2014) used seawater bittern (a by-product of marine salt manufacturing) and bone meal (a by-product of thermal meat waste treatment) as economical sources of magnesium and phosphorus, respectively. Similarly, Melgaço et al. (Melgaço et al., 2021) employed limestone powder and seawater as calcium and magnesium supplements, respectively. Recent studies have proposed the combination of struvite precipitation and ammonia stripping as two simultaneous processes to promote nutrients recovery from DLF (Trotta et al., 2023). Table 5 presents the key findings of the 16 selected research articles that met the eligibility criteria for this review.

3.2.4. Constructed wetlands

CWs are prominent natural treatment methods for DLF due to their ease of operation, cost-effectiveness, high pollutant removal efficiency, and biomass production for bioenergy (Monfet et al., 2018). However, their long-term effectiveness in treating DLF with high organic and suspended solid loads is uncertain due to potential substrate clogging and the negative impact of high NH_4^+ levels and salinity on plant survival (Healy et al., 2007). To address these issues, some studies have diluted DLF with water (from 1:2 to 1:20) or used sedimentation to reduce

Table 5
Main findings on the application of struvite process, constructed wetlands, and microalgae and duckweed cultivation to DLF.

Reference	Year	Article Type	Experimental scale	Location	Aim
Struvite process					
(Estevez et al., 2014a)	2014	Article	Lab-scale	Norway	Investigation of NH_4^+ and PO_4^{3-} fixation of digestate with different substrates (e.g., lignocellulosic biomass, cattle manure and industrial fish waste) by struvite precipitation.
(Estevez et al., 2014b)	2014	Article	Lab-scale	Norway	Investigation of NH_4^+ and PO_4^{3-} from DLF by using struvite precipitation.
(Siciliano and De Rosa, 2014)	2014	Article	Lab-scale	Italy	Application of low-cost reagents for digestate nutrients recovery using struvite precipitation.
(Vaneeckhaute et al., 2017)	2017	Review	General assessment	–	Classification of recycled products in environmental and fertiliser legislations.
(Escalante et al., 2018)	2018	Article	Full-scale	Colombia	Evaluation of struvite precipitation potential for nutrients recovery.
(Martín-Hernández et al., 2018)	2018	Article	General assessment	–	Systematic design framework to optimise nutrients recovery from DLF.
(Macura et al., 2019)	2019	Review	General assessment	–	Review of 30 studies for pH and Mg:PO_4 ratio optimisation in the struvite process.
(Orner et al., 2021)	2021	Article	General assessment	California	Evaluation of nutrients recovery from three different end products.
(Petrovič et al., 2021)	2021	Article	Lab-scale	Slovenia	Assessment of nutrients recovery from DLF using struvite precipitation.
(Melgaço et al., 2021)	2021	Article	Lab-scale	Belgium	Evaluation of two local low-cost ion sources for struvite precipitation from DLF.
(Yang et al., 2022)	2022	Review	General assessment	–	Assessment of challenges and prospects for nutrients recovery from DLF.
(Kovačić et al., 2022)	2022	Review	General assessment	–	Overview of the current state of DLF management regulations and practices.
(Persson and Rueda-Ayala, 2022)	2022	Review	General assessment	–	Assessment of efficacy of DLF by-products when used as fertilisers.
(Rizzioli et al., 2023)	2023	Review	General assessment	–	Study of different technologies for nutrients recovery from DLF.
(Trotta et al., 2023)	2023	Article	Lab-scale	Italy	Combination of struvite precipitation and ammonia stripping processes for nutrients recovery.
(Moyo et al., 2023)	2023	Article	Lab-scale	Zimbabwe	Evaluation of nutrients recovery from DLF using struvite precipitation.
Constructed wetlands					
(Monfet et al., 2018)	2018	Review	General assessment	–	Assessment of DLF processing technologies for nutrient recovery and removal from digestate. CW type: FWS, SSHF and SSVF CWs
(Zhou et al., 2020)	2020	Article	Full-scale	China	Investigation of CWs typology, water flow patterns and filling substrates on pollutant removal performances from DLF. CW type: FWS, SSHF and SSVF CWs
(Piccoli et al., 2021)	2021	Article	Lab-scale	Italy	Test of filters filled with recovery materials for DLF pre-treatment. CW type: Filters without vegetation
(Brienza et al., 2023)	2023	Article	Full-scale	Belgium	Treatment of DLF using ammonia stripping process coupled with aerated CWs. CW type: SSHF and SSVF CWs
(Donoso et al., 2019)	2019	Article	Full-scale	Belgium	Investigation on the influence of artificial aeration in CWs performances treating DLF. CW type: SSHF and SSVF CWs
(Guo et al., 2016)	2016	Article	Lab-scale	China	Study of aeration and effluent recirculation in CWs treating DLF. CW type: SSHF CWs
(Wu et al., 2017)	2017	Article	Lab-scale	China	Investigation of aeration and effluent recirculation in CWs coupled to microbial fuel cell for nitrogen removal from DLF. CW type: VF CWs
Microalgae and duckweed cultivation					
(Guilayn et al., 2020)	2020	Review	General assessment	–	Evaluation of technical feasibility for AD plants to create value-added products from digestate. CW type: Not applicable
(Sfetsas et al., 2022)	2022	Review	General assessment	–	Definition of methods for the treatment of DLF. CW type: General considerations on CWs
(Eze et al., 2018)	2018	Article	Lab-scale	México	Development of a kinetic model of microalgae cultivation for DLF treatment. CW type: Not applicable
(Uggetti et al., 2014)	2014	Article	Lab-scale	France	Assessment of microalgal growth by utilising DLF as substrate. CW type: Not applicable
(Gonzalez-Flo et al., 2023)	2023	Article	Demo-scale	Spain	Assessment of CWs and microalgae in treating digestate. CW type: VF CW

suspended solids and NH_4^+ concentration before CW treatment (Zhou et al., 2020). Pre-treatment of DLF is recommended as a more sustainable solution compared to dilution (Piccoli et al., 2021). Furthermore, concerns have been raised about CWs treating DLF from piggery manure, which may contain fractions of recalcitrant or non-biodegradable organic matter, as reported by Brienza et al. (Brienza et al., 2023). The observed BOD:COD ratios below 0.3 confirmed that a relatively high COD level might indicate an insufficient presence of biodegradable organic matter, potentially resulting in incomplete denitrification (Donoso et al., 2019). Nevertheless, CWs, especially under aerated conditions, have demonstrated the ability to remove high percentages of biodegradable matter, achieving BOD_5 and COD removal rates of 96 and 90 %, respectively. In CWs, dissolved oxygen (DO) plays a crucial role in pollutant remediation. While CW vegetation can contribute oxygen to support microbial biodegradation, fluctuations in plant vitality may limit their effectiveness. To address oxygen limitation, artificial aeration has become a widely adopted strategy in CWs, with intermittent aeration being preferred to create alternating aerobic-anaerobic conditions, enhancing biodegradation processes (Zhou et al., 2018). Artificial aeration in CWs improved TN removal, reaching 80 % (Brienza et al., 2023). This enhancement was attributed to the influence of DO concentration on microbial diversity and composition, as it stands as a significant factor among the regulating elements (Shirdashtzadeh et al., 2022). Additionally, artificial aeration facilitated the removal of TP by 97 %, promoting processes like chemical precipitation and/or binding to iron in the substrate (Ilyas and Masih, 2018). Furthermore, aerated CWs also significantly reduced TSS, achieving a removal rate of 96 %. Lyu et al. (Lyu et al., 2023) found that aerated CWs with nanobubbles showed 30 % higher removal rates of organic pollutants compared to traditional aerated CW systems. Despite the benefits of artificial aeration, complete denitrification may not always be achieved, as evidenced by increased nitrate concentrations in CW effluents. Recirculating the CW effluent, enriched with nitrate, back to the CW inflow has been shown to enhance denitrification and intensify pollutant removal (Wu et al., 2017). Alternative media such as zeolite (Han et al., 2019), biochar (Feng et al., 2020), alum sludge (Zhao et al., 2018), and biodegradable polymers (Liu et al., 2018) can enhance CW performance, by facilitating pollutant adsorption and biofilm attachment. These materials have shown a noteworthy ability to remove heavy metals and emerging contaminants (Hdidou et al., 2022). Hybrid CW setups, combining two or more CWs in series, can decrease treatment time, volume, and required area while improving treatment performance. Zhou et al. (Zhou et al., 2020)have used a medium-scale CW pilot plant with a sequence of two reed vegetated vertical subsurface flow beds in sequence, followed by a reed vegetated horizontal subsurface flow bed and a rice vegetated surface flow bed, achieving total removal efficiencies of 95, 88, and 72 %, for TN, TP, and COD, respectively. Recently, floating treatment wetlands (FTWs) have emerged as a sustainable eco-technology for DLF treatment (Barco and Borin, 2020), showing reductions of 44.1, 35, 17, and 25 % for TN, NO_3, NH_4^+ and COD. However, TP concentrations were not significantly affected by the FTWs. The effectiveness of FTWs depends on *in-situ* parameters and pollutant concentrations at the inlet. The highest treatment performances were observed during the summer, as FTWs vegetation expanded its root system through the water column, enhancing pollutant absorption and fostering a rich microbial biofilm community. A study reported that among 18 different floating species, two halophytes (*P. palustris* and *E. atherica*) demonstrated the highest potential for treating DLF in FTWs, based on their highest dry matter production and nutrients uptake rates (nitrogen 10–15 g/m^2, phosphorous 1–4 g/m^2) (Pavan et al., 2015). CWs and FTWs plants remove nitrogen and phosphorus by directly incorporating them into plant biomass. Most harvested vegetation in CWs and or FTWs is often disposed of in landfills (Hidalgo et al., 2017), though it can be used to produce valuable compounds such as animal feed, biodiesel, adsorbents, and fertilizers. Biomass can also be processed through thermochemical methods (combustion, pyrolysis, gasification, and activation) or biochemical methods (hydrolysis and extraction) (Kwoczynski and Čmelík, 2021). It was reported that biomass from common reed with a dry matter yield of 13.6 Mg/ha was able to produce 108 mc/Mg FM of biomethane during anaerobic fermentation (Gizińska-Górna et al., 2016). Potential uses of plant biomass are illustrated in Fig. 5. In Table 5 were summarised the key findings of the 11 selected research articles that met the eligibility criteria for this review.

3.2.5. Cultivation of microalgae and duckweed

Microalgae cultivation is a biomass harvesting process that effectively binds and utilise nutrients present in DLF (Guilayn et al., 2020). The harvested microalgae biomass can be used in producing biochemicals, biofuels, animal feed, slow-release fertilisers, and as feedstock for anaerobic digesters (Sfetsas et al., 2022). One cubic meter of DLF can yield approximately 14.6 kg of microalgae biomass, incorporating around 22 kg of CO_2 through photosynthesis (Xia and Murphy, 2016). Microalgae can be categorised, based on their energy sources into photoautotrophic, heterotrophic, and mixotrophic types (Eze et al., 2018). Photoautotrophic microalgae have limited growth rates due to light penetration issues and photoinhibition. Heterotrophic microalgae boost biomass production but are prone to contamination. Mixotrophic microalgae combine the advantages of both, offering high growth rates and reduced biomass loss in the absence of light while minimizing operational costs. Characteristics of DLF, such as turbidity, ammonia and phosphorus content, carbon availability, and bacterial contamination, can inhibit microalgae growth. High suspended solids content can limit light penetration, while high ammonia concentration (>10–500 mg/L) can be toxic to microalgae (Uggetti et al., 2014). Diluting DLF is a common practice to mitigate these issues. Optimal N/P and C/N ratios have been reported to be around 7 and 4–8, respectively. Preventing bacterial contamination is crucial to avoid competition for nutrients. Photobioreactors have been recommended for producing microalgal biomass and treating DLF. For instance, Gonzalez-Flo et al. (Gonzalez-Flo et al., 2023) proposed a microalgae-based treatment plant for energy and nutrient recovery, enabling the reuse of reclaimed water. Microalgae-based systems are effective in removing micropollutants and are recognized as green technology for nutrient removal and recovery from agricultural waste. Zhou et al. (Zhou et al., 2021) demonstrated that species like *Chlamydomonas*, *Chlorella*, *Desmodesmus* effectively remove hormones via biodegradation and photodegradation. Duckweed, a free-floating aquatic plant, can be used alone or with microalgae for DLF treatment. Duckweed thrives in high nutrient environments and tolerates a wide range of temperatures (6 to 33 °C) and pH levels (between 5.5 and 8.5), typical of DLF. It can grow in natural ponds, CWs (e.g., FWS) and FTWs. These plants removes inorganic and organic nutrients through filtration and bioaccumulation. Species such as *L. minor*, *L. gibba*, *L.minuta* and *S. polyrhiza* exhibit continuous growth throughout the year, overcoming the limitations of other aquatic plants in CWs. Table 5 summarises the key findings of the 5 selected research articles that met the eligibility criteria, respectively 4 on microalgae cultivation and 1 on duckweed. CWs utilising microalgae and duckweed offer a practical solution for DLF treatment (Li et al., 2020), effectively removing nutrients and enabling their recovery and recycling through biomass resources. As illustrated in Fig. 6, microalgae and/or duckweed can thrive by utilising DLF nutrients during the treatment process. CO_2 from biogas upgrading process can be used with solar irradiation to promote microalgae and/or duckweed growth. The resulting biomass can be used as feedstock for AD, facilitating energy production and recovery, aligning with circular economy principles, environmental protection, and resources optimisation.

4. LCA and TEA for integrated digestate management

LCA is essential for evaluating the environmental impacts of various processes and products, particularly in agricultural waste management.

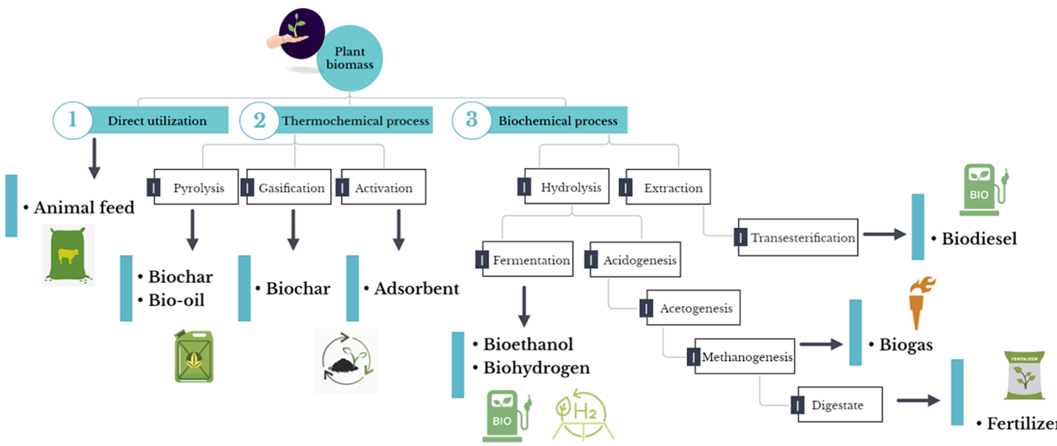


Fig. 5. Possible plant biomass utilisation.
Adapted from Kurniawan et al. (Kurniawan et al., 2021).

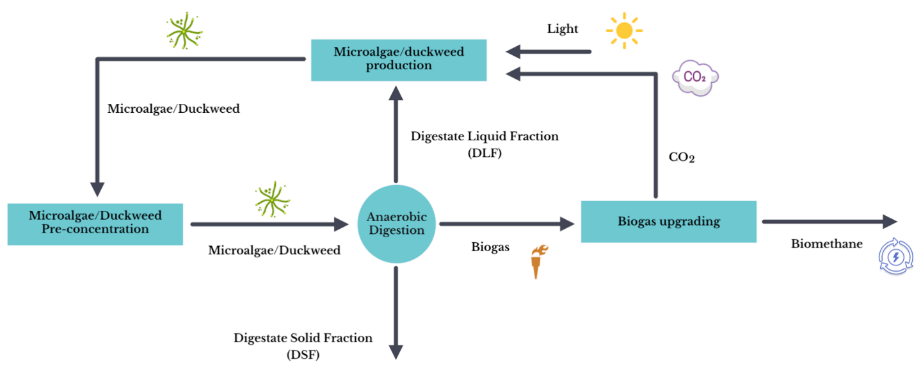


Fig. 6. Possible plant biomass utilisation.
Adapted from Monfet et al. (Monfet et al., 2018).

IDM has gained attention for its efficiency in handling organic residues, with LCA quantifying environmental burdens from raw material extraction to disposal. This section explores LCA's role in assessing IDM's sustainability and environmental impacts, emphasising its importance in promoting eco-friendly agricultural practices. Eight research articles meeting the eligibility criteria were deeply analysed, covering IDM's environmental implications and sustainability. IDM optimises digestate value while minimising environmental impact through composting, land application, and nutrient recovery. Several LCA studies evaluate IDM's environmental performance and sustainability compare environmental impacts of different IDM scenarios, focusing mostly on treatments of raw digestate, including both DLF and DSF. However, exceptions were found in studies that exclusively addressed DLF treatments (Drapanauskaite et al., 2021; Styles et al., 2018), or focused solely on DSF treatments (Chen et al., 2021). LCA was used to evaluate the environmental impacts of post-treatment methods and subsequent utilisation of digestate, aiming to provide a comprehensive understanding of the life cycle sustainability of digestate management practices (Angouria-Tsorochidou et al., 2022). The ReCiPe2016 method, designed and developed jointly by RIVM and Radboud University, CML, and PRé Consultants, at the midpoint level was employed for impact assessment, considering eight impact categories (Huijbregts et al., 2017). Three different digestate management scenarios were compared: raw digestate soil application, DLF and DSF soil application after separation, and advanced post-treatment involving drying of DSF and DLF processing with membrane filtration and reverse osmosis units. The LCA revealed that, for impact categories such as global warming, freshwater eutrophication, and mineral resource scarcity, the scenario of soil application after separating DLF and DSF had the lowest environmental impact. In contrast, for categories such as human non-carcinogenic toxicity, terrestrial ecotoxicity, and fossil resource scarcity, raw digestate soil application exhibited the lowest emissions. Regarding terrestrial acidification and marine eutrophication, scenario 3 (drying of DSF with DLF processing) was considered the most efficient. The study highlights that the evaluated impacts of the analysed scenarios could be further improved by including the contribution to climate change mitigation potential from an increased soil carbon stock. A study on solid digestate disposal strategies to mitigate environmental impact and reduce energy consumption in food waste-based biogas systems explored DSF handling methods, including incineration, composting, and landfill (Chen et al., 2021). Using the CML2001 and CML-IA methods for assessment, minor differences were observed in energy output among scenarios, with composting having the highest net energy consumption and landfill the lowest due to reduced equipment usage. Composting had the lowest total environmental impact, 3 % and 39 % less than incineration and landfill, respectively. Despite higher energy use, in-situ composting had the least environmental impact, while landfill and incineration were technically acceptable for energy consumption. These outcomes align with enhancing the sustainability of food waste-based biogas systems. Environmental sustainability using LCA was explored for DLF converted into solid NH_4HCO_3 fertiliser (Drapanauskaite et al., 2021) under three DLF management scenarios: land application, ammonium bicarbonate production with land application, and ammonium sulphate production with land application, focusing on Global Warming Potential and Eutrophication using the TRACI model. Results showed that ammonium bicarbonate production had a comparable GWP to conventional land application with a 2 % increase but reduced eutrophication potential by over 50 %. Conversely, ammonium sulphate production increased GWP by 29 % compared to conventional methods, despite a 20 % reduction in eutrophication, due to higher energy and air emission impacts. LCA of AD of pig manure coupled with different digestate treatment technologies was investigated comparing four scenarios: land application, composting DSF with DLF pre-treatment, composting DSF with diluted DLF for microalgae cultivation, and composting DSF with powder biofertilizer production via struvite precipitation and ammonia stripping. Using the IMPACT2002 + model, water footprints and total environmental impacts across four damage categories were assessed. Results indicated that direct land application of digestate is optimal if not oversupplied and without extra transport costs. Coupled AD and microalgae production excelled in human health, ecosystem quality, and climate change, while powder biofertilizer treatment was best for resource damage. Coupled AD and microalgae scenarios were also the most water-efficient. Environmental impact of biofertiliser production versus conventional DLF management was investigated (Styles et al., 2018). Using the CML baseline method, five environmental impact categories were assessed. Results showed that biofertiliser production mitigated acidification and eutrophication, outperforming traditional DLF management in all categories, especially in abiotic resource depletion and acidification potential, while avoiding direct and indirect N_2O and CH_4 emissions despite production process emissions. Post-treatment and agricultural reuse of digestate from low-tech digesters were compared (Ziegler-Rodriguez et al., 2023), under three scenarios: post-treatment with a sand filter for biofertiliser reuse, post-treatment with a vermifilter and compost production for biofertiliser reuse, and land application without post-treatment. Using IPCC 2021 and ReCiPe 2016 methods, it was observed that the vermifilter scenario was the most environmentally friendly, reducing impacts up to nine times. Vázquez-Rowe et al. (Vázquez-Rowe et al., 2015) provided a broad environmental assessment of seven digestate treatment technologies, highlighting significant advantages of conversion technologies over direct spreading. The ReCiPe method was used to evaluate 18 impact categories, revealing that most scenarios had better environmental outcomes despite increased global warming and resource use impacts. Alengebawy et al. (Alengebawy et al., 2022) focused on LCA of biofertiliser production from anaerobic digestate, using the CML 2001 model to compare four scenarios. Results showed that biofertilisers from biogas digestate significantly reduced environmental impact compared to chemical fertilisers. Table 6 summarises the primary parameters and key findings from the 8 selected research articles, highlighting substantial variations in approaches and outcomes concerning digestate fraction management and utilisation. Alengebawy et al. (Alengebawy et al., 2022) showed that liquid biofertiliser production from DLF and DSF is environmentally superior to biocompost due to lower greenhouse gas emissions. Angouria-Tsorochidou et al. (Angouria-Tsorochidou et al., 2022) emphasised potential environmental improvements through membrane filtration and reverse osmosis units using the ReCiPe method. Chen et al. (Chen et al., 2021) found that in-situ composting of DSF had the least environmental impact despite higher energy use. Drapanauskaite et al. (Drapanauskaite et al., 2021) highlighted significant environmental drawbacks associated with ammonium sulphate production compared to land application or ammonium bicarbonate production for DLF. Duan et al. (Duan et al., 2020) suggested direct land application of DSF and DLF for pig manure due to its cost-effectiveness and minimal environmental impact. Styles et al. (Styles et al., 2018) demonstrated that digestate biofertiliser outperformed conventional DLF management methods across various impact categories. Vázquez-Rowe et al. (Vázquez-Rowe et al., 2015) showcased substantial environmental advantages of conversion technologies for DSF and DLF before spreading, using the ReCiPe assessment. Ziegler-Rodriguez et al. (Ziegler-Rodriguez et al., 2023) highlighted the environmental benefits of vermifiltration for DLF, significantly reducing impacts compared to other post-treatment and reuse scenarios. Overall, these studies emphasise the importance of tailored approaches to maximize environmental benefits in digestate management. IDM methods, particularly those combining AD with microalgae cultivation, offer significant environmental advantages over direct spreading. The systematic use of LCA in these studies provides valuable insights for achieving more sustainable and environmentally friendly AD processes. As the field of IDM continues to evolve, the integration of LCA remains crucial in shaping environmentally conscious decisions and facilitating the transition towards more sustainable agricultural practices.

To increase the economic viability of biogas production systems, effective, cost-efficient production-scale technologies for nutrient extraction and contaminant removal are needed. Challenges such as partial biodegradation of organic matter, the presence of complex organic pollutants, and high organic content hinder sustainability of the process, which aims to convert digestate into valuable products (Lamolinara et al., 2022). Digestate from AD plants handling animal by-products, such as FW, must be thermally treated to eliminate pathogens before soil application. Although easily implemented, thermal treatment requires a significant amount of energy. Urban-based AD plants processing FW might not have access to sufficient agricultural land for digestate dissemination (Singlitico et al., 2017). While each biogas plant is different, three elements determine the economic feasibility of digestate recovery operations: the plant's size, the allocation of heat produced, and digestate transportation and storage costs borne by farmers (Herbes et al., 2020). The literature on the economic value of digestate is limited; only six research articles that met the eligibility criteria were selected and thoroughly analysed for this review. Main findings, including the substrate used, the digestate fraction, and the TEA method used, are summarised in Table 6. It is important to note that all economic data in this review are reported in consistent units such as € per ton of digestate processed or per m^3 of digestate treated, to ensure comparability across different studies. Regulations must consider the pathogenic load, hazardous component content, agronomic qualities, and LCA impact of digestate to ensure safe and sustainable use (Lamolinara et al., 2022). The extraction of nutrients from digestate as commercial goods is increasingly drawing attention to the operating techniques of AD plants. However, creating a market for digestate remains a challenge for the biogas industry. Therefore, to fully utilise the potential of AD plants, adequate and efficient methods for managing and monetising the substantial volume of digestate produced must be implemented alongside optimising biogas production (Malhotra et al., 2022). TEA is a method for assessing the financial performance of a good, a service, or an industrial process and can forecast profitability under specific assumptions (Elgarahy et al., 2023). Data on capital expenditures (CAPEX) and operating/maintenance costs (OPEX) are used in TEA Economic performance indicators such as Net Present Value (NPV), levelized cost of energy (LCOE), and costs of operation (COT) are utilised in TEA (Bolzonella et al., 2018). A TEA model comprises four processes: process design, process modelling, equipment sizing, and estimation of capital and operating costs (Elgarahy et al., 2023). Under current assumptions, many processing technologies are not economically feasible when considering the entire value chain, from digestate leaving the digester to its application on crops. Future studies on the financial aspects of digestate valorisation should explore two key areas. First, they should evaluate scenarios where digestate is packaged and sold to private households, either directly or through suppliers/merchants, rather than only targeting the agricultural sector. Second, these studies should assess the conditions under which cooperative processing businesses for small biogas plants can achieve profitability (Herbes et al., 2020). From a business perspective, the economic balance of the plant is improved by the profitable management of digestate (Lamolinara et al., 2022). To commercialise digestate as a fertiliser and soil enhancer, it is necessary to harmonise laws and regulations to clarify its legal status, correct beliefs about its origin by educating consumers on its environmental and economic benefits, and explore new marketing methods for current and future digestate marketers. Governments, decision-makers, and other stakeholders must be involved and engaged

Table 6
Key aspects and main results of the selected research articles on LCA and TEA.

Reference	Year	Article type	Digestate Fraction	FU and substrate	Scenarios	Method	Results – Key findings
LCA							
(Alengebawy et al., 2022)	2022	Article	DSF and DLF	1 metric ton raw digestate	1. DSF biofertiliser pellets BFPs 2. DSF biocompost BC 3. DLF for liquid biofertiliser LBF 4. DLF for powder biofertiliser PBF	CML 2001 10 midpoint categories	Among all 4 investigated scenarios liquid biofertiliser production resulted as the optimal method for converting the DLF into ammonium sulphate fertiliser, on the contrary biocompost production scenario contributed to the highest environmental burdens, especially in the GWP impact category.
(Angouria-Tsorochidou et al., 2022)	2022	Article	DSF and DSF	1 kg DM digestate	1. Digestate land application 2. DSF and DLF- land application after centrifuge-separation 3. Drying of DSFand DLF processing with a membrane filtration unit and a reverse osmosis unit, after DLF and DSF centrifuge-separation	ReCiPe 8 midpoint impact categories	Among the studied scenarios, in scenario 3 it was possible to obtain three different types of products that have fertilising value. The results highlighted that the environmental performance of the system could be further improved by including the contribution to climate change mitigation potential from an increased soil carbon stock.
(Chen et al., 2021)	2021	Article	DSF	1 ton of Food waste	1. Inceneration 2. Composting 3. Landfill	CML2001 midpoint and CML-IA endpoint 7 energy indicators 5 impact categories	The three treatment scenarios showed significant differences in environmental impacts and energy consumption. Although in-situ composting DSF had the greatest energy consumption, it showed the least environmental impact. In contrast, co-processing using landfill or incineration plants was found to be an acceptable technical option in terms of energy consumption.
(Drapanauskaite et al., 2021)	2021	Article	DLF	30,000 kg DLF after solid/liquid separation	1. Land application 2. Ammonium bicarbonate production and land application 3. Ammonium sulphate production and land application	TRACI model- midpoint 2 impacts categories	Ammonium sulphate production and land application scenario were markedly worse than land application scenario or ammonium bicarbonate production and land application scenario, in any impact category that is heavily associated with energy use or air emissions, due to the large electricity utility requirement.
(Duan et al., 2020)	2020	Article	DSF and DLF	1 ton pig manure	1. Digestate land application 2. Composting DSF and pre-treatment DLF with integrated flocculation-biological contact oxidation and using it as medium for microalgae cultivation 3. Composting DSF and diluting DLF with water and using it as medium for microalgae cultivation 4. Composting DSF and powder biofertilisers production via struvite precipitation with ammonia stripping	IMPACT2002+ 4 damage categories and water footprint	Directly using digestate on farmlands for land application, without over-supply and without imposing additional transportation costs on farmers, is considered the best choice.
(Styles et al., 2018)	2018	Article	DLF	1 m^3 liquid digestate	1. Conventional management of DLF 2. Production and use of digestate biofertiliser	CML baseline 5 impact categories	Digestate biofertiliser outperforms DLF in all impact categories, especially in abiotic resource depletion and acidification potential, that would benefit the most, with global burdens reduced by up to 1 % and 0.2 %, respectively.

(continued on next page)

Table 6 (*continued*)

Reference	Year	Article type	Digestate Fraction	FU and substrate	Scenarios	Method	Results – Key findings
(Vázquez-Rowe et al., 2015)	2015	Article	DSF and DLF	1-ton digestate	1. Land application 2. Drying and pelletising of digestate 3. Spreading of DSF 4. Composting of DSF 5. Spreading of raw digestate 6. Raw digestate biological treatment, reverse osmosis and drying 7. Digestate ammonia stripping ad drying	ReCiPe assessment midpoint approach	Despite a substantial increase in impacts associated with global warming and energy and mineral use, applying conversion technologies prior to digestate spreading demonstrated to have considerable environmental advantages compared to direct spreading, due to the important reductions of ammonia in air emissions.
(Ziegler-Rodriguez et al., 2023)	2023	Article	DLF	1 m^3 digestate	1. Digestate post-treatment with a sand filter and its reuse as biofertiliser 2. Digestate post-treatment with a vermifilter and the production of compost that is reused as biofertiliser 3. Land application without any post-treatment	IPCC 2021 ReCiPe 2016 – midpoint	The vermifilter resulted as the most environmentally friendly scenario. It reduced by up 9 times the environmental impacts associated with the post-treatment and agricultural use of digestate form low-tech digesters.
TEA							
(Singlitico et al., 2017)	2017	Article	DSF	Food waste	Not applicable	Capital (CAPEX) and operational/ maintenance (OPEX) costs including Net Present Value (NPV), levelised cost of energy (LCOE) and costs of operation (COT):	This study demonstrated that the energy requirements of a biomethane AD plant can be met by cogenerating heat and power from food waste digestates using air gasification, thereby reducing the system's overall carbon footprint. The total estimated treatment costs for dry digestate ranged from 190 to 195 €/ton.
(Bolzonella et al., 2018)	2018	Article	DSF and DLF	Animal Manures	Not applicable	The mass and energy balances of the systems and their performances, along with the capital costs (CAPEX) and operating costs (OPEX)	Less than 40 % of the nitrogen input was recovered by the stripping mechanism. Total estimated treatment costs, including operating expenses and capital cost amortization, ranged from €5.40 to €6.97 per cubic meter of treated digestate. This process involved stripping the membranes, drying them, and then stacking them.
(Herbes et al., 2020)	2020	Article	DSF and DLF	Organic waste	Not applicable	Average Rate of Return (ARR). Cash flow assessments: Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PP)	Current processing technologies are often not economically feasible when considering the full economic impact across the entire value chain, from when the digestate leaves the digester to its application on crops. Total treatment costs per cubic meter of treated digestate are significantly lower for technologies with a capacity of 2000 kW H+compared to those with a capacity of 500 kW H+.
(Lamolinara et al., 2022)	2022	Article	DSF and DLF	Animal manure, Agricultural and municipal organic wastes	Not applicable	Digestate economical value	One of the most promising applications of digestate is its use as a biofertilizer, owing to its rich nutritional content. This not only mitigates direct and indirect environmental and health impacts but also enhances the financial viability of biogas production systems. The total estimated production costs for dry digestate range from 5 to 30 €/ton. When processed into dry pelletized

(*continued on next page*)

Table 6 (*continued*)

Reference	Year	Article type	Digestate Fraction	FU and substrate	Scenarios	Method	Results – Key findings
							digestate and sold in small retail bags, these costs can increase to between 150 and 250 €/ton.
(Malhotra et al., 2022)	2022	Article	DSF and DLF	Organic wastes	Not applicable	Explain valorisation technology commercialization: obstacles and outlook	Commercial digestate utilisation is a tough issue because to the variations in digestate characteristics caused by different types of feedstock and different digestion settings. One major obstacle to the establishment of a digestate-based bioeconomy is the limited commercialisation potential of some technologies. To motivate participation and finance from the public and commercial sectors, the logistics between various sectors and participating parties are crucial.
(Elgarahy et al., 2023)	2023	Review	DSF and DLF	Food waste	Not applicable	Along with a recent bibliometric review of existing literature, a thorough discussion of the life cycle and techno-economic evaluation studies pertaining to the socio-economic, environmental, and engineering elements of FW management will be held.	The study provided a thorough analysis with a focus on two main areas: (1) pre-treatment techniques for food waste; and (2) food waste upcycling into various value products such organic acids, bioplastics, enzymes, fertilizers, char, and single-cell protein in addition to eco-friendly green fuels. The nature, components, composition, and application of food waste pre-treatment technologies are just a few of the many variables that affect them.

in order to improve and regulate the legal frameworks governing the commercialisation of digestates (Malhotra et al., 2022). The primary markets for digestates include fertiliser and soil manufacturers, farmers, horticulturists, and individual consumers. The success of the digestate-based bioeconomy relies heavily on understanding consumer preferences and concerns, as well as educating them about the benefits and safety of digestate. The biogas sector is becoming increasingly interested in the commercialisation of products obtained from digestate, which could potentially supplement or replace its current usage. However, establishing a robust supply chain and validating/certifying the technology are essential steps for the successful commercialisation of novel technologies and the introduction of new products (Malhotra et al., 2022).

5. Future actions

This study outlines a path for future research on optimising digestate treatment technologies, focusing on resource recovery, environmental sustainability, and economic viability. Integrating AD with processes like gasification, hydrothermal carbonisation, and pyrolysis can convert digestate into valuable products and improve energy efficiency. Enhancing resource recovery minimises waste and promotes sustainable practices. Key technologies such as membrane filtration and struvite precipitation are vital for capturing valuable components. Additionally, incorporating NBS such as CWs and microalgae can further enhance sustainability. Tools like LCA and TEA are essential for effective IDM. Future research should explore innovative technologies to boost energy efficiency and reduce emissions, as well as expand digestate's market beyond agriculture. Encouraging collaboration among small digestate plants and standardising regulations will support economic sustainability. Educating consumers about the benefits of digestate can increase acceptance, while incorporating LCA into policy-making can drive eco-friendly practices and foster a shift toward sustainable agriculture.

6. Conclusions

This review highlights the significance of technologies for digestate treatment and agricultural valorisation in advancing circular and green economy objectives. AD offers promise for organic waste management, though challenges remain in digestate utilisation. Diverse treatment methods improve resource recovery and economic viability. Future research should prioritise sustainable and cost-effective solutions to address existing gaps. Additionally, integrating LCA and TEA provides valuable insights into the environmental and economic aspects of digestate management, aiding informed decision-making. LCA indeed emerges as a key tool for evaluating environmental impacts and sustainability of IDM processes, providing valuable insights into treatment and utilisation methods for digestate.

CRediT authorship contribution statement

Giuseppe Mancuso: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Data curation. **Sanae Habchi:** Writing – original draft, Visualization, Investigation. **Mirko Maraldi:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Francesca Valenti:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Hassan El Bari:** Writing – original draft, Visualization, Investigation, Conceptualization.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This publication is part of a research project focused on the valorization of organic waste from various sources through anaerobic digestion and the utilization of the resulting digestate co-product for adsorption and fertilization. The project is conducted under the APRD research program, supported by the Moroccan Ministry of Higher Education, Scientific Research and Innovation, in collaboration with the OCP Foundation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biortech.2024.131252.

References

Alengebawy, A., Mohamed, B.A., Jin, K., Liu, T., Ghimire, N., Samer, M., Ai, P., 2022. A comparative life cycle assessment of biofertilizer production towards sustainable utilization of anaerobic digestate. Sustain. Prod. Consum. 33, 875–889.

Alvarado-Lassman, A., Rustrián, E., García-Alvarado, M.A., Rodríguez-Jiménez, G.C., Houbron, E., 2008. Brewery wastewater treatment using anaerobic inverse fluidized bed reactors. Bioresour. Technol. 99, 3009–3015.

Angouria-Tsorochidou, E., Seghetta, M., Trémier, A., Thomsen, M., 2022. Life cycle assessment of digestate post-treatment and utilization. Sci. Total Environ. 815, 152764.

Antoniou, N., Monlau, F., Sambusiti, C., Ficara, E., Barakat, A., Zabaniotou, A., 2019. Contribution to Circular Economy options of mixed agricultural wastes management: Coupling anaerobic digestion with gasification for enhanced energy and material recovery. J. Clean. Prod. 209, 505–514.

Aragón-Briceño, C.I., Grasham, O., Ross, A.B., Dupont, V., Camargo-Valero, M.A., 2020. Hydrothermal carbonization of sewage digestate at wastewater treatment works: Influence of solid loading on characteristics of hydrochar, process water and plant energetics. Renew. Energy 157, 959–973.

Aragon-Briceño, C., Pożarlik, A., Bramer, E., Brem, G., Wang, S., Wen, Y., Yang, W., Pawlak-Kruczek, H., Niedźwiecki, Ł., Urbanowska, A., Mościcki, K., Płoszczyca, M., 2022. Integration of hydrothermal carbonization treatment for water and energy recovery from organic fraction of municipal solid waste digestate. Renew. Energy 184, 577–591.

Baláš, M., Milčák, P., Elbl, P., Lisý, M., Lachman, J., Kracík, P., 2022. Gasification of fermentation residue in a fluidised-bed gasifier. Energy 245.

Barco, A., Borin, M., 2020. Treatment performances of floating wetlands: A decade of studies in North Italy. Ecol. Eng. 158, 106016.

Belete, Y.Z., Mau, V., Yahav Spitzer, R., Posmanik, R., Jassby, D., Iddya, A., Kassem, N., Tester, J.W., Gross, A., 2021. Hydrothermal carbonization of anaerobic digestate and manure from a dairy farm on energy recovery and the fate of nutrients. Bioresour. Technol. 333, 125164 https://doi.org/10.1016/j.biortech.2021.125164.

Bolzonella, D., Fatone, F., Gottardo, M., Frison, N., 2018. Nutrients recovery from anaerobic digestate of agro-waste: Techno-economic assessment of full scale applications. J. Environ. Manage. 216, 111–119.

Borrello, M., Lombardi, A., Pascucci, S., Cembalo, L., 2016. The seven challenges for transitioning into a bio-based circular economy in the agri-food sector. Recent Pat. Food. Nutr. Agric. 8, 39–47.

Bousek, J., Scroccaro, D., Sima, J., Weissenbacher, N., Fuchs, W., 2016. Influence of the gas composition on the efficiency of ammonia stripping of biogas digestate. Bioresour. Technol. 203, 259–266.

Brienza, C., Donoso, N., Luo, H., Vingerhoets, R., de Wilde, D., van Oirschot, D., Sigurnjak, I., Biswas, J.K., Michels, E., Meers, E., 2023. Evaluation of a new approach for swine wastewater valorisation and treatment: A combined system of ammonium recovery and aerated constructed wetland. Ecol. Eng. 189, 106919.

Cavali, M., Libardi Junior, N., de Mohedano, R.A., Belli Filho, P., da Costa, R.H.R., de Castilhos Junior, A.B., 2022. Biochar and hydrochar in the context of anaerobic digestion for a circular approach: An overview. Sci. Total Environ. 822, 153614.

Cesaro, A., 2021. The valorization of the anaerobic digestate from the organic fractions of municipal solid waste: Challenges and perspectives. J. Environ. Manage. 280, 111742.

Chatterjee, B., Mazumder, D., 2020. New approach of characterizing fruit and vegetable waste (FVW) to ascertain its biological stabilization via two-stage anaerobic digestion (AD). Biomass and Bioenergy 139, 105594.

Chen, G., Guo, X., Cheng, Z., Yan, B., Dan, Z., Ma, W., 2017. Air gasification of biogas-derived digestate in a downdraft fixed bed gasifier. Waste Manag. 69, 162–169.

Chen, T., Qiu, X., Feng, H., Yin, J., Shen, D., 2021. Solid digestate disposal strategies to reduce the environmental impact and energy consumption of food waste-based biogas systems. Bioresour. Technol. 325, 124706.

Chuda, A., Ziemiński, K., 2023. Ultrafiltration of digestate liquid fraction by hollow-fiber membranes: Influence of digestate pre-treatment on hydraulic capacity and nutrient removal efficiency. Chem. Eng. J. 473, 145426.

Costanzo, N.D., Cesaro, A., Capua, F.D., 2021. Exploiting the nutrient potential of anaerobically digested sewage sludge : a review. Energies 14, 8149.

Di Costanzo, N., Cesaro, A., Di Capua, F., Mascolo, M.C., Esposito, G., 2023. Application of high-intensity static magnetic field as a strategy to enhance the fertilizing potential of sewage sludge digestate. Waste Manag. 170, 122–130.

Donoso, N., van Oirschot, D., Biswas, J.K., Michels, E., Meers, E., 2019. Impact of aeration on the removal of organic matter and nitrogen compounds in constructed wetlands treating the liquid fraction of piggery manure. Appl. Sci. 9, 4310.

Drapanauskaite, D., Handler, R.M., Fox, N., Baltrusaitis, J., 2021. Transformation of liquid digestate from the solid-separated biogas digestion reactor effluent into a solid NH4HCO3 fertilizer: sustainable process engineering and life cycle assessment. ACS Sustain. Chem. Eng. 9, 580–588.

Duan, N., Khoshnevisan, B., Lin, C., Liu, Z., Liu, H., 2020. Life cycle assessment of anaerobic digestion of pig manure coupled with different digestate treatment technologies. Environ. Int. 137, 105522.

El Gnaoui, Y., Frimane, A., Lahboubi, N., Herrmann, C., Barz, M., Bari, E.L., H.,, 2022. Biological pre-hydrolysis and thermal pretreatment applied for anaerobic digestion improvement: Kinetic study and statistical variable selection. Clean. Waste Syst. 2, 100005.

Elgarahy, A.M., Eloffy, M.G., Alengebawy, A., El-Sherif, D.M., Gaballah, M.S., Elwakeel, K.Z., El-Qelish, M., 2023. Sustainable management of food waste; pre-treatment strategies, techno-economic assessment, bibliometric analysis, and potential utilizations: A systematic review. Environ. Res. 225, 115558.

Ermolaev, D.V., Karaeva, J.V., Timofeeva, S.S., Kovalev, A.A., Kovalev, D.A., Litti, Y.V., 2023. Modeling of air gasification of dark fermentation digestate in a downdraft gasifier. Int. J. Hydrogen Energy 48, 24255–24263.

Escalante, H., Castro, L., Amaya, M.P., Jaimes, L., Jaimes-Estévez, J., 2018. Anaerobic digestion of cheese whey: Energetic and nutritional potential for the dairy sector in developing countries. Waste Manag. 71, 711–718.

Estevez, M.M., Linjordet, R., Horn, S.J., Morken, J., 2014a. Improving nutrient fixation and dry matter content of an ammonium-rich anaerobic digestion effluent by struvite formation and clay adsorption. Water Sci. Technol. 70, 337–344.

Estevez, M.M., Sapci, Z., Linjordet, R., Morken, J., 2014b. Incorporation of fish by-product into the semi-continuous anaerobic co-digestion of pre-treated lignocellulose and cow manure, with recovery of digestate's nutrients. Renew. Energy 66, 550–558.

Eze, V.C., Velasquez-Orta, S.B., Hernández-García, A., Monje-Ramírez, I., Orta-Ledesma, M.T., 2018. Kinetic modelling of microalgae cultivation for wastewater treatment and carbon dioxide sequestration. Algal Res. 32, 131–141.

Feng, L., Wang, R., Jia, L., Wu, H., 2020. Can biochar application improve nitrogen removal in constructed wetlands for treating anaerobically-digested swine wastewater? Chem. Eng. J. 379, 122273.

Freda, C., Nanna, F., Villone, A., Barisano, D., Brandani, S., Cornacchia, G., 2019. Air gasification of digestate and its co-gasification with residual biomass in a pilot scale rotary kiln. Int. J. Energy Environ. Eng. 10, 335–346.

Gizińska-Górna, M., Czekała, W., Jóźwiakowski, K., Lewicki, A., Dach, J., Marzec, M., Pytka, A., Janczak, D., Kowalczyk-Juśko, A., Listosz, A., 2016. The possibility of using plants from hybrid constructed wetland wastewater treatment plant for energy purposes. Ecol. Eng. 95, 534–541.

Gonzalez-Flo, E., Ortiz, A., Arias, A.C., Díez-Montero, R., Kohlheb, N., Schauser, U.H., García, J., Gregersen, P.K.S., 2023. Sludge treatment wetland for treating microalgae digestate grown in agricultural runoff: a technical, economic, and environmental assessment. Water (Switzerland) 15, 2159.

Guilayn, F., Rouez, M., Crest, M., Patureau, D., Jimenez, J., 2020. Valorization of digestates from urban or centralized biogas plants: a critical review. Rev. Environ. Sci. Biotechnol.

Guo, L., He, K., Wu, S., Sun, H., Wang, Y., Huang, X., Dong, R., 2016. Optimization of high-rate TN removal in a novel constructed wetland integrated with microelectrolysis system treating high-strength digestate supernatant. J. Environ. Manage. 178, 42–51.

Guštin, S., Marinšek-Logar, R., 2011. Effect of pH, temperature and air flow rate on the continuous ammonia stripping of the anaerobic digestion effluent. Process Saf. Environ. Prot. 89, 61–66.

Habchi, S., Lahboubi, N., Karouach, F., Naim, I., Lahlou, Y., Bakraoui, M., Sallek, B., El Bari, H., 2022. Effect of Thermal Pretreatment on the Kinetic Parameters of Anaerobic Digestion from Recycled Pulp and Paper Sludge. Ecol. Eng. Environ. Technol. 23, 192–201.

Habchi, S., Lahboubi, N., Asbik, M., Bari, H.E., 2024. Enhancing biomethane production from food waste using olive pomace hydrochar: An optimization study. Environ. Adv. 15, 100477.

Han, Z., Dong, J., Shen, Z., Mou, R., Zhou, Y., Chen, X., Fu, X., Yang, C., 2019. Nitrogen removal of anaerobically digested swine wastewater by pilot-scale tidal flow constructed wetland based on in-situ biological regeneration of zeolite. Chemosphere 217, 364–373.

Hdidou, M., Necibi, M.C., Labille, J., Hajjaji, S.E., Dhiba, D., Chechbouni, A., Roche, N., 2022. Potential use of constructed wetland systems for rural sanitation and wastewater reuse in agriculture in the moroccan context. Energies 15, 156.

Healy, M.G., Rodgers, M., Mulqueen, J., 2007. Treatment of dairy wastewater using constructed wetlands and intermittent sand filters. Bioresour. Technol. 98, 2268–2281.

Herbes, C., Roth, U., Wulf, S., Dahlin, J., 2020. Economic assessment of different biogas digestate processing technologies: A scenario-based analysis. J. Clean. Prod. 255, 120282.

Hidalgo, A.M., Murcia, M.D., Gómez, M., Gómez, E., García-Izquierdo, C., Solano, C., 2017. possible uses for sludge from drinking water treatment plants. J. Environ. Eng. 143, 04016088.
Hosseini, S.E., Wahid, M.A., Aghili, N., 2013. The scenario of greenhouse gases reduction in Malaysia. Renew. Sustain. Energy Rev. 28, 400–409.
Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147.
Ilyas, H., Masih, I., 2018. The effects of different aeration strategies on the performance of constructed wetlands for phosphorus removal. Environ. Sci. Pollut. Res. 25, 5318–5335.
Kapoor, R., Ghosh, P., Kumar, M., Sengupta, S., Gupta, A., Kumar, S.S., Vijay, V., Kumar, V., Kumar Vijay, V., Pant, D., 2020. Valorization of agricultural waste for biogas based circular economy in India: A research outlook. Bioresour. Technol. 304, 123036.
Khoshnevisan, S., Bazgir, S., 2021. Treatment of dye wastewater by direct contact membrane distillation using superhydrophobic nanofibrous high-impact polystyrene membranes. Int. J. Environ. Sci. Technol. 18, 1513–1528.
Khoshnevisan, B., Duan, N., Tsapekos, P., Awasthi, M.K., Liu, Z., Mohammadi, A., Angelidaki, I., Tsang, D.C.W., Zhang, Z., Pan, J., Ma, L., Aghbashlo, M., Tabatabaei, M., Liu, H., 2021. A critical review on livestock manure biorefinery technologies: Sustainability, challenges, and future perspectives. Renew. Sustain. Energy Rev. 135, 110033.
Kovačić, Đ., Lončarić, Z., Jović, J., Samac, D., Popović, B., Tišma, M., 2022. Digestate Management and Processing Practices: A Review. Appl. Sci. 12, 9216.
Kratzeisen, M., Starcevic, N., Martinov, M., Maurer, C., Müller, J., 2010. Applicability of biogas digestate as solid fuel. Fuel 89, 2544–2548.
Kumar, A., Saini, K., Bhaskar, T., 2020. Hydochar and biochar: production, physicochemical properties and techno-economic analysis. Bioresour. Technol. 310, 123442.
Kurniawan, S.B., Ahmad, A., Said, N.S.M., Imron, M.F., Abdullah, S.R.S., Othman, A.R., Purwanti, I.F., Hasan, H.A., 2021. Macrophytes as wastewater treatment agents: Nutrient uptake and potential of produced biomass utilization toward circular economy initiatives. Sci. Total Environ. 790, 148219.
Kwoczynski, Z., Čmelík, J., 2021. Characterization of biomass wastes and its possibility of agriculture utilization due to biochar production by torrefaction process. J. Clean. Prod. 280, 124302.
Lamolinara, B., Pérez-Martínez, A., Guardado-Yordi, E., Guillén Fiallos, C., Diéguez-Santana, K., Ruiz-Mercado, G.J., 2022. Anaerobic digestate management, environmental impacts, and techno-economic challenges. Waste Manag. 140, 14–30.
Li, X., Guo, J., Dong, R., Ahring, B.K., Zhang, W., 2016. Properties of plant nutrient: Comparison of two nutrient recovery techniques using liquid fraction of digestate from anaerobic digester treating pig manure. Sci. Total Environ. 544, 774–781.
Li, Y., Park, S.Y., Zhu, J., 2011. Solid-state anaerobic digestion for methane production from organic waste. Renew. Sustain. Energy Rev. 15, 821–826.
Li, X., Wu, S., Yang, C., Zeng, G., 2020. Microalgal and duckweed based constructed wetlands for swine wastewater treatment: A review. Bioresour. Technol. 318, 123858.
Li, Y., Zhang, R., He, Y., Zhang, C., Liu, X., Chen, C., Liu, G., 2014. Anaerobic co-digestion of chicken manure and corn stover in batch and continuously stirred tank reactor (CSTR). Bioresour. Technol. 156, 342–347.
Liu, H., Hu, Z., Zhang, Y., Zhang, J., Xie, H., Liang, S., 2018. Microbial nitrogen removal of ammonia wastewater in poly (butylenes succinate)-based constructed wetland: effect of dissolved oxygen. Appl. Microbiol. Biotechnol. 102, 9389–9398.
Lyu, T., Wu, Y., Zhang, Y., Fan, W., Wu, S., Mortimer, R.J.G., Pan, G., 2023. Nanobubble aeration enhanced wastewater treatment and bioenergy generation in constructed wetlands coupled with microbial fuel cells. Sci. Total Environ. 895, 165131.
Macura, B., Johannesdottir, S.L., Piniewski, M., Haddaway, N.R., Kvarnström, E., 2019. Effectiveness of ecotechnologies for recovery of nitrogen and phosphorus from anaerobic digestate and effectiveness of the recovery products as fertilisers: A systematic review protocol. Environ. Evid. 8, 1–9.
Malhotra, M., Aboudi, K., Pisharody, L., Singh, A., Banu, J.R., Bhatia, S.K., Varjani, S., Kumar, S., González-Fernández, C., Kumar, S., Singh, R., Tyagi, V.K., 2022. Biorefinery of anaerobic digestate in a circular bioeconomy: Opportunities, challenges and perspectives. Renew. Sustain. Energy Rev. 166.
Mancuso, G., Lavrnić, S., Canet-Martí, A., Zaheer, A., Avolio, F., Langergraber, G., Toscano, A., 2023. Performance of lagoon and constructed wetland systems for tertiary wastewater treatment and potential of reclaimed water in agricultural irrigation. J. Environ. Manage. 348, 119278.
Mancuso, G., Foglia, A., Chioggia, F., Drei, P., Eusebi, A.L., Lavrnić, S., Siroli, L., Carrozzini, L.M., Fatone, F., Toscano, A., 2024. Demo-scale up-flow anaerobic sludge blanket reactor coupled with hybrid constructed wetlands for energy-carbon efficient agricultural wastewater reuse in decentralized scenarios. J. Environ. Manage. 359, 121109.
Martín-Hernández, E., Sampat, A.M., Zavala, V.M., Martín, M., 2018. Optimal integrated facility for waste processing. Chem. Eng. Res. Des. 131, 160–182.
Melgaço, L., Robles-Aguilar, A., Meers, E., Mota, C., 2021. Phosphorus recovery from liquid digestate by chemical precipitation using low-cost ion sources. J. Chem. Technol. Biotechnol. 96, 2891–2900.
Miliotti, E., Casini, D., Rosi, L., Lotti, G., Rizzo, A.M., Chiaramonti, D., 2020. Lab-scale pyrolysis and hydrothermal carbonization of biomass digestate: Characterization of solid products and compliance with biochar standards. Biomass Bioenergy 139, 105593.
Monfet, E., Aubry, G., Ramirez, A.A., 2018. Nutrient removal and recovery from digestate: a review of the technology. Biofuels 9, 247–262.
Monlau, F., Sambusiti, C., Antoniou, N., Barakat, A., Zabaniotou, A., 2015a. A new concept for enhancing energy recovery from agricultural residues by coupling anaerobic digestion and pyrolysis process. Appl. Energy 148, 32–38.
Monlau, F., Sambusiti, C., Ficara, E., Aboulkas, A., Barakat, A., Carrère, H., 2015b. New opportunities for agricultural digestate valorization: Current situation and perspectives. Energy Environ. Sci. 8, 2600–2621.
Monlau, F., Francavilla, M., Sambusiti, C., Antoniou, N., Solhy, A., Libutti, A., Zabaniotou, A., Barakat, A., Monteleone, M., 2016. Toward a functional integration of anaerobic digestion and pyrolysis for a sustainable resource management. Comparison between solid-digestate and its derived pyrochar as soil amendment. Appl. Energy 169, 652–662.
Moyo, L.B., Simate, G.S., Mamvura, T.A., Danha, G., 2023. Recovering phosphorus as struvite from anaerobic digestate of pig manure with ferrochrome slag as a magnesium source. Heliyon 9, e15506.
Nan, X., Lavrnić, S., Mancuso, G., Toscano, A., 2023. Effects of design and operational conditions on the performance of constructed wetlands for agricultural pollution control – critical review. Water, Air, Soil Pollut. 234, 434.
Neumann, J., Meyer, J., Ouadi, M., Apfelbacher, A., Binder, S., Hornung, A., 2016. The conversion of anaerobic digestion waste into biofuels via a novel Thermo-Catalytic Reforming process. Waste Manag. 47, 141–148.
Orduña-Gaytán, F., Vallejo-Cantú, N.A., Alvarado-Vallejo, A., Rosas-Mendoza, E.S., Sandoval-Herazo, L.C., Alvarado-Lassman, A., 2022. Evaluation of the removal of organic matter and nutrients in the co-treatment of fruit and vegetable waste using a bioreactor-constructed wetlands system. Processes 10, 278.
Orner, K.D., Smith, S.J., Breunig, H.M., Scown, C.D., Nelson, K.L., 2021. Fertilizer demand and potential supply through nutrient recovery from organic waste digestate in California. Water Res. 206, 117717.
Pappalardo, G., Selvaggi, R., Bracco, S., Chinnici, G., Pecorino, B., 2018. Factors affecting purchasing process of digestate: evidence from an economic experiment on Sicilian farmers' willingness to pay. Agric. Food Econ. 6, 6–16.
Parmar, K.R., Ross, A.B., 2019. Integration of hydrothermal carbonisation with anaerobic digestion;Opportunities for valorisation of digestate. Energies 12.
Pavan, F., Breschigliaro, S., Borin, M., 2015. Screening of 18 species for digestate phytodepuration. Environ. Sci. Pollut. Res. 22, 2455–2466.
Pawlak-Kruczek, H., Niedzwiecki, L., Sieradzka, M., Mlonka-Mędrala, A., Baranowski, M., Serafin-Tkaczuk, M., Magdziarz, A., 2020. Hydrothermal carbonization of agricultural and municipal solid waste digestates – Structure and energetic properties of the solid products. Fuel 275, 117837.
Pecchi, M., Baratieri, M., 2019. Coupling anaerobic digestion with gasification, pyrolysis or hydrothermal carbonization: A review. Renew. Sustain. Energy Rev. 105, 462–475.
Peng, D., Xiang, X., Deng, Z., Zhou, X., Wang, B., He, C., 2024. Study on emission factor and reduction potential of organic solid waste gasification process. Case Stud. Therm. Eng. 53, 103978.
Persson, T., Rueda-Ayala, V., 2022. Phosphorus retention and agronomic efficiency of refined manure-based digestate - A review. Front. Sustain. Food Syst. 6, 993043.
Petrovič, A., Simonič, M., Čuček, L., 2021. Nutrient recovery from the digestate obtained by rumen fluid enhanced anaerobic co-digestion of sewage sludge and cattail: Precipitation by MgCl2 and ion exchange using zeolite. J. Environ. Manage. 290, 112593.
Piccoli, I., Virga, G., Maucieri, C., Borin, M., 2021. Digestate liquid fraction treatment with filters filled with recovery materials. Water (Switzerland) 13, 21.
Rizzioli, F., Bertasini, D., Bolzonella, D., Frison, N., Battista, F., 2023. A critical review on the techno-economic feasibility of nutrients recovery from anaerobic digestate in the agricultural sector. Sep. Purif. Technol. 306, 122690.
Selvaggi, R., Valenti, F., 2021. Assessment of fruit and vegetable residues suitable for renewable energy production: GIS-based model for developing new frontiers within the context of circular economy. Appl. Syst. Innov. 4, 1–15.
Serna-Maza, A., Heaven, S., Banks, C.J., 2015. Biogas stripping of ammonia from fresh digestate from a food waste digester. Bioresour. Technol. 190, 66–75.
Sfetsas, T., Patsatzis, S., Chioti, A., Kopteropoulos, A., Dimitropoulou, G., Tsioni, V., Kotsopoulos, T., 2022. A review of advances in valorization and post-treatment of anaerobic digestion liquid fraction effluent. Waste Manag. Res. 40, 1093–1109.
Sharma, H.B., Panigrahi, S., Sarmah, A.K., Dubey, B.K., 2020. Downstream augmentation of hydrothermal carbonization with anaerobic digestion for integrated biogas and hydrochar production from the organic fraction of municipal solid waste: A circular economy concept. Sci. Total Environ. 706, 135907.
Sheets, J.P., Yang, L., Ge, X., Wang, Z., Li, Y., 2015. Beyond land application: Emerging technologies for the treatment and reuse of anaerobically digested agricultural and food waste. Waste Manag. 44, 94–115.
Shirdashtzadeh, M., Chua, L.H.C., Brau, L., 2022. Microbial Communities and Nitrogen Transformation in Constructed Wetlands Treating Stormwater Runoff. Front. Water 3, 751830.
Siciliano, A., De Rosa, S., 2014. Recovery of ammonia in digestates of calf manure through a struvite precipitation process using unconventional reagents. Environ. Technol. (United Kingdom) 35, 841–850.
Silva, I., Jorge, C., Brito, L., Duarte, E., 2021. A pig slurry feast/famine feeding regime strategy to improve mesophilic anaerobic digestion efficiency and digestate hygienisation. Waste Manag. Res. 39, 947–955.
Singlitico, A., Dussan, K., O'Shea, R., Wall, D., Goggins, J., Murphy, J., Monaghan, R.F. D., 2017. Techno-economic optimisation of combined anaerobic digestion and gasification of food waste as part of an integrated waste management and energy system. Eur. Biomass Conf. Exhib. Proc. 2017, 96–105.
Styles, D., Adams, P., Thelin, G., Vaneeckhaute, C., Chadwick, D., Withers, P.J.A., 2018. Life cycle assessment of biofertilizer production and use compared with conventional liquid digestate management. Environ. Sci. Technol. 52, 7468–7476.

Tayibi, S., Monlau, F., Bargaz, A., Jimenez, R., Barakat, A., 2021. Synergy of anaerobic digestion and pyrolysis processes for sustainable waste management: A critical review and future perspectives. Renew. Sustain. Energy Rev. 152, 111603.
Timofeeva, S.S., Karaeva, J.V., Kovalev, A.A., Kovalev, D.A., Litti, Y.V., 2023. Steam gasification of digestate after anaerobic digestion and dark fermentation of lignocellulosic biomass to produce syngas with high hydrogen content. Int. J. Hydrogen Energy 48, 7559–7568.
Ting, Z.J., Raheem, A., Dastyar, W., Yang, H., Dong, W., Yuan, H., Li, X., Wang, W., Zhang, R., Zhao, M., 2020. Alkaline pyrolysis of anaerobic digestion residue with selective hydrogen production. Int. J. Hydrogen Energy 45, 20933–20943.
Trotta, S., Adani, F., Fedele, M., Salvatori, M., 2023. Nitrogen and phosphorus recovery from cow digestate by struvite precipitation: Process optimization to maximize phosphorus recovery. Results Eng. 20, 101478.
Uggetti, E., Sialve, B., Latrille, E., Steyer, J.P., 2014. Anaerobic digestate as substrate for microalgae culture: The role of ammonium concentration on the microalgae productivity. Bioresour. Technol. 152, 437–443.
Valenti, F., Liao, W., Porto, S.M.C., 2020a. Life cycle assessment of agro-industrial by-product reuse: a comparison between anaerobic digestion and conventional disposal treatments. Green Chem. 22, 7119–7139.
Valenti, F., Porto, S.M.C., Selvaggi, R., Pecorino, B., 2020b. Co-digestion of by-products and agricultural residues: A bioeconomy perspective for a Mediterranean feedstock mixture. Sci. Total Environ. 700, 134440.
Vaneeckhaute, C., Lebuf, V., Michels, E., Belia, E., Vanrolleghem, P.A., Tack, F.M.G., Meers, E., 2017. Nutrient recovery from digestate: systematic technology review and product classification. Waste and Biomass Valorization 8, 21–40.
Vázquez-Rowe, I., Golkowska, K., Lebuf, V., Vaneeckhaute, C., Michels, E., Meers, E., Benetto, E., Koster, D., 2015. Environmental assessment of digestate treatment technologies using LCA methodology. Waste Manag. 43, 442–459.
Wang, W., Chang, J.S., Lee, D.J., 2023. Anaerobic digestate valorization beyond agricultural application: Current status and prospects. Bioresour. Technol. 373, 128742.
Wilk, M., Magdziarz, A., Jayaraman, K., Szymańska-Chargot, M., Gökalp, I., 2019. Hydrothermal carbonization characteristics of sewage sludge and lignocellulosic biomass. A comparative study. Biomass Bioenergy 120, 166–175.
Wu, S., Lv, T., Lu, Q., Ajmal, Z., Dong, R., 2017. Treatment of anaerobic digestate supernatant in microbial fuel cell coupled constructed wetlands: Evaluation of nitrogen removal, electricity generation, and bacterial community response. Sci. Total Environ. 580, 339–346.
Wystalska, K., Kwarciak-Kozłowska, A., 2023. Utilization of digestate from agricultural and food waste for the production of biochar used to remove methylene blue. Sustainability 15, 14723.
Xia, A., Murphy, J.D., 2016. Microalgal Cultivation in Treating Liquid Digestate from Biogas Systems. Trends Biotechnol. 34, 264–275.
Yan, M., Chen, F., Li, T., Zhong, L., Feng, H., Xu, Z., Hantoko, D., Wibowo, H., 2023. Hydrothermal carbonization of food waste digestate solids: Effect of temperature and time on products characteristic and environmental evaluation. Process Saf. Environ. Prot. 178, 296–308.
Yang, D., Chen, Q., Liu, R., Song, L., Zhang, Y., Dai, X., 2022. Ammonia recovery from anaerobic digestate: State of the art, challenges and prospects. Bioresour. Technol. 363, 127957.
Zabaniotou, A., Kamaterou, P., 2019. Food waste valorization advocating Circular Bioeconomy - A critical review of potentialities and perspectives of spent coffee grounds biorefinery. J. Clean. Prod. 211, 1553–1566.
Zhao, X., Hu, Y., Zhao, Y., Kumar, L., 2018. Achieving an extraordinary high organic and hydraulic loadings with good performance via an alternative operation strategy in a multi-stage constructed wetland system. Environ. Sci. Pollut. Res. 25, 11841–11853.
Zhou, X., Jia, L., Liang, C., Feng, L., Wang, R., Wu, H., 2018. Simultaneous enhancement of nitrogen removal and nitrous oxide reduction by a saturated biochar-based intermittent aeration vertical flow constructed wetland: Effects of influent strength. Chem. Eng. J. 334, 1842–1850.
Zhou, S., Wang, C., Liu, C., Sun, H., Zhang, J., Zhang, X., Xin, L., 2020. Nutrient removal, methane and nitrous oxide emissions in a hybrid constructed wetland treating anaerobic digestate. Sci. Total Environ. 733, 138338.
Zhou, X., Zheng, H., van der Hoek, J.P., Yu, K., Cao, Y., 2021. Recent applications of biological technologies for decontaminating hormones in livestock waste and wastewater. Curr. Opin. Environ. Sci. Heal. 24, 100307.
Ziegler-Rodriguez, K., Josa, I., Castro, L., Escalante, H., Garfí, M., 2023. Post-treatment and agricultural reuse of digestate from low-tech digesters: A comparative life cycle assessment. Sci. Total Environ. 894, 164992.
Zielińska, M., Rusanowska, P., Zieliński, M., Dudek, M., Kazimierowicz, J., Quattrocelli, P., Dębowski, M., 2022. Liquid fraction of digestate pretreated with membrane filtration for cultivation of Chlorella vulgaris. Waste Manag. 146, 1–10.