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Valorisation of digestate: Characteristics, products, processes and potential

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ABSTRACT

Anaerobic digestion (AD) plays a critical role in meeting renewable energy needs and managing solid and liquid waste streams, thereby making significant contributions towards sustainability and the circular economy. However, AD generates a large amount of digestate as a by-product. Digestate contains undigested organic fractions, micro and macro-nutrients, inorganic materials, trace metals etc. It is essential to develop appropriate ways for managing and valorising digestate for truly harnessing the potential of AD. This review critically analyses the current state of the art on valorisation and management of digestate. It starts with a review of key digestate characteristics that have a great impact on the valorisation potential and products. Different valorisation pathways based on the analysis of digestate properties are then reviewed. The interaction among characteristics of digestate, valorisation technologies, potential products and economic challenges is critically reviewed and discussed. Furthermore, the separation technologies, advanced valorisation processes and their potential are discussed. Techno-economic aspects are briefly discussed. Some comments on policies and regulations are included. Key conclusions on the state of the art, specific suggestions for further research, and some comments on the outlook are included at the end. The review will be useful to researchers, technologists, and policymakers interested in sustainability and the circular economy.

1. Introduction

Bioenergy production from biomass is essential to tackle the growing need for renewable energy. It supports global sustainability goals and places a high priority on environmental sustainability [1,2]. Anaerobic digestion (AD) is the most promising renewable technology among the numerous ways of handling organic waste because of its effectiveness in turning organic matter into useful resources [3,4]. This process supports a circular economy by producing energy, reducing greenhouse gas (GHG) emissions, minimizing waste, and decreasing the volume of waste sent to landfills. About 35 million tonnes of oil equivalent (Mtoe) of biomethane in 2018 were produced globally from the waste and AD processes. Most of this production is concentrated in European and North American markets, with countries like Denmark and Sweden having significant shares of biogas/biomethane, comprising over 10 % of total gas sales. Beyond North America and Europe, countries such as China, Brazil and India are rapidly expanding their biomethane infrastructure, with the number of upgrading facilities tripling since 2015, highlighting the global commitment to sustainable energy solutions [5,6].

AD is a biochemical process that converts biodegradable organic matter into methane-rich biogas and digestate through a complex community of microorganisms without oxygen. Compared to other biological and thermochemical processes, this is acknowledged as one of the best renewable energy technologies [4,7]. While AD technology is highly effective, managing a huge amount of digestate poses significant challenges. Forecasts predict that the installation of AD plants and biogas use will increase significantly by 2040, resulting in a fourfold increase in digestate production [6]. In 2021, Europe produced an estimated 222–258 Mt of fresh digestate, which offers significant advantages such as excellent organo-mineral fertilizer properties, the potential to replace synthetic fertilizers and various environmental benefits [8]. However, the substantial daily production of digestate poses significant challenges, particularly during transportation and GHG emissions during storage. The untreated and excessive disposal of digestate can negatively impact the receiving environment. Concerns include water pollution from excess nutrients, heavy metal accumulation, pathogen contamination, and the buildup of recalcitrant organics [9]. The digestate was primarily considered a fertilizer in agriculture due to its undigested organic content and high levels of nitrogen and phosphorus. However, soils with high phosphorus content may not be suitable for receiving digestate for additional nitrogen, as the digestate

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also contains additional phosphorus [10,11]. Additionally, digestate must meet specific minimum standards to be marketed and used as fertilizer [12].

Digestate comprises partially digested organic matter, water, and a blend of micro and macronutrients, and therefore holds significant potential for valorisation. Various sources of digestate and potential valorisation pathways are shown schematically in Fig. 1. The perception of digestate is evolving and is getting transformed from waste to a valuable resource by the principles of the circular economy and maximizing the benefits of digestate valorisation [13]. The literatures reviewed in this study were collected using the Scopus database, applying keyword combinations such as “Digestate”, “Valorisation”, “Pretreatment”, “Biogas”, and “Digestate management”. The search was restricted to publications written in English and published between 2000 and 2025. Only peer-reviewed research articles, review papers, and select book chapters were included, while theses and encyclopedia entries were excluded from consideration. To maintain thematic relevance, only documents directly addressing digestate processing, valorisation and nutrient recovery were retained; studies lacking alignment in titles or keywords were filtered out. This strategy ensured a targeted and reliable literature base for the present review. Considering the large number of different valorisation pathways shown in Fig. 1, there is a need to assess the valorisation potential of digestate and the pathways for realizing it. Such an attempt is made in this work.

An appropriate understanding of the digestate properties is necessary for an effective valorisation process. The properties and composition of digestate are greatly impacted by various factors, such as the feedstock type, microbial communities, and operational parameters like temperature, retention time, and pressure. As a result, there is considerable variation in the characteristics and composition of digestate, which presents difficulties in terms of standardization and utilization [14]. Digestate valorisation can convert this nutrient-rich material into an array of valuable products, including biofertilizers, biogas with potential energy applications, biohydrogen and even specialized chemicals that find utility in diverse industrial sectors. The diverse components of the digestate can be utilized through different processes to create multiple alternative products and pathways for valorisation. Potential value-added products from digestate are shown in Fig. 2. These include nutrients like nitrogen and phosphorus which may be used as fertilizers. The organic fraction of digestate may be used to produce biogas through AD or biohydrogen through fermentation, thereby converting the organic matter into renewable energy. Additionally, the lignocellulosic components may be used to produce biofuels or bio-based chemicals, contributing to sustainable energy and materials. The maximum potential for valorisation could be achieved when each component is optimally utilized for its specific application, resulting in minimal waste. Various studies have been conducted to valorise digestate to certain

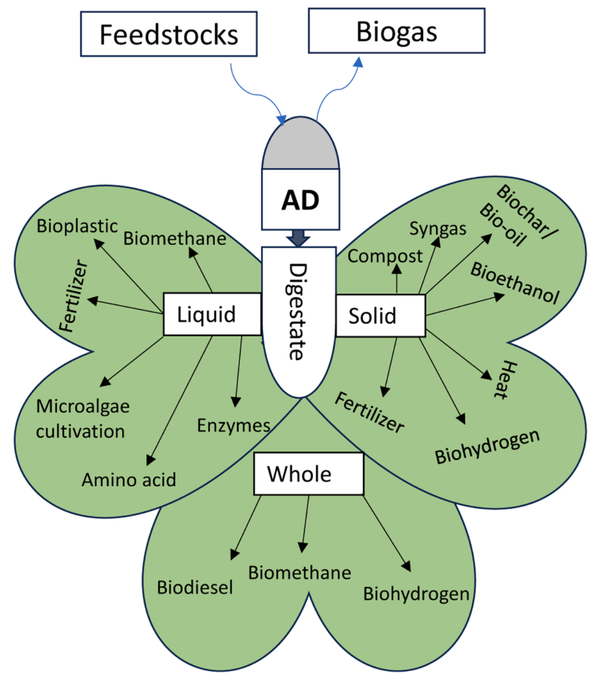


Fig. 2. Value-added products from digestate.

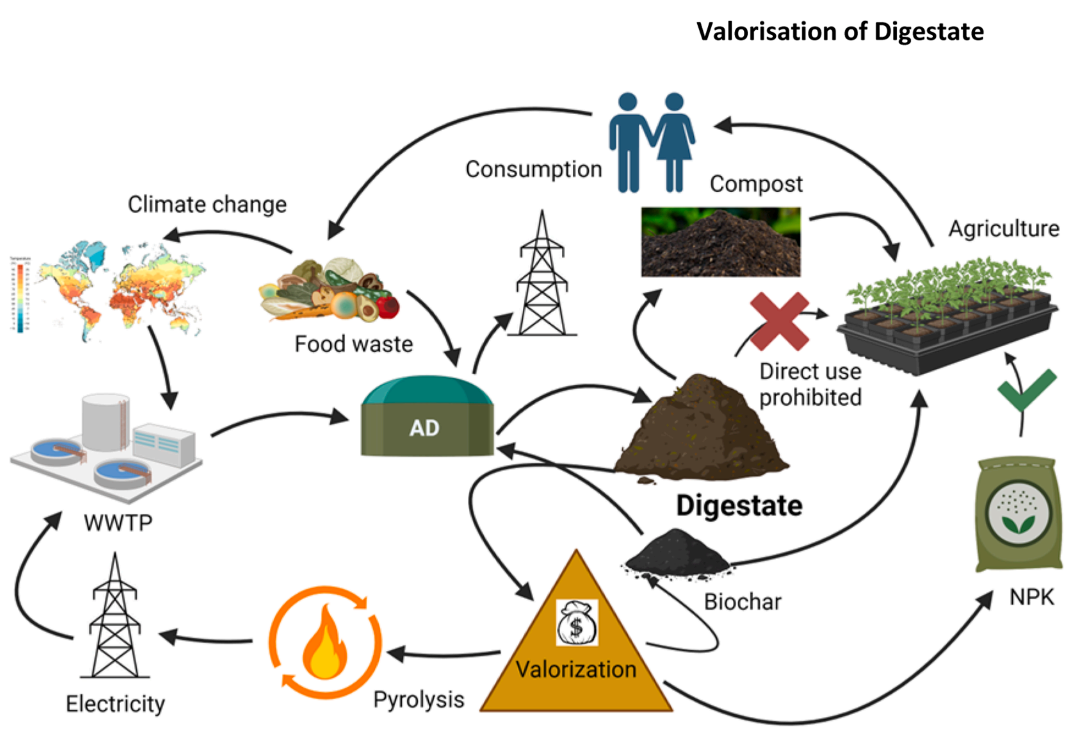


Fig. 1. Digestate generation and valorisation pathways.

products such as a feedstock for microalgal and fungal cultivation [15,16], liquid fertilizer, struvite, vivianite [17–20] biofuel production (biogas, biohydrogen and biodiesel) [21,22] compost [23] animal bedding, aquaculture and fish feed [24,25] and other applications.

While several recent reviews [26–29] explore digestate valorisation or its specific applications, there remains a clear need for a comprehensive and systematic review focused specifically on digestate characterization, valorisation pathways, product recovery, and the evaluation of economic sustainability, an aspect that has received limited attention and is critically addressed in this manuscript. Table 1 summarizes the limitations of recent studies and highlights the novelty of the present work.

This review aims to fill these gaps by comprehensively analysing the composition and characteristics of digestate derived from various feedstocks, including livestock manures, agricultural residues, food and vegetable wastes, industrial wastes, and Sewage Sludge (SS) as the first step. It then examines the challenges and opportunities associated with the valorisation of digestate, focusing on its potential as a nutrient-rich soil amendment, fertilizer, and renewable energy source. By providing consolidated data and insights into the characteristics and treatment of digestate, this work provides a comprehensive review of the different processes and the sustainable utilization of digestate in various applications. Some comments on the prospects and outlook are included at the end. The future of digestate valorisation looks promising with the need for an in-depth understanding of properties, optimized processes, standardized quality assessments, and integration with existing biogas and agricultural systems to enhance sustainability and economic viability.

2. Composition and characteristics of digestate and potential products for valorisation

2.1. Characterisation and composition of the digestate

Digestate consists of undigested feedstocks (organic and inorganic fractions), water and a mixture of micro and macronutrients [39]. To comprehend the properties of digestate, it is essential to examine the feedstock and its characteristics. The characteristic features of digestate highly depend on some major factors such as the feedstock/substrate (compositional and structural properties), microbial communities and the operational parameters employed during the process i.e., temperature, retention time, pressure, digester type and other relevant factors [40]. These factors significantly impact the properties and composition of the resulting digestate, leading to considerable variation. Consequently, no standard methods for digestate characterization have been established yet. Researchers typically use methods suitable for sludges and slurry to characterize their parameters. Fig. 3 illustrates the suitable characterization methods for ultimate, proximate, and compositional analyses of digestate. The most critical parameters such as pH and EC can be monitored using pH and EC electrodes. Researchers predominantly use the gravimetric method to determine total solids (TS) and volatile solids (VS). Spectrophotometric methods can be employed to measure chemical oxygen demand (COD), total organic carbon (TOC), total nitrogen (TN), ammonia, and total phosphate (TP), and alternative titration methods have also proved useful. Ultimate analysis (CHNSO) is necessary to determine the theoretical product generation potential of digestate using a CHNSO analyzer [41–43]. The consolidated characteristics data of digestate for different feedstocks from the published studies are illustrated in Table 2, and the elemental composition of digestates from various sources and their theoretical biochemical methane potential (BMP) capacity are listed in Table 3.

The diversity in digestate composition and nutrient availability (see Tables 2 and 3) has emerged as a significant obstacle to the utilization of digestate, posing limitations on the potential growth of biogas industries in the future. During AD, simple organic matter is converted into methane (CH_4) and carbon dioxide (CO_2) easily, while complex organic matter like lignin remains in the digestate, leading to an increase in its effective organic carbon (OC) content. Apart from the presence of a significant amount of suspended and colloidal organic matters, phosphorous and complex nitrogen, it is filled with significant amount of macro (N, P, K, S, Mg and Ca) and micronutrients (B, Cl, Cu, Fe, Mn, Mo, Ni and Zn) in the digestate [63–65].

Digestates exhibit elevated $N—NH_4^+$/TKN ratios and low C/N ratios when derived from highly degradable feedstocks such as poultry and pig manure, whereas low-N lignocellulosic feedstocks, such as sorghum and maize silage, result in low $N—NH_4^+$/TKN ratios in digestate [66]. Anaerobic digesters commonly utilize a variety of feedstocks, including livestock manures, corn and maize silage, waste feed, food and vegetable wastes, slaughterhouse wastes, dairy effluent, industrial wastes, and SS. Based on the availability and compositional changes, the produced digestate can be broadly categorized into four types, i.e., 1) Sewage sludge digestate, 2) Food/vegetable waste digestate, 3) Agriculture waste digestate and 4) Mixed feedstock digestate. Characteristics of digestate from different AD feedstocks are discussed in the following (classified as per the AD feedstock). The rheological behaviour and its significance on the digestate valorisation are also discussed collectively after discussing other digestate characteristics.

2.1.1. Sewage sludge digestate (SSD)

Sewage sludge (primary and secondary) is one of the important feedstock options for AD because of its abundance, richness in organic matter, and essential methane-producing microorganisms. Digestate

Table 1
Focus and limitations of recent reviews compared to the present study.

Focus	References	Limitations	Present Review
Digestate characterisation	[30–32]	• Limited discussion on feedstock-specific digestate behaviour • No discussion on digestate rheology	• Comprehensive discussion on composition, characterisation based on feedstock source, • Rheological behaviour and analysis methods. (Section 2)
Pre-processing methods	[28,33–36]	• Focussed on solid-liquid separation and nutrient extraction strategies (e.g., centrifugation, filtration) • Limited or no discussion of pretreatment technologies such as hydrodynamic cavitation, microwave-based systems, or MW-assisted hydrothermal methods • No consideration to approaches like co-digestion	• Dedicated analysis of physical and chemical pre-processing strategies. (Section 3) • Extensive overview of mechanical, thermal, chemical, and biological pre-treatments. (Section 3) • Extensive discussion on integrated preprocessing approaches like co-digestion, digestate recirculation on valorisation pathways
Valorisation pathways and products	[13,30,37]	• Focussed on products such as biochar, compost, and fertilizers • Limited details on energy recovery routes (e.g., residual biogas, syngas), or preprocessing	• Holistic mapping of valorisation routes: energy conversion, renewable fuels, fertiliser and other novel products. (Section 4) • Covered all major valorisation pathways and products
Techno-economics	[30,37]	• EU-centric, with minimal applicability to developing economies or small-scale plants	• Dedicated section (Section 5) for the technoeconomic aspects of digestate in the EU and other countries.
Policy frameworks	[28,29,31,38]	• Predominantly focused on EU and US regulatory frameworks • Lack cross-regional comparison and developing country context	• Discussed a comprehensive multi-regional policy overview and compliance mechanisms including EU, US, India, Ukraine, and other countries (Section 5).

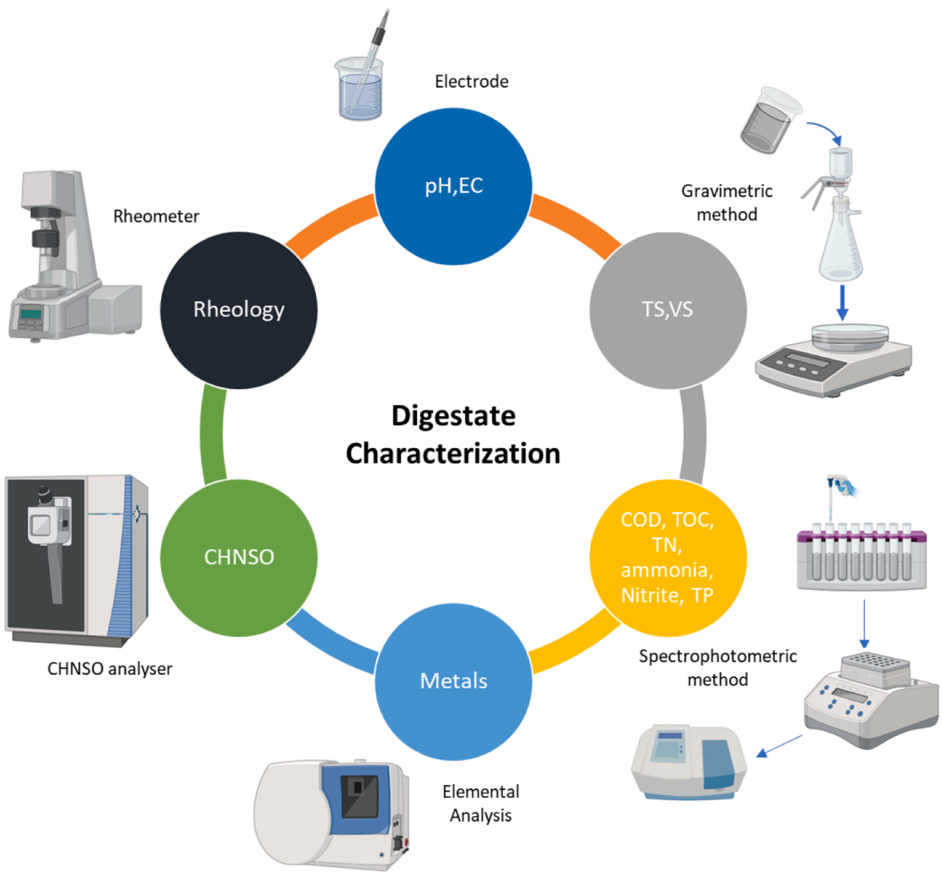


Fig. 3. Standard methods for digestate characterization.

Table 2
Characteristics of digestate based on their feedstock. WAS: waste-activated sludge; DM: Diary manure; PM: pig manure; SM: swine manure.

Categories	Feedstocks	pH	TS (g/L)	VS (g/L)	COD (g/L)	TOC (g/L)	TN (g/L)	TP (g/L)	References
SS	Primary WAS	7.9	28	15	18	–	2.75	0.480	[44]
	SS	6.62	18.4	5.6	–	–	0.039	0.032	
	SS	7.9	86	54	69.9	–	1.5	–	
	SS	7.60	52.7	30.4	46.1	0.612.7	–	–	
Agriculture residues	Wheat Straw	7.62	9.27	5.5	0.668	–	–	–	[45]
	Wheat Straw	7.88	6.31	3.97	0.591	–	–	–	
Food waste	FW	7.97	90	72	136.8	–	–	–	[36]
	FW	8.3	–	–	–	34.4	4.5	–	[46]
	FW	8.0	68.1	50.2	–		5.9	0.0485	[47]
	Sugar beet pulp	8.14	37.50	32.39	–	–	3.1	0.032	[48]
Animal manure	Guinea pig manure	7.10	7	3		0.139	–	0.188	[38]
	PM	7.63	25.6	16.3	–	–	174.61 g/kg DM	18.92 g/kg DM	[49]
	CM	7.81	23.8	15.3	–	–	229.83 g/kg DM	13.46 g/kg DM	
	DM	7.52	31.2	21.6	–	–	105.77 g/kg DM	6.75 g/kg DM	
	DM	–	66	51	23.76	–	3.45	0.249	[50]
	DM	7.49	70.7	32.5	84.9	–	1.6	0.961	[51]
	Sheep slaughter waste	7.91	68.7	41.9	3.8	–	49.95 g/kg DM	–	[52]
	Cattle slaughter waste	7.86	83.7	46.7	3.72	–	47.32 g/kg DM	–	
Mixed waste	Livestock waste and Agro waste	8.2	94	65	74	–	5.21	4.87	[44]
	Energy crops, Food industry by-products and Animal manure	7.9	96	73	–	–	–	–	[53]
	WWTP sludge and Dairy waste	7.8	93.44	51.71	97.17	21.51	4.35	1.83	[54]

produced from sludge-based AD retains substantial organic material and diverse plant nutrients, making it suitable for agricultural use as a fertilizer, except for certain extracellular polymeric substances (EPS) and harmful substances. The TS and VS of SSD lie between 7–8 % and 30–40 % of TS, respectively [40,67]. Some studies suggest the presence of potentially hazardous materials, such as high content of trace metals and

Table 3
Ultimate analysis of digestate (% dry basis).

Digestate source	C	H	N	S	O	Theoretical BMP (mL/gm VS)	CHNSO	References
FW	48.86	7.25	3.08	1.40	13.82	789	$CH_{1.8}N_{0.054}S_{0.011}O_{0.2}$	[55]
Biomass	46.70	5.50	1.50	0.50	36.90	492	$CH_{1.4}N_{0.027}S_{0.004}O_{0.6}$	[56]
FW	43.52	4.84	1.92	0.11	39.40	432	$CH_{1.3}N_{0.038}S_{0.001}O_{0.7}$	[57]
Biowaste	34.14	2.89	4.32	0.33	20	488	$CHN_{0.11}S_{0.004}$	[58]
Maize silage	46.60	5.80	1.10	0.08	40.70	473	$CH_{1.5}N_{0.02}S_{0.001}O_{0.7}$	[59]
Organic household waste	34.30	4.00	1.90	0.20	23.90	521	$CH_{1.4}N_{0.04}S_{0.002}O_{0.4}$	[60]
Cow manure digestate	42.60	5.00	2.00	0.40	34.30	478	$CH_{1.4}N_{0.04}S_{0.001}O_{0.5}$	
Energy crops digestate	40.30	4.60	2.10	0.30	24.00	569	$CH_{1.4}N_{0.045}S_{0.011}O_{0.6}$	
Groats (9 %), olive oil cake (29 %), silage of triticale (57 %) and chicken manure (5 %)	42.50	6.10	1.40	0.14	42.10	444	$CH_{1.7}N_{0.028}S_{0.001}O_{0.7}$	[61]
Animal sewage (43 %), cow manure (20 %), maize and triticale silages (25 %) and cereal bran (12 %)	43	6.20	1.30	0.14	39.50	473	$CH_{1.7}N_{0.13}S_{0.025}O_{0.8}$	
Solid swine manure	37.22	5.51	4.56	1.49	31.95	443	$CH_{1.7}N_{0.105}S_{0.02}O_{0.6}$	[62]
FW, Grass and Dairy waste	33.99	4.88	5.15	2.31	15.12	593	$CH_{1.8}N_{0.054}S_{0.011}O_{0.9}$	[54]

pathogens [68,69], and pharmaceutical residues [70], microplastics [71] and organic contaminants in SSD that might exceed the legal limits are not suitable for fertilizer [72]. The phytotoxicity nature of the sludge digestate is closely linked to the presence of low-weight carboxylic acids, trace metals, and phenols. The presence of excessive salinity and iron content in the sludge digestate also significantly hinders seedling germination [73,74]. Additionally, during the AD process, the complexation of aromatic carboxylic and phenolic functional structures in humic acids (HA) helps regulate the presence of metal ions [73]. A lower carbon conversion ratio, longer retention time, low volatile fatty acids (VFAs) conversion efficiency, and high recalcitrant materials in digestate limit mono-digestion of SS. However, adding co-substrates to co-digest with SS can enhance AD performance. The co-digestion could help the digestate quality in terms of diluted toxic compounds, synergistic effects on microbial growth, nutrient balance, increased organic loading rate, enhanced methane yield, and improved buffer capacity [75].

2.1.2. *Food waste digestate (FWD)*

Due to its relatively simple composition, food waste (FW) is highly desirable for AD and other biorefinery processes. Amidst the ongoing trend of urbanization and population growth, the excess of FW has transformed into a valuable organic resource, serving as a significant input to produce bioenergy. However, despite being nutrient-rich, the rural regions practice the traditional AD of FW and other organic wastes, such as animal manure and SS to satisfy the microbial diversity and sufficient feedstock load [76]. Typically, the generation of FWD per ton of FW feedstock is estimated at 0.20–0.47 tons [77]. Due to the abundant presence of salts and proteins in FW, the resulting FWD from the digestion process contains elevated levels of phosphate (PO_4^{3-}), ammonium (NH_4^+), sodium (Na^+), potassium (K^+), and chloride (Cl^-) ions [14, 76]. However, the phosphorus content in fruit and vegetable waste digestate is approximately 2.5 %, whereas swine dung digestate contains 4.5 % phosphorus [11,78]. Numerous studies indicate that the alkaline nature of FWD (with a pH ranging from approximately 7.5 to 9) can improve acidic soil properties by increasing pH, enhancing bioavailable nutrients, and boosting dissolved organic carbon and microbial biomass carbon levels. However, there is a risk of ammonia volatilization during the process and storage. Acidifying FWD with sulfuric acid can reduce the digestate pH and stabilize NH_4—N and prevent volatilization [15,79, 80]. FWD typically contains higher levels of ammonia nitrogen, ranging from 0.8 to 6 g/kg, and has a higher nitrogen-to-phosphorus ratio compared to other digestate like dairy or sludge based digestate [46]. It has a moisture content of about 65 % to 97 %, organic matter content of roughly 36 % to 90 % with 32 % of TOC (ranges from 12.8 % – 43.5 %), and TN content of around 1 % to 9.5 % with an average value of 6.4 % [14,81]. Lignocellulosic analysis of FWD shows similar cellulose and hemicellulose content (approximately 32–33 %) and about 13.4 % lignin, as reported in previous studies [82]. The lignin content in FWD is higher than in regular FW due to the low biodegradability of this complex organic polymer in the AD process [83]. FWD could be a good biofertilizer due to its micronutrient richness; however, details regarding the crucial trace elements it contains are still lacking. According to research, the FWD exhibits considerably reduced amounts of trace metals when compared to SSs and manures. These properties of FWD indicate the suitability for manufacturing organic fertilizer, biorefinery and other value-added products [84,85]. Moreover, the alkaline nature of FW helps preserve nutrient content during digestion by converting it into other chemical forms, such as struvite (magnesium ammonium phosphate) [86].

2.1.3. *Agriculture waste digestate (AWD)*

The agriculturally based feedstocks have more digestion and digestate valorisation difficulties than other feedstocks. In other words, the AD process preferentially targets hemicelluloses, leaving behind relatively higher amounts of cellulose and lignin in the solid residue after digestion [87,88]. Consequently, a range of treatment techniques (including physical, thermo-chemical, chemical, biological, or a combination of these methods) are necessary to degrade the stubborn layer of residual lignin and decrease the crystallinity of cellulose. By doing so, these treatment methods enhance cellulose accessibility to anaerobic microorganisms, facilitating a more efficient AD process [89] conducted a study on the properties of agricultural digestate, revealing that its pH typically ranges from slightly basic to around 7 to 8.5. The pH tends to increase when the amount of ammonia rises and when VFAs are converted to methane. Conversely, the pH decreases when carbonate and phosphate precipitation reactions occur or VFAs accumulate in the system. The TS content in AD digestate can vary widely, from 1 % to 25 %, depending on the biodegradability of the input substrates. Higher TS content is usually associated with lignocellulosic substrates, common in agricultural residues with lower digestibility. On the other hand, readily biodegradable substrates result in a digestate with lower TS content and a reduced ratio of VS to TS [90]. During AD, organic phosphorus is converted into orthophosphate, but approximately 90 % of phosphate interacts and precipitates with Ca^{2+} and Mg^{2+} cations, increasing the P concentration in the solid fraction of the digestate [91]. AD commonly utilizes feedstocks such as animal manure, the organic fraction of municipal solid waste and SS, for co-digestion with agricultural residues i.e. particularly lignocellulosic biomass, to maintain the carbon/Nitrogen ratio for AD process [92–94]. Thus, the digestate from energy crop or grass or agri-waste based AD comes under AWD. However, it is important to note that digestate produced by agricultural biogas plants may not comply with relevant soil regulations due to its higher lignin content. Thus, additional treatment is necessary to recycle the digestate and mitigate potential environmental risks.

2.1.4. Mixed waste digestate (MWD)

Mixing different feedstocks for AD provides several advantages, including improved biogas production, minimization of digestate, process stability, waste utilization, and flexibility. Additionally, as discussed above, the characteristics of the digestate, such as nutrient content, heavy metal levels, pH, alkalinity, and organic matter, can be influenced by the composition of the feedstock mix. This makes it important to carefully manage the selection and combination of materials for optimal outcomes; for example, pig slurry as a feedstock contains more potassium [95], whereas co-digested cattle slurry can increase the concentration of phosphorus [96]. Livestock manures with other feedstock, though lower-energy feedstocks are a popular choice for AD because they possess neutral pH, high buffering capacity, and a natural mix of anaerobic microbes, making them suitable for digestion. Moreover, manure offers abundant nutrients and can be easily obtained in large quantities. AD can also effectively handle animal wastes mixed with bedding, like chicken litter containing wood chips or sawdust [97]. In such cases, the woody material passes through the digestion process without breaking down due to its lignin structure. Since certain energy-dense feedstocks are acidic, lack naturally occurring microbes, and may be nutrient-deficient, using manure as a base is essential to support efficient AD [98,99]. By blending different feedstocks, farms operating AD systems can increase biogas production and balanced nutrient-rich digestate, potentially benefiting from additional revenue through fertilizer. A complete blend of seed digestate containing cattle manure 45 %, corn silage 25 %, chicken manure 15 %, and olive pomace 15 % can be a good feedstock for hydrogen production [100]. However, in some cases the addition of mixed substrate to balance the N content in AD of maize silage resulting the increase of nitrogen in the final digestate [101].

This divergence in digestate properties arises from the diverse array of organic materials fed into the anaerobic digester. Factors such as the carbon-to-nitrogen ratio, moisture content, nutrient concentration, and presence of contaminants influence the resultant digestate's behaviors. Consequently, the valorisation methods employed for digestate must be optimized to tackle this variability. Depending on the specific digestate composition, various valorisation routes can be pursued. For instance, digestate with higher nutrient content can be utilized as a nutrient-rich soil amendment or fertilizer, enhancing agricultural productivity and reducing the need for synthetic fertilizers. Similarly, digestate rich in organic matter and energy content may be directed towards upgrading biogas to enhance its potential as a renewable energy source and extracting other value-added products.

2.2. Rheological behaviour of digestate

It is important to understand and quantify the rheological behaviour of digestates (including yield stress and non-Newtonian viscosity), as it significantly impacts the overall fluid mechanics of mixing, mass transfer (including diffusion and convection), and the power requirements for handling digestate. The complex rheological properties are closely associated with the water content in the digestate [102]. Rheological properties such as viscosity and flow behaviour are critical for determining how effectively digestate can be mixed and transported within pre-treatment units and anaerobic digesters. Digestate typically exhibits shear-thinning behaviour, meaning its viscosity decreases with increased shear, which enhances mixing efficiency and biogas production while reducing energy consumption for agitation [103]. Elevated viscosity in digestate can impede mass transfer and microbial interactions, thereby reducing organic matter degradation and biogas yield. For instance, substrates with lower viscosity have shown up to 7.6 % higher biogas production and a shift in microbial community toward more active methanogens, demonstrating better microbial access and mass transfer benefits [104]. Higher viscosity also impairs post-digestion solid-liquid separation and increases the energy demands of pumping and filtration systems. Therefore, understanding and managing rheology through feedstock selection, temperature control, or pretreatment is essential for improving both digestion performance and downstream processing. A higher TS content in the digestate leads to increased resistance to deformation, resulting in inadequate mixing and the formation of dead zones within the system, which impede the flow [105]. Additionally, poor kinetic properties contribute to the accumulation of VFAs and ammonia, further reducing methane production [106]. Table 4 provides an overview of the reviewed studies, detailing the measurement systems used, the source of digestate, the TS content of the digestate, and specific outcomes from the studies. Certain pretreatment methods, such as hydrodynamic cavitation or ultrasonic, affect the biomass or digestate's rheology and help increase the digestate's biodegradability. Garuti and their team studied how HC affects the viscosity and particle size of digestate, which helps reduce the energy required for mixing, heating, and pumping. Their findings showed that viscosity decreased with increasing rotational speed, with up to a 37 % reduction observed after shredding and HC treatment of the digestate compared to the untreated sample [107]. All investigations have concurred that an increase in TS content results in elevated viscosity and consistency index (K), leading to challenges in mass transfer. The relationship between rheology and mass transfer has been discussed qualitatively rather than quantitatively [108]. Various studies on the rheological behaviour of SSD have examined variables such as temperature, TS content, and hydraulic retention time. It is suggested that solids in the fluid plays a crucial role in inducing non-Newtonian flow behaviour, more significantly than temperature [108–110].

3. Digestate valorisation preprocessing

Valorising digestate is crucial for sustainable waste management by transforming it into valuable products. This approach aligns with circular economy strategies by closing the resource loop. There is a significant potential to convert this nutrient-rich material into an array of valuable products, including biofertilizers, biogas with potential energy applications, and even specialized chemicals that find utility in diverse industrial sectors. The presence of undigested complex materials, lignin, and recalcitrant compounds challenges valorisation. Therefore, preprocessing is essential to reduce complexity and facilitate further digestate processing for valorisation. Preprocessing makes the digestate acceptable for agriculture by removing pathogens and pollutants using techniques like pasteurization and ammonia stripping [39,116,117]. An appropriate preprocessing tailored to the specific digestate source can enhance carbon conversion, enhance biodegradability, reduce nitrogen content, decrease toxicity, and improve nutrient recovery (Fig. 4).

It also produces more homogeneous fractions, facilitating easier use as soil conditioners and fertilizers. This preprocessing of digestate can be broadly categorized into three sections: 1) Solid-liquid separation, 2) Co-digestion/recirculation, and 2) Pretreatment. The solid-liquid separation reduces volumes for improved handling, decreases transportation and storage costs, and enables substance fractionation into concentrated solid and liquid fractions for further valorisation. Various pretreatment methods for digestate are often necessary to improve its quality, enhance biodegradability, reduce phytotoxicity, accelerate stabilization, conserve nutrients, and to improve its valorisation potential. The specific sections of this review covering the relevant steps/ products are also indicated in Fig. 5.

3.1. Solid -liquid separation

Digestate is a semi-solid, heterogeneous mixture consisting of concentrated suspended solids and dissolved substances in an aqueous medium. A typical digestate from an AD plant has a high-water content and a relatively low dry matter (DM) percentage, between 2–10 % (as shown in Table 2). However, the presence of higher DM was noticed in the case of grass-based digestate [118]. This highly diluted digestate can hinder further valorisation processes and complicate transportation and

Table 4
Rheology of digestate.

Composition of digestate	TS [%]	Measurement system	T (°C)	γ' [s $^{-1}$]	Parameter [K in Pa s ^{n}]	Flow behaviour	Results	Reference
FW and SS	25.52	Rotational rheometer	25	0–100	K = 214.640 ± 14.542 n = 0.195 ± 0.020	Shear thinning	The mass diffusion coefficient decreased logarithmically as the TS content increased.	[111]
WAS	4.10	Stress controlled rheometer	25	1 to 300	K = 1.31 n = 0.20	Shear thinning	The hydrolysis rate is indirectly proportional to rheological properties (flow consistency index, yield stress, and viscoelastic module)	[112]
WAS	5.02	Stress controlled rheometer	20 ± 1	–	K = 2.33	–	Rheological measurements may indicate the hydrolysis stage, VS removal efficiency, and the dewaterability of the digestate.	[112]
Digested rye and maize silage mixture	8	Rotational rheometer	38	50 to 5000	K = 50.6 n = 0.1	Shear thinning	An increase in TS resulted in a rise in apparent viscosity, with the yield stress and consistency index following an exponential equation.	[113]
Cow slurry with straw	11.6	Magnetic Bearing Rheometer	37	–	K = 0.43 n = 0.8	Shear thinning	Slurries are highly viscous and display shear-thinning, non-newtonian behavior with negligible yield stress.	[114]
PM, energy crops, triticale silage, beet molasses, grain meal	–	Torsion viscometer	42	–	–	Shear thinning	Viscosity decreased with increasing rotational speed, with up to a 37 % reduction observed after shredding and hydrodynamic cavitation treatment of the digestate.	[107]
CS, green plant silage, Crop, manure, dung, grass silage	3.8–12.8	Mixing rheometer	40	1–10,000	K= 2.11–3.67 n= 0.24–0.28	Shear thinning	The viscosity of centrifuged digestate remains significantly higher than that of water.	[115]

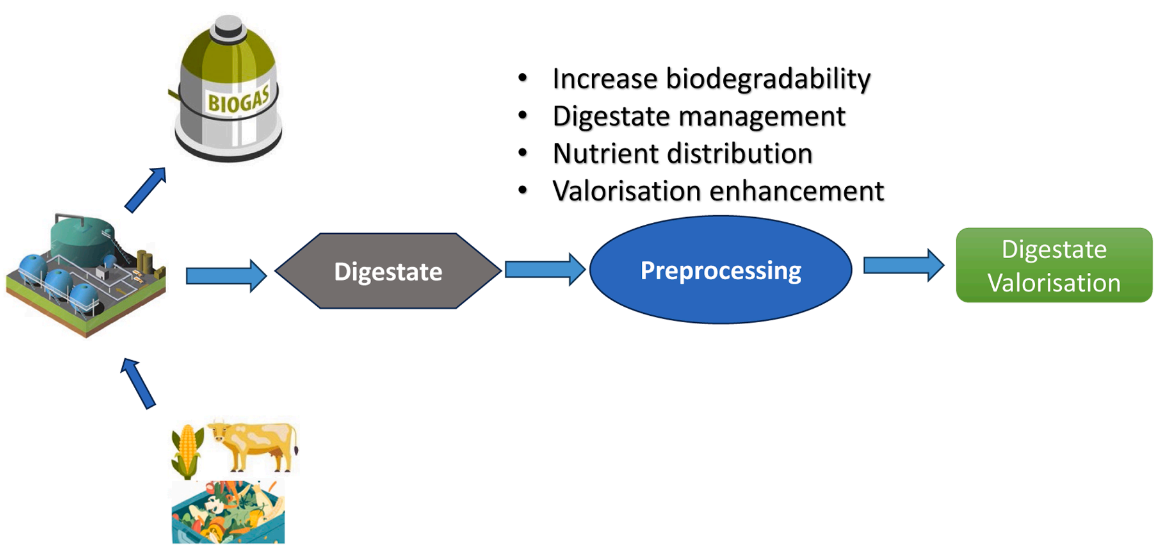


Fig. 4. Advantages of preprocessing for digestate valorisation.

storage. Efficient separation of digestate opens numerous opportunities for independent utilization or processing, enabling better control over valorisation processes [86,119]. Consequently, digestate processing often involves multiple treatment steps, with solid-liquid separation typically being the initial process [90]. The major components of the solid /liquid fractions are DM (mainly containing organic matter), TN and TP. The solid fraction (SF) of digestate mainly contains undigested substrates, recalcitrant fibers, organic nitrogen, total phosphorus, and a liquid fraction (LF) carrying most of the water, ammonical nitrogen, and total potassium [120]. The nutrient flow in the separation process analysed by [121] indicated that >87 % of nitrogen flows to the liquid fraction, while the solid fraction contained only 13 % of the total nitrogen. Therefore, nitrogen recovery is probably easier and more convenient from LF of digestate than from SF. This study claimed the liquid fraction accounted for 87 % of total kjeldahl nitrogen (TKN), and 71 % of P_2O_5, while the solid fraction accounted for 13 % of TKN, and 29 % of P_2O_5. Due to the redistribution of nitrogen (N) and phosphorus (P) between the solid and liquid fractions, the N/P ratio typically increases in the liquid fraction. This results in a more balanced nutrient profile for crops and helps reduce phosphorus buildup in the soil.

The separation methods are typically classified as mechanical, chemical, biological or a combination thereof, depending on the process type and resulting by-products [48]. The discussion emphasizes conventional separation methods due to their proven cost-effectiveness and practical applicability. In contrast, many novel techniques, while promising, are still in early stages and lack techno-economic viability at scale. Among these separation techniques, screw press and centrifugation are the most well-known mechanical separations because of their efficiency and influence on the LF and SF properties.

3.1.1. *Screw press*

Screw presses operate by separating materials based on particle size, pushing the digestate against a mesh screen. This process allows liquids and smaller solids to pass through the mesh, forming the liquid fraction. The effectiveness of dewatering depends on the specific screens used and the DM content of the feedstock substrate [90,122]. In a case study

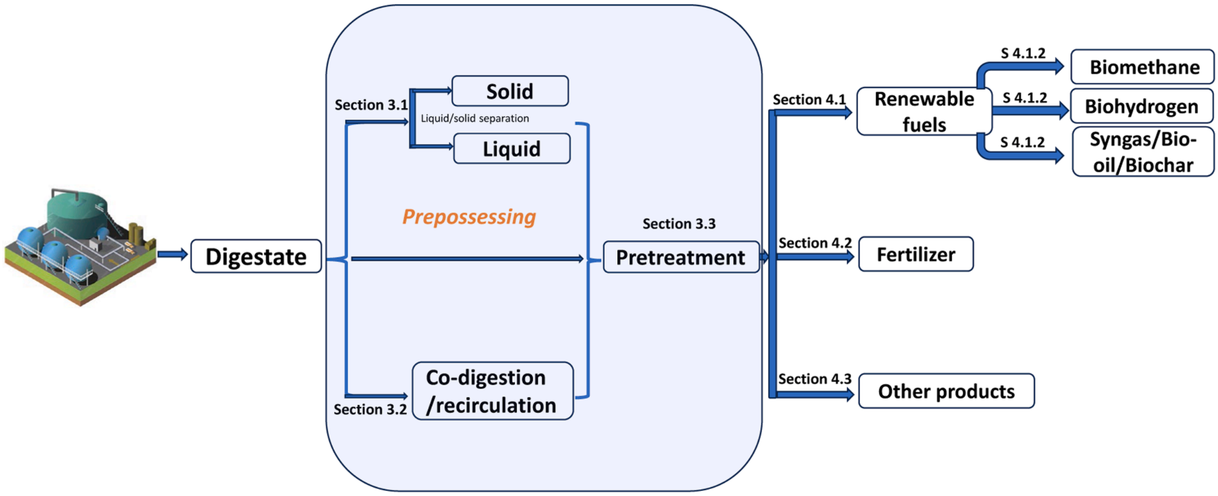


Fig. 5. Processes for digestate valorisation.

conducted by [123] indicated that the screw press effectively increases the DM content in the solid phase of the digestate. On average, 61.8 % of the DM from the inflow is recovered in the solid fraction. Similar trends were observed for VS, ash, and carbon components. For example, the VS content in the inflow was 5.38 %. In the solid phase, VS increased to 16.54 %; in the liquid phase, it dropped to 3.13 %. Approximately 58 % of the VS from the inflow was present in the solid phase. These partition tendencies highlight the effectiveness of the screw press separator in concentrating valuable components of the digestate. Another study done by Tambone and the team indicates the DM separation efficiency of 32.5 % (Solid phase) and 68.5 % (liquid phase) achieved using a screw press separator [121].

3.1.2. Centrifugation

Among other phase separation techniques such as screw press, filtration and sedimentation, decanter centrifuge is the most efficient process . Decanter centrifuges operate on the principle of density separation by spinning digestate within a rotating bowl, the solids are pushed toward the bowl's wall by an internal drill, facilitating their separation. Compared to screw presses, decanter centrifuges can retrieve smaller particles as they aren't constrained by mesh screen size. Decanter centrifuges come in both vertical and horizontal configurations. This rotation generates centrifugal force, causing solids and liquids to segregate along the wall, forming an inner layer with a high DM concentration and an outer layer comprising a liquid mixture containing colloids, organic materials, and salts. Separation using a decanter centrifuge produced a greater mass of solid fraction compared to screw press separation. However, it consumes more energy compared to screw press. According to a study, the two-hour screw press operations consumed around 10 kWh of electricity, whereas the three-hour decanter centrifuge runs required approximately 15 kWh to power the mixer [124].

In a recent review, [125] discovered that while decanter centrifuges demonstrate superior efficiency in partitioning phosphorus (P) into the solid fraction compared to screw presses, there remains substantial variability in reported separation efficiencies, with total P partitioning ranging from 6 % to 33 % for screw presses and from 40 % to 82 % for decanter centrifuges. In a recent study conducted by [124], it was found that the decanter centrifuge demonstrated a higher efficiency in separating phosphorus compared to the screw press. The phosphorus separation efficiency of the decanter centrifuge ranged from 51 % to 71.5 %. In contrast, the screw press exhibited efficiencies ranging from 8.5 % to 10.9 % for digestate containing approximately 5 % solids, such as slurry/grass silage mix. By utilizing the decanter centrifuge, up to 56 % of nitrogen was found to be partitioned into solid fractions. The separation efficiency could be $>$ 20 % in the case of a decanter centrifuge as compared to a screw press of $<$ 5 %. However, the wide range of reports on separation efficiencies and diverse feedstocks suggests that factors such as feedstock properties, separation methods, and specific separator settings all contribute to the observed separation efficiencies and nutrient distribution in LF and SF. Table 5 summarizes the separation efficiency of both the screw press and the decanter centrifuge for pig and cattle slurry. Table 6 compares the parameters between the screw press and the decanter centrifuge.

Overall, the choice of separation method depends on the desired outcome: screw presses are more energy-efficient and simpler to operate, but decanter centrifuges offer greater separation efficiency, particularly for phosphorus and nitrogen. However, factors such as feedstock characteristics, desired nutrient distribution, and energy considerations must be carefully evaluated to select the most appropriate technology for specific applications.

The solid and liquid fractions obtained after digestate separation can be individually valorized through various pathways. The solid fraction is suitable for applications such as anaerobic digestion, biohydrogen production, and biochar synthesis, as outlined in Sections 4.1.1, 4.1.2, and 4.1.3. In contrast, the liquid fraction can be utilized for ammonium recovery and microalgae cultivation, as described in Sections 4.3.1 and 4.3.2. The liquid digestate (LD) is typically rich in dissolved ammonium nitrogen, phosphorus, suspended and colloidal solids, and pathogenic microorganisms. Membrane-based technologies have emerged as an effective strategy for the removal of these contaminants and the recovery of valuable nutrients, thereby enhancing the overall sustainability of digestate management.

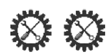
3.2. Co-digestion and recirculation of digestate

The properties of digestate indicate a low C/N ratio and the presence of high bacterial biomass and other recalcitrant substances, regardless of the feedstock used. To maximize the C/N ratio and minimize inhibition, co-digestion and recirculation could be effective options for valorisation. Co-digestion of different feedstocks offers several benefits,

Table 5
Separation efficiencies for pig and cattle slurry [126].

	Screw press		Decanting centrifuge	
Separation efficiencies	Solid	Liquid	Solid	Liquid
Mass separation efficiency (%)	10.0	90.0	12.6	87.4
DM separation efficiency (%)	32.5	68.5	50.9	49.1
Nitrogen separation efficiency (%)	13.1	86.9	24.6	75.4
Phosphorus separation efficiency (%)	28.4	71.6	63.9	36.1
References	[121]		[127]	

Table 6
Comparison of operational parameters between screw press and decanter centrifuge.

Separator	Screw press	Decanter centrifuge
Low-concentration sludge		
Cake dryness		
Power consumption		
Footprint (Physical space)		
Trained operator requirement		
Maintenance		
Shelf life		
Noise		
Operational cost		

including organic matter stabilization, enhanced energy generation, and increased microbial digestion rate [128]. Previous studies also suggested that digestate recirculation in a two-stage system can enhance substrate conversion and reduce chemical costs. This improvement is due to preventing VFA accumulation through rejuvenating fermentation bacteria, which consequently reduces the amount of chemicals needed to maintain optimal pH levels [129]. The possible scenario of an integrated system involving the pretreatment and recirculation of digestate could be an effective solution for extracting more energy from digestate. LD can help stabilize digestion and boost methane production by reducing ammonia loss and maintaining alkalinity. It can also be used to dilute feedstocks, like dairy sludge, that need better bacterial digestion [7, 130]. The highest biogas production recorded was 8.5 and 12.4 L kg^{-1} VS d^{-1} under mesophilic and thermophilic anaerobic co-digestion conditions, respectively. These were achieved using a 1:1 ratio of digestate and rice straw. This resulted in increases of 46.6 % and 25.3 %, respectively, compared to the control groups [131]. Optimizing the digestate-to-substrate ratio is crucial for efficient biogas production. A study conducted by [100] found that the optimal biohydrogen yield was 50.4 mL/g VS (45.8 mL/g COD) when using seed digestate to FW ratio of 6:4 at pH 6.5 resulting in a COD removal rate of 43.33 %. However, despite these benefits, there are some limitations. The need to optimize the digestate-to-substrate ratio is crucial for achieving efficient biogas production, as an improper balance can hinder microbial activity. Furthermore, the risk of VFAs accumulation and high operational costs in managing the recirculation process can limit the scalability of this approach. Careful system design and substrate selection are essential to harness the full potential of co-digestion and digestate recirculation.

3.3. *Pretreatment for valorisation*

The main objective of digestate pretreatment is to break down complex organic materials (enhance the hydrolysis effect), reduce contaminants, and enhance the potential for valorisation (Fig. 6). The discussion on digestate pretreatment is quite limited and closely resembles biomass pretreatment methods. Therefore, all biomass pretreatment techniques are applicable to digestate pretreatment. Additionally, the characteristics of digestate are largely influenced by the pretreated AD feedstock. Pretreatment methods for digestate valorisation are broadly divided into three major categories: physical, chemical, and biological, each defined by its mechanism of action. Physical pretreatments include mechanical, thermal, ultrasonic, microwave, steam explosion, and electrochemical. Chemical pretreatments use substances such as alkaline and acidic, ozonation, Fenton, wet oxidation, and inorganic salts. Biological pretreatments employ enzymatic and fungal processes to degrade organic matter efficiently. Physical pretreatment typically demands high energy input, chemical methods can produce secondary pollutants, and biological processes tend to be slow and less effective. Choosing the appropriate pretreatment method is crucial and should be based on the physical and chemical characteristics of the substrate to meet specific requirements and energy requirements effectively [132]. However, pretreatment methods must fulfil specific criteria, including reducing substrate size and enhancing porosity, improving the substrate's degradability and solubility, eliminating inhibitory compounds, and requiring lower energy input to ensure cost-effectiveness. Here, we discussed some of the promising pretreatment technologies for digestate valorisation [133].

Cavitation-based pretreatment is an emerging method known for its non-chemical nature, low energy consumption, and high yield. Cavitation is the formation and implosion of vapor-filled cavities or bubbles in a liquid, caused by rapid changes in pressure. This process generates intense local energy, including high temperatures and pressures, and shock waves [135]. Bubble collapses produce free radicals that accelerate chemical reactions, facilitating the synthesis of nanomaterials and

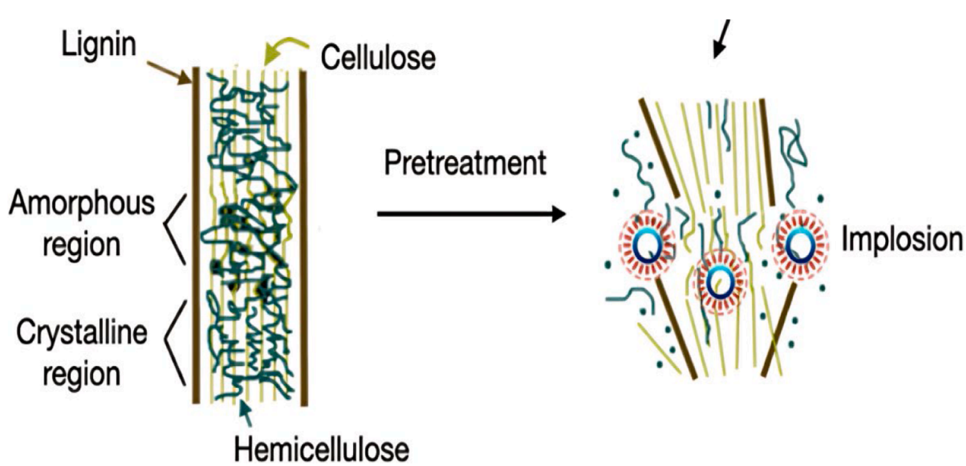


Fig. 6. Pretreatment effect for lignocellulosic biomass (Open access [134]).

polymers, as well as the degradation of organic pollutants. Cavitation offers significant advantages in sludge disintegration [136]. The intense local energy generated by the implosion of cavitation bubbles effectively breaks down the complex organic molecules in sludge, reducing particle size and increasing the surface area available for microbial action [137–140]. This enhances the hydrolysis process, making the sludge more amenable to subsequent biological treatments such as AD. The improved breakdown of organic matter leads to higher biogas production and increased methane yields. Hydrodynamic cavitation (HC) based pretreatment has recently demonstrated high effectiveness in both laboratory and industrial settings for converting lignocellulosic biomass (LCB) into value-added products (Fig. 6). Another study on hydrodynamic cavitation (HC) based pretreatment method was developed to enhance the AD of DAF sludge. The pretreatment demonstrated a significant increase in BMP, surpassing 82 % of theoretical BMP, with VS removal exceeding 73 %. The highest methane yield achieved was 756 mL/g VS of sludge. The net energy gain (after subtracting the energy required for pretreatment) was found to be over 100 kWh/ton of sludge [7]. The net energy gain from a specific pretreatment condition is determined by considering the additional biomethane generated as a result of the pretreatment and the energy consumed during the pretreatment process. The energy consumption (E_C) for HC-based pretreatment can be calculated using Eq. (1) as:

$$E_C = \frac{\Delta P\ n}{3.6\ \times 10^6\ \eta}\ \frac{kWh}{m^3} \tag{1}$$

Where ΔP = pressure drop, n number of passes through the cavitation device and η = efficiency of the pump. The energy gained by HC pretreatment can be calculated using Eq. (2):

$$E_G = \Delta H_{cal}\ y_{VS}[\Delta G_{max}]\ \frac{kWh}{m^3} \tag{2}$$

Where ΔH_{cal} is a typical electricity generation of methane (10 kWh/m^3), y_{VS} is %VS of the co-digested sample (w/w) and ΔG_{max} is enhanced generation of methane per ton of VS due to HC pre-treatment. Considering typical values for digestate, E_C is ~100 kWh/m^3 and E_G is ~102 kWh/m^3 [54].

The vortex-based HC devices and pre-treatment based on these have been scaled up to 50 m^3/h and have been implemented in commercial plants [141]. The HC pre-treatment based on rotor–stator devices has also been scaled up and used in operational biogas plants [107]. These developments indicate the potential of modular and retrofit-ready HC pre-treatment units for installation upstream of digesters to enhance substrate digestibility, reduce hydraulic retention times and enhance biomethane yield. Digestate contains a significant amount of recalcitrant and lignocellulosic materials, making hydrodynamic cavitation a better option for valorisation.

Like HC, ultrasound (US) employs cycling sound pressure waves with a minimum frequency of 20 kHz to generate cavities in the liquid. When these cavities implode, they produce mechanical shear forces that break down organic matter, reduce particle size, and hydrolyze complex organic compounds into more soluble molecules [142]. This reduction in particle size results in an increased surface area, thereby enhancing the hydrolytic rate of microorganisms. A study showed ultrasound power intensities ranging from 0.05 to 0.21 kW/L (equivalent to 4.13 to 16.52 kW h/kg TS) were applied at a frequency of 20 kHz for durations of 5 to 20 min to digestate from a domestic wastewater treatment plant. The highest release of material was observed at an ultrasonic energy intensity of 0.21 kW h/L. Additionally, the impact of ultrasound on methane (CH_4) production was examined through the AD process. Applying ultrasound at intensities of 0.05 to 0.21 kW h/L resulted in a 1.6 to 2.3-fold increase in net CH_4 production. Energy analysis revealed that only about 4 % and 11 % of the energy input was recovered as additional CH_4 production at 0.21 and 0.05 kWh/L, respectively [142].

Another pretreatment method, Microwave-assisted hydrothermal pre-treatment (MLHT) is an efficient biomass processing method that enhances the breakdown of organic matter, particularly in low-cellulose digestate, through dehydration and decarboxylation at reduced carbonization temperatures. In a study by Deng and colleagues, MLHT was applied to digestate derived from grass silage, resulting in significant improvements in the quality of the produced hydrochar. At 180 °C, the hydrochar from digested grass silage exhibited a mass yield of 0.79 g/g TS, with a carbon content of 63.6 % and an ash-free heating value of 27.6 kJ/g VS. Additionally, the process liquor generated during MLHT had a biomethane potential of 68.7 mL CH4/g TS, demonstrating the potential for bioenergy recovery alongside hydrochar production [143, 144].

Among other biological pretreatment, enzymatic hydrolysis is a process that involves the breakdown of bio-macromolecules, such as polysaccharides and proteins, into monomers like amino acids and sugars through the action of specific enzymes such as proteases and cellulases. To ease the AD process enzymatic hydrolysis is an important process of pretreatment [145]. The research investigated the utilization of the solid fraction of digestate in contrast to wheat straw, serving as a benchmark for the production of lignocellulolytic enzymes (including endo- and exo-glucanase, xylanase, β-glucosidase, and laccase) by fungi [146]. Chemical treatments, mainly with sodium hydroxide, can enhance the sugar yield of digested manure during enzymatic hydrolysis. Additionally, digested manure contains various nutrients essential for sugar fermentation by yeasts or bacteria. The elimination of lignin could enhance cellulose hydrolysis, and the recovered lignin post-lignocellulosic fermentation holds significant potential for fermentative valorisation due to its elevated heating value (ranging from 21.5 to 23.5 MJ/kg on a dry basis [147,148].

This section outlines three main categories of pretreatment technologies for digestate valorisation: physical, chemical, and biological. Preference is given to pretreatment technologies that do not require the external addition of chemicals or enzymes. Their non-chemical nature offers particular advantages for downstream processing by reducing the risk of secondary contamination and preserving the quality of the digestate for subsequent recovery or reuse applications. An attempt has been made to estimate the CAPEX/OPEX of three pretreatment methods: HC, MW, and MLHT, which operate without the use of chemical or biological additives. The technology readiness level (TRL) of MLHT remains low, and therefore, reliable estimates of CAPEX and OPEX are not available. To the best of the authors' knowledge, MW treatment has not yet been applied in commercial AD plants. However, some pilot tests have been conducted in recent years. The HC pretreatment method has been implemented at a commercial scale. Obtaining reliable CAPEX and OPEX values remains challenging due to confidentiality constraints. Private discussions with developers and suppliers of MW and HC pretreatment technologies have been conducted, and ranges of energy consumption and CAPEX are included where possible. These quoted values, while not referenced due to their confidential nature, may serve as reasonable indicators of CAPEX and OPEX. Pilot tests of MW-based pretreatment indicate energy requirements in the range of 40–60 kWh/ton. The estimated CAPEX of an MW pretreatment unit for processing 50 tons/day of feed is approximately €200,000 to €500,000. Energy requirements for HC-based pretreatment are in the range of 4–10 kWh/ton, with an estimated CAPEX of €100,000 to €200,000 for a 50 tons/day processing unit.

Some physical pretreatment methods are used in full-scale applications, but they often face drawbacks such as high energy consumption, costly maintenance, and the formation of unforeseen by-products. Techniques like microwave radiation and pulsed electric field pretreatment are still in the developmental phase and are primarily applied at the batch or pilot scale. MLHT is particularly notable for its ability to produce high-quality hydrochar and improve biomethane potential. However, very little work has been done on digestate pretreatment and technoeconomic analysis using these methods. Table 7 compares these methods based on their efficiency and advantages. Moreover, the choice

Table 7
Comparison of the pretreatment methods.

Feature	Hydrodynamic Cavitation	Microwave-Assisted Pretreatment	Microwave-Assisted Hydrothermal Pretreatment (MLHT)
Mechanism	Formation and implosion of vapor-filled cavities	Rapid heating of biomass through microwave radiation	Microwave heating combined with hydrothermal reactions
Energy	Consumption Low energy consumption	Moderate energy consumption	Moderate to high energy consumption
Temperature	Range Typically operates at ambient to moderate temperatures	Generally higher temperatures	Operates at temperatures between 160 °C and 230 °C
Effect on Biomass	Reduces particle size and enhances surface area	Improves solubilization of organic matter	Enhances breakdown of organic matter, especially low-cellulose digestates
Pretreatment Efficiency	High efficiency in disrupting lignin-carbohydrate matrix.	Effective in breaking down complex structures, varies with material.	Highly effective in specific localized treatments
Benefits	Non-chemical, environmentally friendly	Fast processing, effective for various feedstocks	High-quality hydrochar production and effective for low-cellulose digestates
Limitations	Limited studies on digestate	Process optimization required	Need for scalability and integration into existing processes
Applications	Sludge treatment, biomass valorisation	Biomass pretreatment for anaerobic digestion	Hydrochar production and bioenergy recovery from digestate

of pretreatment methods and the sequence of the pretreatment processes are influenced by the characterization of the digestate and the desired end products. Fig. 7 describes possible options for the pretreatment of digestate to enhance residual methane production or another valorisation.

4. Digestate valorisation pathways and products

In continuation of the previous section, the valorisation process and the products are significantly dependent on the digestate characterization. Considering the composition of the material, there are several alternative pathways and products for valorisation. These pathways include nutrient recovery, where essential elements like nitrogen and phosphorus are extracted for fertilizers, maximizing the material's potential to enhance agricultural productivity. Another approach involves utilizing the organic fraction to produce biogas and biohydrogen, converting organic matter into renewable energy. Additionally, the lignocellulosic components can be employed in the production of biofuels or bio-based chemicals, contributing to sustainable energy and materials.

4.1. Renewable fuels

4.1.1. Biomethane

In countries like Germany, high energy costs and supportive government incentives make the use of digestate for nutrient-rich irrigation more attractive than bioenergy production. In contrast, in North America, where energy prices are relatively low, operators often seek alternative revenue streams to maintain economic viability. As a result, converting digestate into bioenergy represents a valuable approach for nutrient recovery and reuse in the North American context [149].

AD involves converting approximately 20 % to 95 % of the carbon (C) present in the feedstock into gaseous carbon compounds, with a specific percentage depending on the feedstock type and its resistance to decomposition [150]. The remaining digestate may be degraded 15 to 25 % in the storage tank via post-methanation, where the digested waste is often kept for months before application to agricultural land. This process reduced the revenue and generated GHGs for the environment. There is a huge potential for residual biogas generation from digestate.

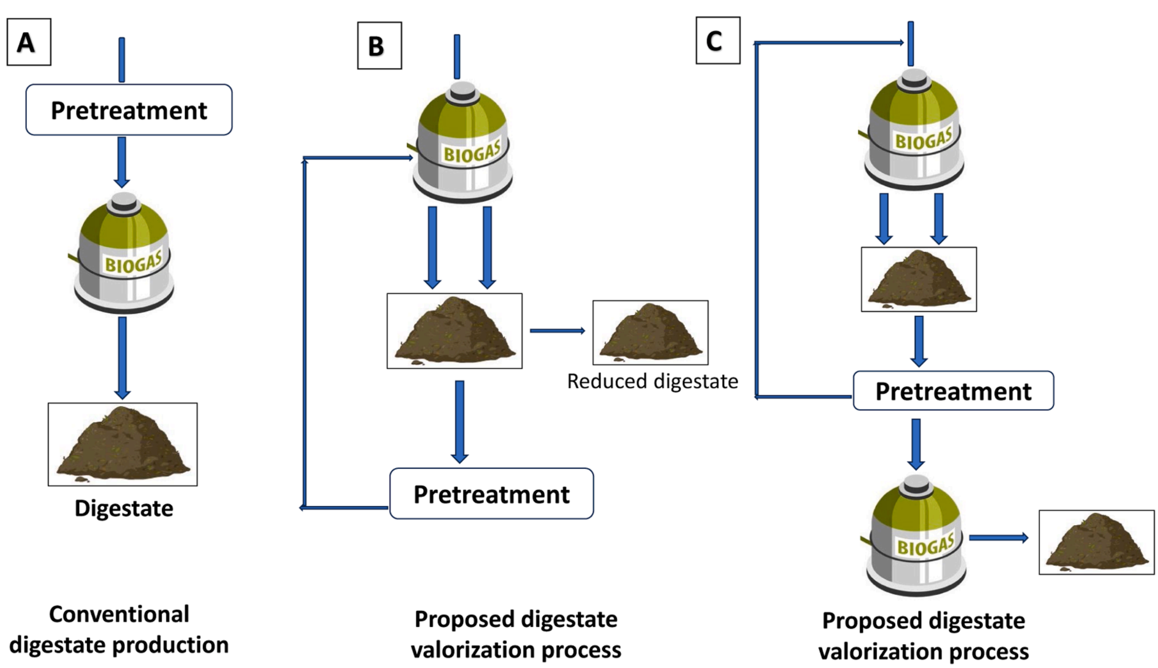


Fig. 7. Possible options for digestate pretreatment for valorisation: A) Conventional feedstock pretreatment; B) Recirculation of pretreated digestate; C) Pretreated digestate to secondary digester.

Table 3 mentioned the theoretical residual BMP of digestate according to the elemental analysis data. However, that amount of methane generation would not be possible due to the presence of indigestible materials. The post-treatment of digestate reduces greenhouse gas emissions from storage or land application and enhances methane recovery. The remaining percentage of organic matter and carbon in digestate depends on two vital parameters to convert into biogas: 1) hydraulic retention time (low) and 2) organic loading rate (high) in the AD process, apart from the C/N ratio. Analysing data from Table 2 and 3 on digestate sources and compositions reveals a notable amount of carbon percentage and their theoretical BMP or other carbon-based products. Digestates from FW and biomass exhibit higher carbon percentages, with FW ranging from 43.52 % to 48.86 % and biomass at 46.70 %, which corresponds to relatively high theoretical BMP values of 432 to 789 mL/g VS. This suggests that digestate-rich in carbon, such as those from FW and biomass, have higher potential for methane production, indicating their suitability for bioenergy applications. Prioritizing digestate with higher carbon content can optimize methane yield for effective bioenergy production. A study was conducted by [151] on the residual biogas potential from the storage tank of raw digestate and liquid fraction digestate. Significant production of 19.5 and 7.90 N m^3 biogas $MWhel^{-1}$ (megawatt-hours per unit of electricity) was noted. Another batch study was conducted by the same research group with different waste digestates where their methane yields were heterogeneous and varied between 2.88 and 37.63 L/kg VS. Table 8 illustrates the previous studies on residual methane production from digestate.

Optimizing digestion processes and pre-treatment of digestate significantly enhances methane recovery of the digestate. Feedstock composition, rheology of digestate, and hydraulic retention time are crucial for maximizing residual methane production efficiency. A co-digestion and recirculation optimization study could be a way forward to the solution (discussed in Section 3.3). Following the pretreatment process, a minimum of 35 % of the organic material could be reduced in the digestate [21,155].

Another convenient way to valorise digestate is the biogas generation from LD through the efficiency of the single dairy manure biogas facility in Cantabria, located in Northern Spain, which was evaluated based on the separation of liquid and solid components, as well as the AD of the liquid portion. The separated liquid component underwent successful treatment in a continuous stirred-tank reactor (CSTR) digester, with HRTs varying from 20 to 10 days and organic loading rates ranging from 2 to 4.5 kg VS/ (m^3d). Consistent biogas production rates of 0.66 to 1.47 m^3/ (m^3d) were attained. Stable biogas production from 0.66 to 1.47 m^3/(m^3d) was achieved when the screened liquid fraction of digestate from a dairy manure biogas plant in Cantabria (Northern coast of Spain) was treated in a CSTR digester with organic loading rates ranging from 2.0 to 4.5 kg VS/ (m^3d) [153].

Some research delves into the possible advantages of reintroducing concentrated digestate back into biogas digesters by assessing the BMP of the digestate. The BMP varied between 156 and 240 CH_4 NL kg^{-1} VS, showing similarity to the BMP of untreated cattle slurry. However, the gravimetric BMP (BMP per kg of wet waste) was significantly higher for the digestate, estimated at 15–49 CH_4 NL kg^{-1}, compared to the untreated animal slurry. These findings suggest that recirculating concentrated digestate into biogas digesters could enhance biogas yield and improve process stability [154]. Due to the pre-established AD plant and its well-understood biochemical mechanisms, valorisation of digestate through biogas production is a convenient option. However, the preprocessing of digestate could lead to an enhanced residual biogas generation.

4.1.2. Biohydrogen

Unlike biomethane, the biohydrogen potential (BHP) primarily relies on the composition of the substrate, particularly the presence of soluble carbohydrates, along with lipids and proteins. Because of the hydrolysis rate, these different substrate-based digestate end up being a limiting factor for the production of biohydrogen. The production of hydrogen from digestate is very difficult because of the presence of high recalcitrant materials, low COD removal rate, reduction of pH, and high hydrogen partial pressure, which hinder microbial activities. However, these factors are also applicable to the fresh substrate [156,157]. Study showed a significant amount of hydrogen production from various complex waste biomass digestate materials such as potato and pumpkin wastes (171.1 ± 7.3 mL H_2/g VS), followed by buffalo manure (135.6 ± 4.1 mL H_2/g VS), dried blood (from slaughterhouse waste, 87.6 ± 4.1 mL H_2/g VS), fennel waste (58.1 ± 29.8 mL H_2/g VS), olive pomace (54.9 ± 5.4 mL H_2/g VS), and olive mill wastewater (46.0 ± 15.6 mL H_2/g VS) by pretreatment using dark fermentation method [158]. In the Campania Region, the common agro-industrial waste digestate holds significant promise for harnessing dark fermentation processes to produce hydrogen (H_2). Among these waste sources, fruit and vegetable waste, buffalo manure, and slaughterhouse waste (specifically dried

Table 8
Residual biogas generation from digestate.

Type of digestate	Feedstock	Experimental condition	Biogas	Methane	References
Raw separated digestate	Farmyard manure (31 %), Poultry manure (8 %), Maize silage (27 %), Drying maize residue (21 %) and Cattle slurry (12 %)	The biogas recovery device from storage was made up of a squared floating polyethylene and stainless-steel frame (2.5 m × 2.5 m: total surface 6.25 m^2) covered by a PVC two-side-coated polyester fiber membrane.	83–319 LN biogas m^{-2} surface day^{-1}	–	[152]
Digested liquid fraction	Farmyard manure (24 %), Maize silage (26 %) Triticale silage (11 %), Drying maize residue (3 %), Kiwi (3 %), Cattle slurry (33 %)		2.32 NL biogas m^{-3} surface day^{-1}	–	
Digestate before storage	Animal manure (70 %), Energy crops (20 %) Food industries by-products (10 %)	Each reactor was filled with 0.9 L of digestate and sealed with glass taps connected to Tedlar gas bags. Samples were incubated at 40 °C (±1 °C) in a temperature-controlled room for 70 days.	81.67 NL/kg VS	37.63 NL/kg VS	[151]
	Animal manure (55 %), Energy crops (45 %)		47.06 NL/kg VS	19.07 NL/kg VS	
	Energy crops (47 %), Food industries by-products (16 %), Animal manure (37 %)		25.12 NL/kg VS	3.53 NL/kg VS	
	Energy crops (17 %) Pig slurry (87 %)		20.75 NL/kg VS	2.88 NL/kg VS	
Liquid fraction digestate	Dairy manure	Treated in a CSTR digester at HRTs from 20 to 10 days with organic loading rates ranging from 2.0 to 4.5 kg VS/ (m^3 d).	0.66 to 1.47 m^3/(m^3 d)	12.7 to 102.4 L/g VS	[153]
Concentrated digestate	Pig manure + 15 % fish mucus	The I:S ratio was set to 3:1 on a DM basis and a mixture of inoculum and substrate was digested at 36 °C in triplicate for 60 days.	–	240 CH_4 NL /kg VS	[154]

blood) stand out as favourable options for dark fermentation due to their capacity for biohydrogen production. The recirculation of digestate into the main reactor or two-staged AD is more advantageous than a single-stage process because of the optimum conditions for bacterial activity during each stage of either H_2 production or CH_4 production [159,160]. Hydrogen-producing microorganisms are inhibited by acidic environments, making pH management crucial for hydrogen production. A co-digestion system or recirculation is a technical method to adjust fermentation conditions to support the growth and hydrogen production of these microorganisms [100]. Unlike residual methane generation from digestate, the co-digestion process can significantly enhance biohydrogen production. Studies have shown a substantial biohydrogen yield of 50.4 mL/g-VS and a COD removal rate of 43.33 % from anaerobic fermentation of chicken/cattle digestate combined with high carbohydrate content [100]. Similarly, another study showed the effect of digestate recirculation ratio (RR) on both biohydrogen and biomethane production. A maximum hydrogen production rate of 3 L-H_2 L^{-1} d^{-1} and a yield of 135 L-H_2 kg^{-1} VS were achieved with a recirculation ratio (RR) of 0.3, a hydraulic retention time (HRT) of 5 days, and an organic loading rate (OLR) of 18 kg VS m^{-3} d^{-1}. The energy recovered from the recirculation process boosted hydrogen production by 8 %. Various studies suggested that using the recirculated digestate could be viable to regulate pH levels in two-stage reactors. This approach can potentially lower the need for alkaline solutions, ultimately resulting in cost savings during operations. The hydrogen production increased by 208 % with a recirculation ratio of 0.25 [161]. To avoid the pH fluctuation, a study was conducted with whole digestate recirculation from the methanogenic reactor. Results showed that hydrogen was produced (0.117 Nm^3 kg^{-1} VS, 47.7 %) when recirculating the whole digestate with an organic loading rate of 20 kg TVS m^{-3} day^{-1} [160]. However, the other parameters need to be optimized for valorisation as digestate such as the effect of viscosity and agitation on the hydrogen production potential of digestate [22]. Microbial Electrochemical Technologies (METs) could be a promising technology to valorize digestate and generate hydrogen energy. METs, i.e. a Microbial Electrolysis Cell (MEC) and a Microbial Fuel Cell (MFC), were introduced for converting organic matter into electrical energy or hydrogen [162]. When the substrate of MFC and MEC was digestate, the MFC showed a coulombic efficiency of 35 %, with a volumetric power produced of 14.2 ± 0.15Wm^{-3} where MEC systems produced 1.90 ± 0.04 $LH_2l^{-1}d^{-1}$ using a stainless-steel mesh (SSM) and 2.02 ± 0.03 $LH_2l^{-1}d^{-1}$ using a platinum cathode from digestate [163].

Future research on biohydrogen production from digestate should focus on optimizing key process parameters such as pH, viscosity, and organic loading rates to enhance hydrogen yields. Co-digestion with high-carbohydrate waste and the recirculation of digestate in two-stage anaerobic digestion systems have shown potential but need further exploration at industrial scales. The integration of pretreatment methods, such as hydrodynamic cavitation and enzymatic hydrolysis, could improve the bioavailability of recalcitrant materials, boosting hydrogen production. Advances in microbial electrochemical technologies (METs), including microbial electrolysis cells (MECs) and microbial fuel cells (MFCs), offer promising directions for recovering both biohydrogen and energy from digestate. Additionally, developing cost-effective strategies to manage hydrogen partial pressure and mitigate pH fluctuations will be critical for scaling up production. Future efforts should focus on developing sustainable, low-energy, and economically feasible methods for large-scale biohydrogen production, with a focus on reducing the environmental impact and maximizing energy recovery from waste streams.

4.1.3. Syngas, bio-oil, and biochar

The production of major renewable fuels from digestate such as biogas and biohydrogen are discussed in the previous sections. Apart from these two valorising products, other valuable renewable fuels have been produced from the discarded digestate. Generally discarded digestate after valorisation also contains 20–30 % carbon in the form of some recalcitrant such as lignin, microplastic and others. The thermochemical process for valorisation is currently best suited to highly homogenous dry materials (dried fibrous digestate). Many studies have been conducted to verify the potential of digestate for other renewable fuels than biomethane and biohydrogen (Table 9). The primary purpose is to convert digestate into syngas, comprised of hydrogen and methane, to enhance overall energy efficiency. A study showed that the lignocellulosic-based digestate could be a suitable raw material for gasification and pyrolysis. Antoniou and the team managed to produce synthesis gas (syngas) from agricultural waste-derived digestate using in a downdraft fixed-bed reactor through gasification at 750–850 °C and observed 2.88 MJ/Nm^3 lower heating value (LHV) of the syngas [164]. Another study was conducted on the digestate gasification from manure and straw within a 600–800 °C temperature range while maintaining an air equivalence ratio between 0.25 and 0.30. The findings revealed that at 800 °C, the LHV of the syngas reached 4.78 MJ/Nm^3 [165]. Steam

Table 9
Renewable fuels from digestate.

Digestate source	Operating condition	Valorising product	References
Manure and straw	The air gasification process was carried out on digestate with a high ash content using a downdraft fixed bed gasifier. The temperatures ranged from 600 °C to 800 °C, while the air equivalence ratio (ER) varied between 0.25 and 0.30.	Biochar and ash	[165]
Anaerobic sludge and fallen leaves	The dried AD residue was mixed with woody biomass and then fed into the fixed-bed downdraft gasifier with a capacity of 10 kg/h, for syngas production.	Syngas	[168]
FW	The fixed-bed horizontal tubular reactor was operated at a heating rate of 10 °C/min, reaching four distinct final temperatures of 300, 400, 500, and 700 °C.	Biochar	[82]
FW residue	The HTPT temperature and time varied from 110 to 200 °C, and 30–90 min, respectively.	Biochar	[93]
A mixture of pig waste, leftover olive residue, corn silage, sorghum silage, and discarded onion pieces	4 g of solid digestate (moisture content of 7 %) in 100 mL Teflon vessels with a magnetic stirring bar; a mixture of PEG and glycerol (at the fixed ratio of 4:1) as a solvent and 3.5 % sulfuric acid, 600 W.	Bio-oil	[169]
Pig manure (43 %), cow manure (20 %), maize and triticale silages (25 %), and cereal bran (12 %)	Air gasification experiments were conducted, in a downdraft fixed-bed reactor, at a temperature range from 750 °C to 850 °C, with λ varying from 0.14 to 0.34. Results have shown that gasification of digestate at 850 °C with λ = 0.24, increased producer gas yield (65.5 wt %), and its LHV (2.88 MJ Nm^{-3}).	LHV and HHV	[164]

gasification could be an option for digestate from AD and dark fermentation of lignocellulosic biomass to produce syngas with high hydrogen content [166]. Integrated AD of aqueous pyrolysis liquor was tried by [167], using pyrolyzed solid digestate in batch mode. The highest methane yield of 199.1 ± 18.5 mL $gCOD^{-1}$ was observed for the 330 °C pyrolysis liquor with a lower dosage.

Hydrothermal carbonization (HTC) is gaining recognition as a promising thermo-chemical process for valorising digestate. In an aqueous environment, HTC may occur at temperatures as high as 300 °C and pressures as high as 10 MPa. Three main products come from this process: i) a gaseous byproduct that is mostly carbon dioxide; ii) a liquid fraction that contains organic chemicals that are soluble in water; and iii) hydrochar, which has the potential to be used as fertilizer because of its characteristics. Unlike gasification and pyrolysis, HTC offers the advantage of treating digestate from wet anaerobic processes without the need for extensive pretreatment, as it doesn't necessitate the drying of the digestate [170].

4.1.3.1. Bio-oil and biochar from pyrolysis. Pyrolysis refers to the process of thermally decomposing organic materials in an anaerobic environment (without oxygen). Pyrolysis of digestate produces combustible gas, liquid, and biochar as the solid product [171,172]. Recently, there has been a growing interest in exploring the potential of pyrolyzing digestate. Numerous studies have examined the pyrolysis performance of digestate derived from various sources, such as FW [57,173], roadside grass [174], SS [175], algae [176], agricultural waste (AW) [177], and the organic fraction of municipal solid waste. However, a significant challenge in effectively utilizing pyrolysis for digestate management lies in the high-water content of digestate, which hampers its transportation and thermal conversion efficiency.

The compositions of the digestate feedstock significantly influence the physical and chemical properties of the resulting biochar [60]. The resulting pyro-oil can be converted into a fuel with a high heating value of 35.2 MJ/kg, low viscosity, and low acid content (a total acid number of 5.1 mg KOH/g). The pyrogas, which contain CO, CO_2, H_2, and CH_4, typically have a high calorific value and can be used to supplement biogas from the thermal treatment process. Pyrolysis significantly enhances the pore properties, reduces nutrient leaching losses (by 11 % for total nitrogen and 69 % for total dissolved phosphorus), and improves the anion and cation exchange capacity and carbon sequestration capacity of the digestate. The study examined the pyrolysis characterization of digestate and the phosphorus availability in the resulting pyrochar. Additionally, pyrochar is enriched with nitrogen, phosphorus, and potassium elements [178,179]. Thermogravimetry (TG) analysis revealed a 15.56 % weight loss between 600 °C and 750 °C due to $CaCO_3$ decomposition. As the final temperature increased from 500 °C to 700 °C, the higher heating value (HHV) of pyro gas slightly increased from 17.20 MJ/Nm^3 to 18.12 MJ/Nm^3, while the relative content of polycyclic aromatic hydrocarbons (PAHs) in the liquid rose from 1.36 % to 6.28 % [179]. Combining catalytic pyrolysis of digestate with anaerobic fermentation can effectively convert all biomass components, transforming waste into high-value products. In digestate pyrolysis, increasing the temperature was found to raise the levels of CO, CH_4, and monocyclic aromatic hydrocarbons (benzene, toluene, and xylene; BTX) while reducing the contents of phenols, acids, aldehydes, and other oxygenates. Additionally, the catalytic pyrolysis process significantly inhibited the formation of acids, phenols, and furans in the liquid, and the yield of BTX increased from 25.45 % to 45.99 %. The selectivity for xylene also rose from 10.32 % to 28.72 % with the addition of ZSM-5, which also suppressed the production of nitrogenous compounds [180].

4.1.3.2. Syngas and heat from gasification. Gasification of biomass is an environmentally friendly and cost-effective technology to produce H_2 and CO. According to the report, the gasification market already attained $119 billion in 2023 and is expected to reach $196.7 billion by 2032 with a growth rate of 5.6 % [181]. Gasification is a process that occurs at high temperatures ranging from 700 to 1000 °C, in which solid fuel is broken down into synthetic gas (syngas). The primary flammable components of syngas are H_2, CH_4, and CO. To address the large volume of solid digestate, this process could be a game changer by converting digestate into potential fuel. However, the quality of syngas from digestate depends on the flammable components, calorific value and impurities i.e. dust and tar. The quality of syngas derived from digestate is highly dependent on the carbon and hydrogen content in the digestate and Table 3 indicates the amount of C and H percentage in various types of digestate. A study indicated that a significant amount of hydrogen (62.7 % DM) was obtained from lignocellulosic-based digestate (crop residue) using a downdraft fixed-bed gasifier. The allothermal conversion process was carried out at a temperature of 1000 °C and a pressure of 2–3 MPa [166]. Another study was conducted at a lower temperature range of 730–760 °C using an atmospheric fluidized bed gasifier. The dry fermented digestate produced syngas with a lower heating value of 3.93–4.42 MJ/Nm^3 and a high cold gas efficiency (CGE) of 73.6–76.8 %. Nanna et al. [182] conducted research where CO_2, steam, and a combination of both were utilized to gasify digestate in a continuous bench-scale rotary kiln at a temperature of 800 °C. The digestate was fed into the kiln at a rate of approximately 0.7 kg/h, resulting in a conversion rate of around 60 wt %. Another study performed gasification experiments on digestate with a high ash content using an electrically heated downdraft fixed-bed gasifier at a laboratory scale. Interestingly, no slagging problems were encountered during the process. The equivalences ratio (ER) ranged from 0.25 to 0.30, the tar content exhibited a significant reduction from 6.48 g/Nm^3 to 1.61 g/Nm^3 [165].

[183] conducted a few gasification experiments in a pilot-scale rotary kiln plant with an approximate biomass feeding rate of 20 kg/h. A combination of digestate and almond shells (60:40 wt %) was utilized for gasification to improve cold gas efficiency. By using this mixture, autothermal conditions were attained at an equivalence ratio of 0.30, resulting in a peak cold gas efficiency of 55 %. The resultant raw gas had a lower heating value ranging from 4 to 5 MJ/Nm^3. Gasification of biomass, particularly digestate, is a promising environmentally friendly and cost-effective technology for producing H and CO. The quality and efficiency of syngas production depend on the type of digestate, operating conditions, and specific gasification methods, with significant advancements demonstrated in both laboratory and pilot-scale studies.

4.2. Fertiliser

The extraction of fertilizer nutrients from digestate becomes exceptionally vital in times of fertilizer scarcity when raw materials are limited, and the production costs of fertilizer energy reach unprecedented levels. In the early stage, the use of digestate as organic fertilizer was the only option for AD plants. However, the presence of high amounts of nitrogen and P_2O_5 restricted the direct use in the field for agricultural purposes. Research suggests that the digestate serves as a top-notch bioorganic fertilizer abundant in essential elements and nutrients like nitrogen (N), phosphorus (P), potassium (K), amino acids, vitamins, and minerals. Additionally, specific helpful bacteria have the potential to boost the soil's humic material content, laying the foundation for enhanced soil fertility [184]. Compared with the control groups using chemical fertilizers, a higher degree of digestate treatment boosts antioxidant capacity, total phenolics content, and levels of ascorbic acid [185]. However, the findings regarding legume nutrient levels present a puzzling outcome. Research has demonstrated that digestate can enhance soil quality, fertility, mobile humic acid concentration, soil durability, and sustainability. The fertilizing potential of digestate is enhanced by the presence of organic carbon, phosphate, and potassium. Following the application of solid and LD to the topsoil layer (0–40 cm) with nitrogen dosages of 170 kg/ha N, the fertility category increased from high (200–300 mg/kg) to very high (>300 mg/kg) based on P_2O_5 levels. This resulted in a fivefold increase in nitrogen content [186]. A study showed the improvement of phenol and flavonoids in cucumber grown in sandy loam soil with digestate [187]. The application of digestate for an extended period has been demonstrated to enhance the microbial biomass in soil [188]. Nevertheless, the effects of AD digestate on microbial biomass and community composition in alternative growing media have yet to be investigated. Table 10 summarizes some studies on digestate application, process and cultivation of vegetables.

An obstacle frequently encountered in employing AD as a fertilizer lies in the division of nutrients between its liquid and solid segments. Typically, the liquid part holds a higher concentration of mineral nitrogen, while the solid component contains increased phosphorus content [36]. Segregating NPK fractions could lead to the production of fertilizers tailored to specific purposes rather than general use, potentially limiting the market for AD-based products. Additionally, the considerable moisture content in AD presents challenges in terms of storage and transportation, as highlighted in prior studies [192]. Struvite extraction and composting could be more effective alternatives to the direct use of digestate, which are discussed here.

4.2.1. *Struvite*

The liquid phase of anaerobic digestate serves as a nutrient source, containing elements like nitrogen (N) and phosphorus (P), often targeted for recovery through various technologies. However, it's important to note that this liquid fraction only holds a portion of the overall nutrient influx, thus limiting the potential for total recovery [193]. To remove the impurities, microfiltration (MF) effectively separates the digestate into a solid-rich retentate and a nutrient-rich aqueous permeate, thereby facilitating subsequent membrane processes aimed at concentrating valuable chemical constituents [194]. Following the removal of suspended solids and macromolecules, the resulting permeate is typically enriched with K and N, making it suitable for use in the formulation of green fertilizers. Similarly, the membrane distillation (MD) is particularly advantageous for ammonia recovery and P enrichment. For instance, direct contact MD has demonstrated over 99 % removal of total phosphorus from the LF of digestate. Among the available technologies suitable for the liquid phase of digestate, two prominent ones are struvite precipitation and ammonia stripping [195, 196],. These methods, identified through systematic mapping of nutrient and carbon recovery technologies from domestic wastewater, offer solutions for P and N recovery. Struvite precipitation primarily focuses on P recovery, involving the formation of struvite, a crystalline mineral composed of magnesium (Mg), ammonium (NH_4), and phosphate (PO_4) [197]. The efficacy of the struvite precipitation process relies on various factors, notably pH and the molar ratio of NH_4, PO_4, and Mg in the liquid solution. Products derived from magnesium-ammonium-phosphate can contain up to 12.65 % of P in its pure compound form, whereas struvite precipitated from organic waste typically contains between 6 and 12 % P [198]. The optimization of pH, molar ratio, and pretreatment is needed to maximize the precipitation. From cow digestate, the average P recovery of 60 % was noticed when the combined process of struvite precipitation and ammonia stripping was tested in the laboratory [199]. With electrochemical precipitation technology, a two-chamber MEC reactor with a fluidized bed cathode could be used to enhance phosphorus removal and reduce cathode scaling. The phosphorus removal of 70–85 % was noticed with the current generation, compared to 10–20 % for the control using digestate. The fluidized bed increased struvite precipitation by producing high surface area particles, which also scoured the cathode to minimize scale buildup [200].

Table 10
Fertilizer using digestate.

Digestate source	Operating condition	Cultivation	References
Animal manure (Poultry, cow, and sheep)	Plastic pots (26 cm diameter × 27 cm height) were filled with 4.5 kg of an alkaline sandy-loam soil and amended with two different digestate separated into liquid and solid fractions	Tomato & Cucumbers	[189]
Biochar, compost, cocopeat, and FW	Every treatment consisted of 2 L containers containing a mixture of 40 % biochar, compost, or cocopeat, along with 60 % soil (volume/ volume). A liquid solution was created by dissolving 1.2 g of fertilizer in 23 mL of tap water, with 250 mL utilized for each round of application.	Tomato	[190]
85.5 % crop residues by weight, 12.5 % plant-based residues from the food industry, and 2 % iron chloride.	Hydroponic nutrient film technique system	Bok choy (Brassica rapa var. chinensis)	[191]

4.2.2. *Compost*

In addition to fresh organic waste, the solid fraction of digestate is an excellent option for composting. Compost mixtures comprising the solid fraction of digestate, derived from the anaerobic co-digestion of cattle slurry and silage, were subjected to composting using the Rutgers system, with or without vine shoot pruning as a bulking agent. The resulting composts demonstrated satisfactory levels of stability and maturity and exhibited favourable physical attributes suitable for utilization as growing media [201]. Notably, the solid fraction holds significant value for composting, underscoring the importance of separating digestate into two fractions before commencing the composting process. The solid fraction of digestate stands out due to its elevated organic matter content, free-flowing structure and porosity. Digestate presents a good option for composting, serving either as the sole feedstock or co-composted with other organics. It can also function as an inoculum or amendment in composting processes, enriching compost feedstock with moisture content and essential nutrients like nitrogen and phosphorus. Additionally, digestate can enhance the biological properties of compost by increasing microbial populations and potentially improving overall composting performance [202]. Its considerable nutrient composition, including nitrogen, phosphorus, and potassium, suggests its potential as an agricultural fertilizer [76]. However, alongside its nutrient richness, solid digestate harbors trace metals like zinc and copper, along with pathogenic bacteria, posing significant environmental contamination risks when used as fertilizer [86]. Consequently, there is a pressing need for a practical and efficient approach to managing solid digestate, as its treatment greatly influences the viability of AD engineering.

Co-composting and the addition of additives to improve the compost quality are now the talk of the town. A study was conducted with FWD co-composting with sawdust and compost, incorporating with additive zeolite to conserve nitrogen. Findings revealed that adding 5 % and 10 % of zeolite decreased NH_3 emission to 1.8 % and 1.6 % respectively, compared to 2.5 % in the control (without zeolite). In summary, integrating zeolite showed a beneficial effect on nitrogen retention, reducing nitrogen loss by 34–39 % with zeolite doses of 5–10 % [23]. The characterization findings indicate that digestate and sawdust possess both macro (N, P, Mg, Na, Ca, and K) and micro (Mn, Zn, Fe, and Cu) nutrients which, upon composting, can serve as biofertilizers or soil enhancers. Furthermore, the resulting compost (biofertilizer) contains Zn, Cr, Cu, Cd, and Pb levels that fall within the recommended thresholds for agricultural utilization [203]. Solid digestate, with its rich organic matter and nutrient content, holds great potential for composting as a biofertilizer. However, careful management is essential to mitigate the risks of heavy metal contamination and ensure safe agricultural use.

4.3. Other valorisation products

In addition to recovering valuable products like renewable fuels and fertilizer, the remaining nutrients found in digestate can also be harnessed indirectly via cultivating various microorganisms or microalgae to manufacture beneficial bio-based chemicals and products such as bioplastics, biosurfactants, biofuel, biopesticides, and enzymes that have diverse commercial uses [204]. Polyhydroxyalkanoate (PHA) is considered one of the most extensively studied types of bioplastics. Biosurfactants, on the other hand, are amphiphilic compounds with detergent-like properties that are biologically synthesized through fermentation. Among the most researched biosurfactants are sophorolipids and rhamnolipids. Recent research revealed the production of a substantial amount of 4.6 g/L PHA with a 75 % cell dry weight content from a combination of sunflower oil and micro-filtered digestate liquor obtained from chicken manure [205] and colleagues have devised a new aeration approach to generate *Bacillus thuringiensis* (Bt) derived biopesticides via solid-state fermentation, employing a combination of digestate and biowaste as feedstocks [206]. The highest production achieved was 1.3 × 108 spores g^{-1} DM for B_{tk} and 4 × 108 spores g^{-1} DM for B_{ti}, resulting in a final yield of 5 and 29 spores produced per initial CFU, respectively. Many studies revealed the potential of digestate for enzyme production. The digestate contains a significant amount of carbon stored as solid structural molecules like lignin and cellulose, forming a noteworthy value-added chain wherein enzyme-producing microbes can access the residual carbon in the digestate solids [146, 207].

The nutrients and functional molecules in the digestate foster enzyme growth, which facilitates the hydrolysis of lignin and cellulose within the digestate. As a result, the digestate residue becomes more degradable, allowing it to be reintroduced into the AD system to boost biogas production. This makes digestate a more technologically and economically attractive alternative to traditional substrates for enzyme production.

4.3.1. Microalgae cultivation

Microalgae, which are rich sources of lipids and protein, grow primarily on mineralized nitrogen (mostly ammoniacal-N) and other nutrients. To achieve peak microalgal productivity, it is critical to constantly supply particular nutritional requirements. Supplying such nutrients from commercial sources will undoubtedly raise the cost of microalgae production [208]. Digestate is a great resource for microalgae since the AD process converts phosphorus and nitrogen into forms of orthophosphate and ammonium that can readily be consumed. Many studies have been conducted on cultivating microalgae in a waste stream and its capacity to reduce the high nutrient content of LD while producing high-value algal biomass (Table 11). After growing microalgae using digestate, the residual waste may be securely disposed of in the environment [15,209].

The LD, abundant in nitrogen and potassium, typically serves as fertilizer when spread onto fields, while the solid phase, containing phosphorus and stabilized carbon, is commonly employed as a soil amendment. Nevertheless, recent research has directed attention towards exploring the potential of utilizing LD as a nutrient reservoir for promoting microalgae growth. The application of microalgae in digestate treatment offers various advantages, including rapid growth and utilization of nutrients, high fertilizer demand, carbon capture, and biomass production. Also, the possible CO_2 supply can be from the biogas as a carbon source from biogas for microalgae cultivation, which can facilitate simultaneous biogas upgradation and digestate treatment. Employing the liquid fraction of digestate as a substrate for microalgae growth presents two significant challenges, primarily associated with its elevated nitrogen content and turbidity level. Specifically, the liquid fraction of digestate is frequently marked by a notable concentration of total suspended solids, leading to inherent turbidity and diminished light penetration. Additionally, it often contains elevated levels of ammonia (> 100 mg N L^{-1}), posing potential toxicity risks to microalgae

Table 11
Microalgal cultivation using digestate.

Digestate source	Operating condition	Microalgae species	References
Green peas waste and corn cobs, grains, leaves and stalks	Two photobioreactors with a working volume of 350 mL each were employed in the study. The initial operation involved the first reactor being exposed to artificial LED light (T8 LED temperature - 6000 K, electric power - 14.5 W, luminous power - 1440 lm) and direct sunlight for a period of 90 days.	*Tetradesmus obliquus* (formerly *Scenedesmus obliquus*), *Desmodesmus subspicatus* and *Microglena* sp.	[210]
FW	Pilot-scale microalgae cultivation trials were carried out over approximately 400 days in four 100 L plastic raceway reactors (RW0.5i, 20 cm liquid depth, 0.5 m^2 aerial area).	*Chlorella sorokiniana* UTEX 1230	[211]
Farming waste	The microalgae sample (10 mL) obtained directly was cultivated in Erlenmeyer flasks with 50 mL of diluted [] for 14 days with light exposure ranging from 107 to 175 μmol/m^2/s, horizontal shaking at 105 rpm, a temperature range of 19 to 23 °C.	*Monoraphidium* sp., *Scenedesmus Quadricauda, Scenedesmus acutus, Scenedesmus* sp	[212]
Farming and agro practices	The raceway consisted of a surface of approximately 3.8 m^2 and volume of 0.50–0.88 m^3, depending on the water depth.	*Scenedesmus-Chroococcus*	[213]
Pig manure	Microalgae and bacteria were introduced into 500 mL conical flasks with 300 mL of sterilized anaerobic digestate. The flasks were then placed in an incubator for a period of 12 days at a consistent temperature of 25 ± 1 °C, while being exposed to a light intensity of 2.5 ± 0.1 K lux.	*Chlorella* sp.-*Lysinibacillus* sp. and *Chlamydomonas* sp.-*Shinella* sp. (bacterial-microalgal symbiosis)	[214]
Textile wastewater	A photosynthetic bioreactor with a working volume of 900 mL and a magnetic stirrer (mixing velocity of 50 rpm) was operated for mixing the reactor content. Both sides of the PBR had an external light source of 11,000 lx (14 W TL5 tungsten filament lamps).	*Scenedesmus* sp.	[215]

[216]. The high concentration of ammonium may induce toxicity, while the increased optical density can hinder light penetration, thereby adversely impacting the rate of biomass production [217]. Dilution with fresh water has often been proposed as a method to enhance the characteristics of digestate for microalgal cultivation purposes. One effective approach for purifying LF of digestate involves the application of pressure-driven membrane technologies, such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO). In general, low-pressure membranes like MF and UF are adequate for achieving effluent quality suitable for environmental discharge, as they effectively remove turbidity, suspended solids, bacteria, certain viruses, color, and high-molecular-weight organic compounds [218].

Furthermore, microalgae rapid growth can significantly minimize the amount of land required for digestate application. However, one obstacle to microalgae development on digestate is its slightly alkaline pH, which favors the free-ammonia form of nitrogen and can significantly impede microalgae growth [219]. A study conducted by Praveen and team showed an impressive growth of microalgae *Chlorella vulgaris* and effective nutrient removal when introduced to nitrified digestate (5–30 % mixed with municipal wastewater) in batch mode. The two-stage symbiotic bacterial-microalgal process achieved a significant reduction for COD, NH_4^+-N, NO_3^--N, and PO_4^{3-}-P of 87 %, 100 %, 30 %, and 77 %, respectively. When applied in continuous mode, the microalgae-based membrane photobioreactor (MPBR) downstream of a membrane bioreactor (MBR) managed to reduce COD of 91 %, NH_4^+-N of 97 %, and >99 % of PO_4^{3-}-P from 10 % digestate [220].

Another study conducted by Xi Chen and team focused on the efficiency of phycoremediation of four microalgae species: *Scenedesmus dimorphus, Scenedesmus quadricauda, Chlorella sorokiniana,* and *Chlorella vulgaris* ESP-6 on anaerobically digested wastewater (ADW). These microalgae were cultivated in a membrane photobioreactor (MPBR) fed with ADW to investigate the efficiency of ammonia and phosphorus removal. The results showed that C. *sorokiniana* had the best performance for the removal of ammonia and phosphorus from ADW. The highest amount of *C. sorokiniana* biomass was 1.15 g/L, and the removal efficiency of phosphate (66.2 %) peaked at an ammonia concentration of 128.5 mg/L after 9 days of incubation [221].

The integration of microalgae cultivation with anaerobic digestate treatment shows great promise in sustainable waste management and resource recovery. Microalgae's ability to rapidly assimilate nutrients and capture CO_2 while generating valuable biomass makes it an attractive solution for nutrient recovery from digestate. However, challenges such as high ammonia toxicity, turbidity, and pH imbalance limit its widespread application. Future research should focus on optimizing these cultivation conditions through dilution, consortia systems, and adaptive microalgae species. Scaling these systems and addressing economic constraints will be crucial to making microalgae-based digestate treatment a commercially viable and environmentally sustainable approach.

4.3.2. Ammonia stripping and recovery

Several technologies have been developed for nitrogen recovery from waste streams, including 1) high-pressure reverse osmosis [222], 2) air-stripping systems [223], 3) ion exchange through zeolite-based adsorption [224], (4) struvite precipitation [197]; and (5) an emerging technique involving gas-permeable membranes [225].

Ammonia stripping denotes the mechanism by which ammonia transitions from the liquid phase to the gas phase [226]. As outline, the ammonia stripping procedure consists of the subsequent steps: (i) transforming ammonium ions (NH_4^+) into free ammonia (FA), (ii) moving FA from the main liquid phase to the boundary between the liquid and gas phases, (iii) shifting FA across this boundary into the gas phase, and (iv) dispersing FA throughout the gas phase. Studies have indicated that ammonia stripping becomes economically viable when the concentration of ammonia nitrogen exceeds 1500 mg/L [32]. Since ammonium ions can be trapped or adsorbed onto suspended organic matter, performing stripping on the liquid fraction of the digestate after solid-liquid separation should theoretically result in higher ammonia recovery [227,228]. The effect of TS on ammonia removal efficiency is controversial, with some researchers arguing that lower TS levels enhance free ammonia stripping, while others see no impact. Overall, there is no consensus, and the studies do not provide sufficient information on how digestate composition influences ammonia recovery. The study also demonstrated the influence of CO_2 in the stripping gas in the model solution, whereas there is not much study on digestate [229]. The process of ammonia stripping can be directly implemented within anaerobic digesters through a method known as side-stream stripping. This approach effectively regulates the concentration of ammonia within the digestate, ensuring it remains below inhibitory levels for methanogenic bacteria [230]. Additionally, vacuum thermal stripping combined with acid absorption is an alternative approach for ammonia recovery from digestate. In this process, applying a vacuum enables the removal of ammonia at temperatures slightly below its standard boiling point. The released ammonia gas is subsequently captured in a sulfuric acid solution, resulting in the formation of ammonium sulfate crystals [231]. The effectiveness of ion exchange for N recovery has been validated in several studies. For example, natural zeolitic rocks have achieved up to 62 % ammonium recovery from the liquid fraction of digestate (LFD), with an adsorption capacity of 159 mg g^{-1}, primarily through cation exchange involving elements such as calcium, silicon, and sodium [232]. Several technologies for ammonia stripping and nitrogen recovery from digestate are available, with their efficiency influenced by ammonia concentration, digestate composition, and process conditions. While several technologies show potential, further research is needed to optimize energy use and assess performance under real digestate conditions.

5. Economic, environmental, regulatory and policy considerations

In early 2022, the European Commission announced its plan to increase the 2030 biomethane production target in the EU from 17 to 35 billion cubic meters to reduce reliance on imported natural gas [233]. Annually, the EU produces approx. 220–258 million tonnes of digestate rich in nitrogen (2–5 kg/m^3) and phosphorus (0.5–1.5 kg/m^3) [8]. However, apart from the benefits and lots of advantages, the nutrient-rich digestate can pose challenges, where local application is not feasible, such as in areas along the Dutch German border, where transport costs for digestate can exceed €10 per ton [234]. The economic and operational feasibility of digestate treatment can vary significantly across global regions, especially in developing economies where infrastructure, regulatory frameworks, and market conditions differ substantially. Currently, the value of digestate as a fertilizer is in the range of €2 to €8 per tonne [122,235]. Additionally, digestate is often viewed negatively in public discourse due to concerns about excessive nutrient loads on land and the resulting environmental damage to groundwater [236]. Considering the major stake of digestate utilized in fertilizer, one case study was conducted on the treatment costs of digestate across four different plants in Belgium, which evaluates the potential fertilizing and humus value (PFHV) of the resulting products, and allocates the cash flows to demonstrate potential regional benefits. Treatment costs for the pre-dried solid fraction of digestate ranged from €19 to €23 per tonne of output. These costs can be offset by selling the treatment products at a price covering at least 34–41 % of their PFHV (approximately €55 per tonne). However, treating raw digestate incurs significantly higher operating costs (€216–247 per tonne of output), which greatly exceed the PFHV of the products (around €35–51 per tonne). To sustain such systems, either financial subsidies from authorities are necessary, or substrate providers need to pay a disposal fee of €13–32 per tonne of input [237]. Pressure-driven membrane technologies, such as ultrafiltration and reverse osmosis, are emerging as significant methods for nutrient recovery, achieving nitrogen and phosphorus removal efficiencies of 75–95 % and 85–99 %, respectively. Additionally, the operational costs of membrane processes are relatively high, ranging from €4 to €12 per m^3 of digestate, compared to other available technologies. The discussion is supported by the recent data from studies conducted in the EU [89]. Despite the recent advances, membrane-based processes face severe challenges and limitations while handling digestate, primarily because of fouling and clogging. Fouling significantly influences membranes' performance, including reduced permeability, increased transmembrane pressure and higher energy consumption. However, induction of pretreatment to the feed/digestate and use of antifouling agents may enhance the effectiveness of the membrane-based processes. However, these additional measures may also increase the overall cost of digestate valorisation.

The recent German fertilizer and fertilization legislation reform has increased the urgency for effective digestate management solutions. Under this reform, farmers must include the nutrients from digestate in their total nutrient calculations, which are capped at 170 kg of nitrogen per hectare [238]. Similar stringent regulations have been introduced in other countries, putting pressure on biogas plants to manage their digestate efficiently. These plants must either transport digestate to areas without nutrient surpluses or market it for non-agricultural uses, such as private gardening [234,239]. Although most digestate in Europe is still used in agriculture, some biogas plants have started selling it to alternative sectors, including private gardening, landscaping, and nurseries [240]. Regarding the economic sustainability of the digestate, upgraded digestate products, with higher nutrient content and lower water content, are more marketable. These products appeal to fertilizer and soil manufacturers, farmers, horticulturists, and private customers. Disposal prices for digestate vary widely, from negative to strongly positive, influenced by regional nutrient availability, agricultural structure, season, feedstock, and the level of processing. Consequently, marketers need to better understand consumer concerns and preferences, and consumers need more education on the safety and benefits of using digestate.

The Nitrate Directive (91/676/EEC) at the EU level establishes the regulatory framework aimed at safeguarding ground and surface water against nitrate pollution. All EU member states are required to integrate it into their national legislation [241]. The new regulation outlines 11 component material categories to produce EU fertilizer products. These Component Material Categories (CMCs) include specific requirements for permissible input materials, acceptable production and processing techniques, and mandatory process parameters. Relevant to digestate are CMC 4 (Fresh crop digestate), CMC 5 (Other digestate than fresh crop digestate), and potentially CMC 3 (Compost). Digestate derived from input materials classified under CMC 5 must not contain >6 mg/kg DM of PAH16 and no >5 g/kg DM of macroscopic impurities such as glass, metal, and plastics over 2 mm, with each type of impurity limited to 3 mg/kg. For both CMC 4 and CMC 5, the maximum residual methane potential is set at 0.25 L/g VS [242].

According to the National Organic Standards Board (NOSB), USA, due to the potential negative impacts on human health from food-borne pathogens, the unproven safety of digestate fiber, and the availability of numerous alternative practices and materials in organic production, the NOSB has concluded that anaerobic digestate, as currently petitioned without pre-harvest application intervals, is not compatible with a system of sustainable agriculture [243]. While digestate presents significant potential for nutrient recovery and bio-based fertilizer production, its economic viability is challenged by high treatment costs, regulatory constraints, and negative public perception. In contrast, India's Fertilizer Control Order (FCO) allows digestate ('Fermented organic liquid fertiliser') as a form of organic fertiliser but lacks clear quality standards, leading to limited adoption and trust [244]. China has issued a national standard "Digestate Fertilizers" (NY/T 2596–2022), nutrient-based thresholds for land application but faces regional enforcement challenges [29]. While there are numerous reports analyzing the economics of digestate as fertilizer across the globe, there is comparatively little analysis on the economic viability of other valorisation methods. Future research should focus on improving cost-efficient treatment technologies, such as membrane processes, and enhancing public awareness and marketability of upgraded digestate products to promote sustainable waste management.

6. Summary of valorisation potential and outlook

This review comprehensively summarizes the valorisation of digestate, a by-product of AD processes, focusing on its composition, potential products, and various processes for its effective utilization. Unlike previous studies, this review uniquely integrates insights on digestate characterisation, rheological behavior, advanced pretreatment technologies, and techno-economic constraints across multiple regions. Digestate typically contains organic matter, water, and a range of macro and micronutrients, the composition of which can vary significantly based on factors like feedstock type, digestion conditions, rheological behavior and valorisation processes. This variability and excess nitrogen and phosphorous poses challenges for standardizing digestate use, especially in agriculture, where it is most commonly applied. The paper explores the potential pathways of converting digestate into value-added products such as fertilizers, soil amendments, nutrients and energy sources. It highlights the importance of separating digestate into solid and liquid fractions for effective valorisation. The review also delves into advanced pretreatment methods like hydrodynamic cavitation, which has shown promise in enhancing biogas production and methane yield from digestate. Economic and regulatory aspects are critical for the widespread adoption of digestate valorisation technologies. The review discusses the financial implications of different treatment methods, the market potential for digestate-derived products, and the impact of stringent regulations on nutrient management. It emphasizes the need for financial incentives and supportive policies to make digestate valorisation economically viable and environmentally sustainable. A major contribution of this review is the consolidation of digestate characteristics across diverse feedstocks and the evaluation of their suitability for various valorisation routes, which has not been systematically addressed in earlier reviews.

The outlook for digestate valorisation is promising but requires significant advancements and collaborative efforts from scientific, industrial communities and policy makers. Future research should focus on optimizing treatment processes to enhance the efficiency and cost-effectiveness of digestate conversion technologies. Developing standardized methods for assessing the quality and composition of digestate will be crucial for its broader application and acceptance. There is a need for innovative solutions to address the challenges of nutrient management and regulatory compliance, particularly in regions with strict environmental regulations. Scaling up successful laboratory and pilot-scale technologies to industrial levels will be essential to meet the growing demand for sustainable waste management solutions. Furthermore, integrating digestate valorisation with existing biogas and agricultural systems could provide synergistic benefits, improving the overall sustainability and economic viability of these sectors. Policymakers should consider providing subsidies and incentives to encourage the adoption of advanced digestate treatment technologies and support the development of markets for digestate-derived products.

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CRediT authorship contribution statement

Jagdeep Kumar Nayak: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Vivek V Ranade:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

One of the authors (VR) is a Director of Vivira Process Technologies which commercially offers vortex-based hydrodynamic cavitation devices (www.vorta.com).

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Data availability

Data will be made available on request.

References

[1] R. Gautam, J.K. Nayak, U.K. Ghosh, A. Daverey, Emerging sustainable opportunities for waste to bioenergy: an overview, Waste-to-Energy Approaches Towards Zero Waste, Interdiscip. Methods Control. Waste (2022) 1–55, https://doi.org/10.1016/B978-0-323-85387-3.00001-X.

[2] D. Nayeri, P. Mohammadi, P. Bashardoust, N. Eshtiaghi, A comprehensive review on the recent development of anaerobic sludge digestions: Performance, mechanism, operational factors, and future challenges, Results Eng. 22 (2024) 102292, https://doi.org/10.1016/J.RINENG.2024.102292.

[3] P.M.V. Subbarao, T.C. D' Silva, K. Adlak, S. Kumar, R. Chandra, V.K. Vijay, Anaerobic digestion as a sustainable technology for efficiently utilizing biomass in the context of carbon neutrality and circular economy, Environ. Res. 234 (2023) 116286, https://doi.org/10.1016/J.ENVRES.2023.116286.

[4] D.J. Prasanna Kumar, R.K. Mishra, S. Chinnam, P. Binnal, N. Dwivedi, A comprehensive study on anaerobic digestion of organic solid waste: A review on configurations, operating parameters, techno-economic analysis and current trends, Biotechnol. 5 (2024) 33–49, https://doi.org/10.1016/J.BIOTNO.2024.02.001.

[5] What does net-zero emissions by 2050 mean for bioenergy and land use? – Analysis - IEA, (2021). https://www.iea.org/articles/what-does-net-zero-emissions-by-2050-mean-for-bioenergy-and-land-use (accessed October 14, 2024).

[6] IEA: Outlook for Biogas and Biomethane. Prospects... - Google Scholar, (2018). https://scholar.google.com/scholar_lookup?title=Outlook%20for%20Biogas%20and%20Biomethane.%20Prospects%20for%20Organic%20Growth&publication_year=2020&author=IEA (accessed July 9, 2024).

[7] M.S. Islam, V.V. Ranade, Enhancement of biomethane potential of brown sludge by pre-treatment using vortex based hydrodynamic cavitation, Heliyon 9 (2023), https://doi.org/10.1016/j.heliyon.2023.e18345.

[8] 2022. Statistical report. https://www.europeanbiogas.eu/wp content/uploads/2022/12/EBA-Statistical-Report-2022_-Short-version.pdf.

[9] M. Malhotra, K. Aboudi, L. Pisharody, A. Singh, J.R. Banu, S.K. Bhatia, S. Varjani, S. Kumar, C. González-Fernández, S. Kumar, R. Singh, V.K. Tyagi, Biorefinery of anaerobic digestate in a circular bioeconomy: Opportunities, challenges and perspectives, Renew. Sustain. Energy Rev. 166 (2022), https://doi.org/10.1016/j.rser.2022.112642.

[10] Y. Li, Y. Han, Y. Zhang, Y. Fang, S. Li, G. Li, W. Luo, Factors affecting gaseous emissions, maturity, and energy efficiency in composting of livestock manure digestate, Sci. Total Environ. 731 (2020) 139157, https://doi.org/10.1016/j.scitotenv.2020.139157.

[11] K.R. Parmar, A.B. Ross, Integration of hydrothermal carbonisation with anaerobic digestion; Opportunities for valorisation of digestate, Energies 12 (9) (2019) 1586, https://doi.org/10.3390/en12091586.

[12] T. Rehl, J. Müller, Life cycle assessment of biogas digestate processing technologies, Resour. Conserv. Recycl. 56 (2011) 92–104, https://doi.org/10.1016/J.RESCONREC.2011.08.007.

[13] W. Wang, J.S. Chang, D.J. Lee, Anaerobic digestate valorization beyond agricultural application: Current status and prospects, Bioresour. Technol. 373 (2023) 128742, https://doi.org/10.1016/J.BIORTECH.2023.128742.

[14] S. Dutta, M. He, X. Xiong, D.C.W. Tsang, Sustainable management and recycling of food waste anaerobic digestate: A review, Bioresour. Technol. 341 (2021) 125915, https://doi.org/10.1016/j.biortech.2021.125915.

[15] D. Chuka-ogwude, M. Nafisi, H. Taher, J.C. Ogbonna, N.R. Moheimani, Food waste digestate as a source of nitrogen for the cultivation of Dunaliella salina: Influence on growth and carotenogenesis under hyper osmotic stress, J. Appl. Phycol. 34 (2022) 101–112, https://doi.org/10.1007/s10811-021-02663-1.

[16] E. Sobolewska, S. Borowski, D. Kręgiel, Cultivation of yeasts on liquid digestate to remove organic pollutants and nutrients and for potential application as co-culture with microalgae, J. Environ. Manage 362 (2024) 121351, https://doi.org/10.1016/J.JENVMAN.2024.121351.

[17] M. Axelsson Bjerg, E.M. Ekstrand, I. Sundgren, S. Shakeri Yekta, J. Moestedt, A. Björn, Moderate thermal post-treatment of digestate to improve biomethane production from agricultural- and food waste, Bioresour. Technol. Rep. 27 (2024) 101887, https://doi.org/10.1016/J.BITEB.2024.101887.

[18] Y. Liu, J. Jin, J. Li, Z. Zou, R. Lei, J. Sun, J. Xia, Enhanced phosphorus recovery as vivianite from anaerobically digested sewage sludge with magnetic biochar addition, Sustainability, 2022, 14(14), 8690; 10.3390/su14148690.

[19] H. Yazıcı, B.S. Kumbul, K. Ekinci, Assessment of the effectiveness of process-induced struvite crystallization process on the recovery of nutrients from high-strength liquid digestate of an anaerobic biogas plant, J. Environ. Chem. Eng. 12 (2024) 112129, https://doi.org/10.1016/J.JECE.2024.112129.

[20] A. Urbanowska, I. Polowczyk, M. Kabsch-Korbutowicz, Treatment of Liquid Fraction of Digestate by Integrated Process Struvite Precipitation—Forward Osmosis, Energies, 16 (2023) 47, 10.3390/EN16010047.

[21] S. Uludag-Demirer, G.N. Demirer, Post-anaerobic treatability and residual biogas potential of digestate, Biomass Conv. Bioref. 12 (2022) 1695–1702, https://doi.org/10.1007/s13399-021-01290-7.

[22] B. Chezeau, C. Vial, Combined effects of digestate viscosity and agitation conditions on the fermentative biohydrogen production, Biochem Eng. J. 142 (2019) 105–116, https://doi.org/10.1016/J.BEJ.2018.11.016.

[23] M.K. Manu, C. Wang, D. Li, S. Varjani, J.W.C. Wong, Impact of zeolite amendment on composting of food waste digestate, J. Clean Prod. 371 (2022) 133408, https://doi.org/10.1016/J.JCLEPRO.2022.133408.

[24] A. Choudhury, C. Lepine, F. Witarsa, C. Good, Anaerobic digestion challenges and resource recovery opportunities from land-based aquaculture waste and seafood processing byproducts: A review, Bioresour. Technol. 354 (2022) 127144, https://doi.org/10.1016/J.BIORTECH.2022.127144.

[25] B. Gurmessa, S. Cocco, A.J. Ashworth, R.P. Udawatta, V. Cardelli, A. Ilari, D. Serrani, F. Fornasier, A. Del Gatto, E.F. Pedretti, G. Corti, Short term effects of digestate and composted digestate on soil health and crop yield: Implications for sustainable biowaste management in the bioenergy sector, Appl. Sci. 906 (2024) 167208, https://doi.org/10.1016/J.SCITOTENV.2023.167208.

[26] E. Abdelfatah-Aldayyat, S. González-Rojo, X. Gómez, Reviewing Digestate Thermal Valorization: Focusing on the Energy Demand and the Treatment of Process Water, Environments 11 (2024) 239, https://doi.org/10.3390/environments11110239.

[27] G. Mazzanti, F. Demichelis, D. Fino, T. Tommasi, A closed-loop valorization of the waste biomass through two-stage anaerobic digestion and digestate exploitation, Renew. Sustain. Energy Rev. 207 (2025) 114938, https://doi.org/10.1016/J.RSER.2024.114938.

[28] Đ. Kovačić, Z. Lončarić, J. Jović, D. Samac, B. Popović, M. Tišma, Digestate Management and Processing Practices: A Review, Appl. Sci. 12 (2022) 9216, https://doi.org/10.3390/APP12189216.

[29] D. Guan, J. Zhao, Y. Wang, Z. Fu, D. Zhang, H. Zhang, J. Xie, Y. Sun, J. Zhu, D. Wang, A critical review on sustainable management and resource utilization of digestate, Process Saf. Environ. Prot. 183 (2024) 339–354, https://doi.org/10.1016/J.PSEP.2024.01.029.

[30] I. Adnane, H. Taoumi, K. Lahrech, Fertahi, M. Ghodbane, From waste to resource: biogas and digestate valorization strategies for sustainable energy and agriculture, Biomass Bioenergy 200 (2025) 108006, https://doi.org/10.1016/J.BIOMBIOE.2025.108006.

[31] P. Dhull, V. Mozhiarasi, S. Kumar, P.M. Benish Rose, R.K. Lohchab, Current and prognostic overview of digestate management and processing practices, regulations and standards, Biocatal Agric. Biotechnol. 61 (2024) 103345, https://doi.org/10.1016/J.BCAB.2024.103345.

[32] M. Sobhi, J. Guo, M.S. Gaballah, B. Li, J. Zheng, X. Cui, H. Sun, R. Dong, Selecting the optimal nutrients recovery application for a biogas slurry based on its characteristics and the local environmental conditions: A critical review, Sci. Total Environ. 814 (2022) 152700, https://doi.org/10.1016/J.SCITOTENV.2021.152700.

[33] A.H. Shafaghat, A. Merenda, D. Seccombe, S. Phuntsho, H.K. Shon, From waste to high-value fertilisers: Harvesting nutrients from liquid anaerobic digestate for a circular bioeconomy, Desalination 596 (2025) 118266, https://doi.org/10.1016/J.DESAL.2024.118266.

[34] G. Carraro, K. Tonderski, A. Enrich-Prast, Solid-liquid separation of digestate from biogas plants: A systematic review of the techniques' performance, J. Environ. Manage 356 (2024) 120585, https://doi.org/10.1016/J.JENVMAN.2024.120585.

[35] G. Mancuso, S. Habchi, M. Maraldi, F. Valenti, H. El Bari, Comprehensive review of technologies for separate digestate treatment and agricultural valorisation within circular and green economy, Bioresour. Technol. 409 (2024) 131252, https://doi.org/10.1016/J.BIORTECH.2024.131252.

[36] W. Peng, A. Pivato, Sustainable management of digestate from the organic fraction of municipal solid waste and food waste under the concepts of back to earth alternatives and circular economy, Waste Biomass Valor. 10 (2019) 465–481, https://doi.org/10.1007/s12649-017-0071-2.

[37] C. Grandas Tavera, T. Raab, L. Holguin Trujillo, Valorization of biogas digestate as organic fertilizer for closing the loop on the economic viability to develop biogas projects in Colombia, Cleaner and Circular, Bioeconomy 4 (2023) 100035, https://doi.org/10.1016/J.CLCB.2022.100035.

[38] B. Lamolinara, A. Pérez-Martínez, E. Guardado-Yordi, C. Guillén Fiallos, K. Diéguez-Santana, G.J. Ruiz-Mercado, Anaerobic digestate management, environmental impacts, and techno-economic challenges, Waste Manag. 140 (2022) 14–30, https://doi.org/10.1016/J.WASMAN.2021.12.035.

[39] C. Vaneeckhaute, V. Lebuf, E. Michels, E. Belia, P.A. Vanrolleghem, F.M.G. Tack, E. Meers, Nutrient Recovery from Digestate: Systematic Technology Review and

Product Classification, Waste Biomass Valor. 8 (2017) 21–40, https://doi.org/10.1007/s12649-016-9642-x.

[40] P.S. Selvaraj, K. Periasamy, K. Suganya, K. Ramadass, S. Muthusamy, P. Ramesh, R. Bush, S.G.T. Vincent, T. Palanisami, Novel resources recovery from anaerobic digestates: Current trends and future perspectives, Crit. Rev. Environ. Sci. Technol. 52 (2022) 1915–1999, https://doi.org/10.1080/10643389.2020.1864957.

[41] K. Velkushanova, M. Reddy, T. Zikalala, B. Gumbi, C. Archer, B.J. Ward, N. Andriessen, S. Sam, L. Strande. Laboratory Procedures and Methods for Characterisation of Faecal Sludge, 2021.

[42] A. Public Health Association. APHA Method 4500-F: Standard Methods for the Examination of Water and Wastewater, 1992.

[43] ISO 10693:1995 - Soil quality — Determination of carbonate content — Volumetric method, (1995). https://www.iso.org/standard/18781.html (accessed July 21, 2024).

[44] L. Zuliani, N. Frison, A. Jelic, F. Fatone, D. Bolzonella, M. Ballottari, Microalgae Cultivation on Anaerobic Digestate of Municipal Wastewater, Sewage Sludge and Agro-Waste, "Int. J. Mol. Sci. 17 (2016) 1692, https://doi.org/10.3390/IJMS17101692.

[45] L. Kabaivanova, J. Ivanova, E. Chorukova, V. Hubenov, L. Nacheva, I. Simeonov, Algal biomass accumulation in waste digestate after anaerobic digestion of wheat straw, Fermentation 8 (2022) 715, https://doi.org/10.3390/fermentation8120715.

[46] B. Song, M.K. Manu, D. Li, C. Wang, S. Varjani, N. Ladumor, L. Michael, Y. Xu, J. W.C. Wong, Food waste digestate composting: Feedstock optimization with sawdust and mature compost, Bioresour. Technol. 341 (2021) 125759, https://doi.org/10.1016/J.BIORTECH.2021.125759.

[47] E. Tampio, T. Salo, J. Rintala, Agronomic characteristics of five different urban waste digestates, J. Environ. Manage 169 (2016) 293–302, https://doi.org/10.1016/J.JENVMAN.2016.01.001.

[48] A. Chuda, K. Ziemiński, Digestate mechanical separation in industrial conditions: Efficiency profiles and fertilising potential, Waste Manag. 128 (2021) 167–178, https://doi.org/10.1016/J.WASMAN.2021.04.049.

[49] X. Ran, N.S.T. Uppuluri, Y. Deng, Y. Zheng, R. Dong, J. Müller, H. Oechsner, B. Li, J. Guo, Comparison of phosphorus species in livestock manure and digestate by different detection techniques, Sci. Total Environ. 874 (2023) 162547, https://doi.org/10.1016/J.SCITOTENV.2023.162547.

[50] L. Wang, Y. Li, P. Chen, M. Min, Y. Chen, J. Zhu, R.R. Ruan, Anaerobic digested dairy manure as a nutrient supplement for cultivation of oil-rich green microalgae Chlorella sp, Bioresour Technol. 101 (2010) 2623–2628, https://doi.org/10.1016/J.BIORTECH.2009.10.062.

[51] L. Wang, M. Addy, J. Liu, C. Nekich, R. Zhang, P. Peng, Y. Cheng, K. Cobb, Y. Liu, H. Wang, R. Ruan, Integrated process for anaerobically digested swine manure treatment, Bioresour Technol. 273 (2019) 506–514, https://doi.org/10.1016/J.BIORTECH.2018.11.050.

[52] D.S. Matjuda, M. Tekere, M.J. Thaela-Chimuka, Characterization of the physicochemical composition of anaerobically digested (digestate) high throughput red meat abattoir waste in South Africa and the determination of its quality as a potential biofertilizer, Heliyon 9 (2023) e21647, https://doi.org/10.1016/J.HELIYON.2023.E21647.

[53] S. Menardo, P. Balsari, E. Dinuccio, F. Gioelli, Thermal pre-treatment of solid fraction from mechanically-separated raw and digested slurry to increase methane yield, Bioresour Technol. 102 (2011) 2026–2032, https://doi.org/10.1016/j.biortech.2010.09.067.

[54] J.K. Nayak, V.V. Ranade, Hydrodynamic cavitation-based pretreatment of primary digestate: feasibility and role in overall enhancement of valorization, ACS Omega 10 (2025) 36276–36284, https://doi.org/10.1021/ACSOMEGA.5C04230.

[55] N. Wang, D. Huang, C. Zhang, M. Shao, Q. Chen, J. Liu, Z. Deng, Q. Xu, Long-term characterization and resource potential evaluation of the digestate from food waste anaerobic digestion plants, Sci. Total Environ. 794 (2021) 148785, https://doi.org/10.1016/J.SCITOTENV.2021.148785.

[56] E. Miliotti, D. Casini, L. Rosi, G. Lotti, A.M. Rizzo, D. Chiaramonti, Lab-scale pyrolysis and hydrothermal carbonization of biomass digestate: Characterization of solid products and compliance with biochar standards, Biomass Bioenergy 139 (2020) 105593, https://doi.org/10.1016/j.biombioe.2020.105593.

[57] J. Liu, S. Huang, K. Chen, T. Wang, M. Mei, J. Li, Preparation of biochar from food waste digestate: Pyrolysis behavior and product properties, Bioresour. Technol. 302 (2020) 122841, https://doi.org/10.1016/j.biortech.2020.122841.

[58] A. Cerda, L. Mejias, P. Rodríguez, A. Rodríguez, A. Artola, X. Font, T. Gea, A. Sánchez, Valorisation of digestate from biowaste through solid-state fermentation to obtain value added bioproducts: A first approach, Bioresour Technol. 271 (2019) 409–416, https://doi.org/10.1016/j.biortech.2018.09.131.

[59] Z. Cao, B. Hülsemann, D. Wüst, L. Illi, H. Oechsner, A. Kruse, Valorization of maize silage digestate from two-stage anaerobic digestion by hydrothermal carbonization, Energy Convers. Manag. 222 (2020), https://doi.org/10.1016/j.enconman.2020.113218.

[60] Z. Cao, D. Jung, M.P. Olszewski, P.J. Arauzo, A. Kruse, Hydrothermal carbonization of biogas digestate: Effect of digestate origin and process conditions, Waste Manag. 100 (2019) 138–150, https://doi.org/10.1016/j.wasman.2019.09.009.

[61] F. Monlau, M. Francavilla, C. Sambusiti, N. Antoniou, A. Solhy, A. Libutti, A. Zabaniotou, A. Barakat, M. Monteleone, 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, App.l Energy 169 (2016) 652–662, https://doi.org/10.1016/j.apenergy.2016.02.084.

[62] C.Y. Hung, W.T. Tsai, J.W. Chen, Y.Q. Lin, Y.M. Chang, Characterization of biochar prepared from biogas digestate, Waste Manag. 66 (2017) 53–60, https://doi.org/10.1016/j.wasman.2017.04.034.

[63] K. Risberg, Sveriges lantbruksuniversitet. Quality and Function of Anaerobic Digestion Residues, 2015.

[64] K.R. Baral, R. Labouriau, J.E. Olesen, S.O. Petersen, Nitrous oxide emissions and nitrogen use efficiency of manure and digestates applied to spring barley, Agric. Ecosyst. Environ. 239 (2017) 188–198, https://doi.org/10.1016/j.agee.2017.01.012.

[65] X. Jin, W. Ai, W. Dong, Lignocellulose degradation, biogas production and characteristics of the microbial community in solid-state anaerobic digestion of wheat straw waste, Life Sci. Space Res. (Amst) 32 (2022) 1–7, https://doi.org/10.1016/j.lssr.2021.09.004.

[66] K. Möller, T. Müller, Effects of anaerobic digestion on digestate nutrient availability and crop growth: A review, Eng. Life Sci. 12 (2012) 242–257, https://doi.org/10.1002/ELSC.201100085.

[67] N. Di Costanzo, A. Cesaro, F. Di Capua, M.C. Mascolo, G. Esposito, Application of high-intensity static magnetic field as a strategy to enhance the fertilizing potential of sewage sludge digestate, Waste Manag. 170 (2023) 122–130, https://doi.org/10.1016/J.WASMAN.2023.08.005.

[68] I. Al-Sulaimi, J.K. Nayak, A. Al-Mamun, A. Sana, Effective removal of Helminths Ova from wastewater and its inactivation from sewage sludge using thermophilic anaerobic digestion, Environ. Nanotechnol Monit. Manag. 20 (2023), https://doi.org/10.1016/j.enmm.2023.100793.

[69] H. Geng, Y. Xu, L. Zheng, H. Gong, L. Dai, X. Dai, An overview of removing heavy metals from sewage sludge: Achievements and perspectives, Environ. Pollut. 266 (2020), https://doi.org/10.1016/j.envpol.2020.115375.

[70] K. Styszko, J. Durak, B. Kończak, M. Głodniok, A. Borgulat, The impact of sewage sludge processing on the safety of its use, Sci. Rep. 12 (2022), https://doi.org/10.1038/s41598-022-16354-5.

[71] F. Hassan, K.D. Prasetya, J.N. Hanun, H.M. Bui, S. Rajendran, N. Kataria, K. S. Khoo, Y.F. Wang, S.J. You, J.J. Jiang, Microplastic contamination in sewage sludge: Abundance, characteristics, and impacts on the environment and human health, Environ. Technol. Innov. 31 (2023), https://doi.org/10.1016/j.eti.2023.103176.

[72] A. Montusiewicz, A. Szaja, I. Musielewicz, A. Cydzik-Kwiatkowska, M. Lebiocka, Effect of bioaugmentation on digestate metal concentrations in anaerobic digestion of sewage sludge, PLoS One 15 (2020), https://doi.org/10.1371/journal.pone.0235508.

[73] Y. Tang, X. Li, B. Dong, J. Huang, Y. Wei, X. Dai, L. Dai, Effect of aromatic repolymerization of humic acid-like fraction on digestate phytotoxicity reduction during high-solid anaerobic digestion for stabilization treatment of sewage sludge, Water Res. 143 (2018) 436–444, https://doi.org/10.1016/j.watres.2018.07.003.

[74] L. Guo, Y. Xie, W. Sun, Y. Xu, Y. Sun, Research progress of high-salinity wastewater treatment technology, Water 15 (2023) 684, https://doi.org/10.3390/w15040684.

[75] P. Li, H. Zhao, C. Cheng, T. Hou, D. Shen, Y. Jiao, A review on anaerobic co-digestion of sewage sludge with other organic wastes for methane production: Mechanism, process, improvement and industrial application, Biomass Bioenergy 185 (2024) 107241, https://doi.org/10.1016/J.BIOMBIOE.2024.107241.

[76] J.C. Cheong, J.T.E. Lee, J.W. Lim, S. Song, J.K.N. Tan, Z.Y. Chiam, K.Y. Yap, E. Y. Lim, J. Zhang, H.T.W. Tan, Y.W. Tong, Closing the food waste loop: Food waste anaerobic digestate as fertilizer for the cultivation of the leafy vegetable, xiao bai cai (Brassica rapa), Sci. Total Environ. 715 (2020), https://doi.org/10.1016/j.scitotenv.2020.136789.

[77] Y. Ren, M. Yu, C. Wu, Q. Wang, M. Gao, Q. Huang, Y. Liu, A comprehensive review on food waste anaerobic digestion: Research updates and tendencies, Bioresour Technol. 247 (2018) 1069–1076, https://doi.org/10.1016/j.biortech.2017.09.109.

[78] O.A. Awadalla, W.A. Atawy, M.Y. Bedaiwy, S.S. Ali, Y.A.G. Mahmoud, Anaerobic digestion of lignocellulosic waste for enhanced methane production and biogas-digestate utilization, Ind. Crops Prod. 195 (2023), https://doi.org/10.1016/j.indcrop.2023.116420.

[79] A. Pantelopoulos, J. Magid, L.S. Jensen, Thermal drying of the solid fraction from biogas digestate: Effects of acidification, temperature and ventilation on nitrogen content, Waste Manag. 48 (2016) 218–226, https://doi.org/10.1016/j.wasman.2015.10.008.

[80] W. Fuchs, B. Drosg, Assessment of the state of the art of technologies for the processing of digestate residue from anaerobic digesters, Water Sci. Tech. 67 (2013) 1984–1993, https://doi.org/10.2166/WST.2013.075.

[81] M.K. Manu, D. Li, L. Liwen, Z. Jun, S. Varjani, J.W.C. Wong, A review on nitrogen dynamics and mitigation strategies of food waste digestate composting, Bioresour Technol. 334 (2021) 125032, https://doi.org/10.1016/J.BIORTECH.2021.125032.

[82] S.A. Opatokun, T. Kan, A. Al Shoaibi, C. Srinivasakannan, V. Strezov, Characterization of food waste and Its digestate as feedstock for thermochemical processing, Energy Fuels 30 (2015) 1589–1597, https://doi.org/10.1021/ACS.ENERGYFUELS.5B02183.

[83] N. Wang, D. Huang, C. Zhang, M. Shao, Q. Chen, J. Liu, Z. Deng, Q. Xu, Long-term characterization and resource potential evaluation of the digestate from food waste anaerobic digestion plants, Sci. Total Environ. 794 (2021) 148785, https://doi.org/10.1016/J.SCITOTENV.2021.148785.

[84] J. Lu, S. Xu, Post-treatment of food waste digestate towards land application: A review, J. Clean Prod. 303 (2021), https://doi.org/10.1016/j.jclepro.2021.127033.

[85] J.A. Alburquerque, C. de la Fuente, A. Ferrer-Costa, L. Carrasco, J. Cegarra, M. Abad, M.P. Bernal, Assessment of the fertiliser potential of digestates from farm and agroindustrial residues, Biomass Bioenergy 40 (2012) 181–189, https://doi.org/10.1016/j.biombioe.2012.02.018.

[86] M. Logan, C. Visvanathan, Management strategies for anaerobic digestate of organic fraction of municipal solid waste: Current status and future prospects, Waste Manag. Research 37 (2019) 27–39, https://doi.org/10.1177/0734242X18816793.

[87] M. Krishania, V. Kumar, V.K. Vijay, A. Malik, Analysis of different techniques used for improvement of biomethanation process: A review, Fuel 106 (2013) 1–9, https://doi.org/10.1016/j.fuel.2012.12.007.

[88] C. Sambusiti, E. Ficara, F. Malpei, J.P. Steyer, H. Carrère, Benefit of sodium hydroxide pretreatment of ensiled sorghum forage on the anaerobic reactor stability and methane production, Bioresour Technol. 144 (2013) 149–155, https://doi.org/10.1016/j.biortech.2013.06.095.

[89] F. Rizzioli, D. Bertasini, D. Bolzonella, N. Frison, F. Battista, A critical review on the techno-economic feasibility of nutrients recovery from anaerobic digestate in the agricultural sector, Sep. Purif. Technol. 306 (2023), https://doi.org/10.1016/j.seppur.2022.122690.

[90] Drosg, B., Fuchs, W., Al Seadi, T., Madsen, M., & Linke, B. (2015). Nutrient recovery by biogas digestate processing, Bernhard Drosg Werner Fuchs. https://www.ieabioenergy.com/wp-content/uploads/2015/08/NUTRIENT_RECOVERY_RZ_web2.pdf (accessed July 31, 2024).

[91] M.L. Christensen, M. Hjorth, K. Keiding, Characterization of pig slurry with reference to flocculation and separation, Water Res. 43 (2009) 773–783, https://doi.org/10.1016/j.watres.2008.11.010.

[92] S. Chozhavendhan, G. Karthigadevi, B. Bharathiraja, R. Praveen Kumar, L.D. Abo, S. Venkatesa Prabhu, R. Balachandar, M. Jayakumar, Current and prognostic overview on the strategic exploitation of anaerobic digestion and digestate: A review, Environ Res 216 (2023), https://doi.org/10.1016/j.envres.2022.114526.

[93] C. Li, J. Li, L. Pan, X. Zhu, S. Xie, G. Yu, Y. Wang, X. Pan, G. Zhu, I. Angelidaki, Treatment of digestate residues for energy recovery and biochar production: From lab to pilot-scale verification, J. Clean Prod. 265 (2020), https://doi.org/10.1016/j.jclepro.2020.121852.

[94] M. Pecchi, F. Patuzzi, V. Benedetti, R. Di Maggio, M. Baratieri, Thermodynamics of hydrothermal carbonization: Assessment of the heat release profile and process enthalpy change, Fuel Process. Techn. (2020), https://doi.org/10.1016/j.fuproc.2019.106206, 197.

[95] Y. Zhan, F. Yin, C. Yue, J. Zhu, Z. Zhu, M. Zou, H. Dong, Effect of pretreatment on hydraulic performance of the integrated membrane process for concentrating nutrient in biogas digestate from swine manure, Membranes (Basel) 10 (2020) 1–13, https://doi.org/10.3390/membranes10100249.

[96] S. Bachmann, S. Wentzel, B. Eichler-Löbermann, Codigested dairy slurry as a phosphorus and nitrogen source for Zea mays L. and Amaranthus cruentus L, J. Plant Nut. Soil Sci. 174 (2011) 908–915, https://doi.org/10.1002/jpln.201000383.

[97] D. Sharma, T. Espinosa-Solares, D.H. Huber, Thermophilic anaerobic co-digestion of poultry litter and thin stillage, Bioresour Technol. 136 (2013) 251–256, https://doi.org/10.1016/j.biortech.2013.03.005.

[98] R. Nag, A. Auer, B.K. Markey, P. Whyte, S. Nolan, V. O'Flaherty, L. Russell, D. Bolton, O. Fenton, K. Richards, E. Cummins, Anaerobic digestion of agricultural manure and biomass – Critical indicators of risk and knowledge gaps, Sci. Total Env. 690 (2019) 460–479, https://doi.org/10.1016/j.scitotenv.2019.06.512.

[99] S. Ervasti, J. Kostensalo, E. Tampio, Effects of seasonal and local co-feedstocks on the performance of continuous anaerobic digestion of cattle slurry, Bioresour Technol. Rep. 19 (2022), https://doi.org/10.1016/j.biteb.2022.101207.

[100] M.Y. Shen, M. Torre, C.Y. Chu, P. Tratzi, M. Carnevale, F. Gallucci, V. Paolini, F. Petracchini, Green biohydrogen production in a Co-digestion process from mixture of high carbohydrate food waste and cattle/chicken manure digestate, Int. J. Hydrogen Energy 47 (2022) 40696–40703, https://doi.org/10.1016/J.IJHYDENE.2022.09.104.

[101] Biogas Production from Maize Grains and Maize Silage, Pol J Environ Stud 19 (2010) 323–329. https://www.pjoes.com/Biogas-Production-from-Maize-Grains-and-Maize-Silage,88387,0,2.html (accessed October 20, 2024).

[102] Z. Wang, Y. Hu, S. Wang, G. Wu, X. Zhan, A critical review on dry anaerobic digestion of organic waste: Characteristics, operational conditions, and improvement strategies, Renew. Sustain. Energy Rev. 176 (2023) 113208, https://doi.org/10.1016/J.RSER.2023.113208.

[103] P. Kaparaju, I. Buendia, L. Ellegaard, I. Angelidakia, Effects of mixing on methane production during thermophilic anaerobic digestion of manure: Lab-scale and pilot-scale studies, Bioresour Technol. 99 (2008) 4919–4928, https://doi.org/10.1016/J.BIORTECH.2007.09.015.

[104] X. Cao, X. Wang, H. Wang, F. Liu, Effects of Substrate Rheological Properties on Microbial Community and Biogas Production in Anaerobic Digestion, J. Environ. Eng. 149 (2023) 04023042, https://doi.org/10.1061/JOEEDU.EEENG-7223.

[105] Q. Gao, L. Li, K. Wang, Q. Zhao, Mass transfer enhancement in high-solids anaerobic digestion of organic fraction of municipal solid wastes: A review, Bioengineering 10 (2023) 1084, https://doi.org/10.3390/BIOENGINEERING10091084.

[106] H.F. Wang, Y.N. Bai, W. Zhang, H.J. Wang, R.J. Zeng, Supplementary in-depth analysis of the waste activated sludge dewatering process using a rheological analysis, ACS ES and T, Engineering 1 (2021) 289–297, https://doi.org/10.1021/ACSESTENGG.0C00126.

[107] M. Garuti, M. Langone, C. Fabbri, S. Piccinini, Monitoring of full-scale hydrodynamic cavitation pretreatment in agricultural biogas plant, Bioresour Technol. 247 (2018) 599–609, https://doi.org/10.1016/J.BIORTECH.2017.09.100.

[108] E. Hong, A.M. Yeneneh, T.K. Sen, H.M. Ang, A. Kayaalp, A comprehensive review on rheological studies of sludge from various sections of municipal wastewater treatment plants for enhancement of process performance, Adv. Colloid Interface Sci. 257 (2018) 19–30, https://doi.org/10.1016/J.CIS.2018.06.002.

[109] X. Dai, X. Gai, B. Dong, Rheology evolution of sludge through high-solid anaerobic digestion, Biores. Tech. 174 (2014) 6–10, https://doi.org/10.1016/j.biortech.2014.09.122.

[110] P. Wei, W. Uijttewaal, J.B. van Lier, M. de Kreuk, Impacts of shearing and temperature on sewage sludge: Rheological characterisation and integration to flow assessment, Sci. Total Env. 774 (2021) 145005, https://doi.org/10.1016/j.scitotenv.2021.145005.

[111] L. Li, K. Wang, W. Mei, Q. Gao, Q. Zhao, H. Zhou, J. Jiang, Rheology-dependent mass diffusion characteristics of high-solids anaerobic co-digestate of food waste and sewage sludge, Biochem Eng. J. (2023) 109043, https://doi.org/10.1016/J.BEJ.2023.109043, 199.

[112] S. Miryahyaei, K. Olinga, F.A. Abdul Muthalib, T. Das, M.S. Ab Aziz, M. Othman, J.C. Baudez, D. Batstone, N. Eshtiaghi, Impact of rheological properties of substrate on anaerobic digestion and digestate dewaterability: New insights through rheological and physico-chemical interaction, Water Res. 150 (2019) 56–67, https://doi.org/10.1016/J.WATRES.2018.11.049.

[113] L. Kamkeng, P. Marchal, A. Bertrandias, B. Le Creurer, E. Olmos, Rheological characteristics of an anaerobically digested rye and maize silage mixture: Impact of solid concentration and particle size on rheological properties, Chem. Eng. Res. Des. 196 (2023) 309–318, https://doi.org/10.1016/J.CHERD.2023.06.045.

[114] R. Hreiz, N. Adouani, D. Fünfschilling, P. Marchal, M.N. Pons, Rheological characterization of raw and anaerobically digested cow slurry, Chem. Eng. Res. Des. 119 (2017) 47–57, https://doi.org/10.1016/J.CHERD.2017.01.005.

[115] T. Gienau, M. Kraume, S. Rosenberger, Rheological characterization of anaerobic sludge from agricultural and bio-waste biogas plants, Chem. Ing. Tech. 90 (2018) 988–997, https://doi.org/10.1002/CITE.201700102.

[116] F. Guilayn, M. Rouez, M. Crest, D. Patureau, J. Jimenez, Valorization of digestates from urban or centralized biogas plants: a critical review, Rev. Env. Sci. Bio./Tech. 19 (2) (2020) 419–462, https://doi.org/10.1007/S11157-020-09531-3.

[117] F. Guilayn, J. Jimenez, F. Monlau, C. Vaneeckhaute, Valorisation of anaerobic digestate: towards value-added products. 10.1007/978-3-030-87633-3_9.

[118] A. Petrovič, S. Vohl, T. Cenčič Predikaka, R. Bedoić, M. Simonič, I. Ban, L. Čuček, Pyrolysis of solid digestate from sewage sludge and lignocellulosic biomass: Kinetic and thermodynamic analysis characterization of biochar, Sustainability, 2021, 13(17), 9642, 10.3390/su13179642.

[119] F. Guilayn, J. Jimenez, M. Rouez, M. Crest, D. Patureau, Digestate mechanical separation: Efficiency profiles based on anaerobic digestion feedstock and equipment choice, Bioresour Technol. 274 (2019) 180–189, https://doi.org/10.1016/J.BIORTECH.2018.11.090.

[120] C. Romio, A.J. Ward, H.B. Møller, Characterization and valorization of biogas digestate and derived organic fertilizer products from separation processes, Front. Sustain. Food Syst. 8 (2024), https://doi.org/10.3389/fsufs.2024.1415508.

[121] F. Tambone, V. Orzi, G. D'Imporzano, F. Adani, Solid and liquid fractionation of digestate: Mass balance, chemical characterization, and agronomic and environmental value, Bioresour Technol. 243 (2017) 1251–1256, https://doi.org/10.1016/J.BIORTECH.2017.07.130.

[122] M. Nowak, W. Czekała, Sustainable use of digestate from biogas plants: separation of raw digestate and liquid fraction processing, Sustainability 16 (2024) 5461, https://doi.org/10.3390/SU16135461.

[123] A. Bauer, H. Mayr, K. Hopfner-Sixt, T. Amon, Detailed monitoring of two biogas plants and mechanical solid–liquid separation of fermentation residues, J. Biotechnol. 142 (2009) 56–63, https://doi.org/10.1016/J.JBIOTEC.2009.01.016.

[124] A. Cathcart, B.M. Smyth, G. Lyons, S.T. Murray, D. Rooney, C.R. Johnston, Optimising mechanical separation of anaerobic digestate for total solids and nutrient removal, J. Environ. Manage 345 (2023) 118449, https://doi.org/10.1016/J.JENVMAN.2023.118449.

[125] G.A. Lyons, A. Cathcart, J.P. Frost, M. Wills, C. Johnston, R. Ramsey, B. Smyth, Review of two mechanical separation technologies for the sustainable management of agricultural phosphorus in nutrient-vulnerable zones, Agronomy 11 (2021) 836, https://doi.org/10.3390/AGRONOMY11050836.

[126] A. Cathcart, B.M. Smyth, G. Lyons, S.T. Murray, D. Rooney, C.R. Johnston, An economic analysis of anaerobic digestate fuel pellet production: can digestate fuel pellets add value to existing operations? Clean Eng. Technol. 3 (2021) 100098, https://doi.org/10.1016/J.CLET.2021.100098.

[127] S. Gilkinson, P. Frost, Main Report-Gilkinson & Frost, 2007 Evaluation of mechanical separation of pig and cattle slurries | Agri-Food and Biosciences Institute, (2007). https://www.afbini.gov.uk/article/evaluation-mechanical-separation-pig-and-cattle-slurries (accessed October 21, 2024).

[128] E. Tampio, I. Laaksonen, K. Rimhanen, N. Honkala, J. Laakso, H. Soinne, K. Rasa, Effect of manure co-digestion on methane production, carbon retention, and fertilizer value of digestate, Sci. Total Env. 927 (2024) 172083, https://doi.org/10.1016/J.SCITOTENV.2024.172083.

[129] D.E. Algapani, W. Qiao, M. Ricci, D. Bianchi, S.M. Wandera, F. Adani, R. Dong, Bio-hydrogen and bio-methane production from food waste in a two-stage

anaerobic digestion process with digestate recirculation, Renew. Energy 130 (2019) 1108–1115, https://doi.org/10.1016/J.RENENE.2018.08.079.
[130] X. Peng, I.A. Nges, J. Liu, Improving methane production from wheat straw by digestate liquor recirculation in continuous stirred tank processes, Renew Energy 85 (2016) 12–18, https://doi.org/10.1016/J.RENENE.2015.06.023.
[131] P. Ai, M. Chen, Y. Ran, K. Jin, J. Peng, A.E.F. Abomohra, Digestate recirculation through co-digestion with rice straw: Towards high biogas production and efficient waste recycling, J.. Clean Prod. 263 (2020) 121441, https://doi.org/10.1016/J.JCLEPRO.2020.121441.
[132] M.R. Atelge, A.E. Atabani, J.R. Banu, D. Krisa, M. Kaya, C. Eskicioglu, G. Kumar, C. Lee, Y. Yildiz, S. Unalan, R. Mohanasundaram, F. Duman, A critical review of pretreatment technologies to enhance anaerobic digestion and energy recovery, Fuel 270 (2020) 117494, https://doi.org/10.1016/J.FUEL.2020.117494.
[133] T. Liu, X. Zhou, Z. Li, X. Wang, J. Sun, Effects of liquid digestate pretreatment on biogas production for anaerobic digestion of wheat straw, Bioresour Technol. 280 (2019) 345–351, https://doi.org/10.1016/J.BIORTECH.2019.01.147.
[134] T.A. Bimestre, J.A.M. Júnior, E.V. Canettieri, C.E. Tuna, Hydrodynamic cavitation for lignocellulosic biomass pretreatment: a review of recent developments and future perspectives, Bioresources and Bioprocessing 9 (1) (2022) 1–16, https://doi.org/10.1186/S40643-022-00499-2.
[135] V.V. Ranade, V.M. Bhandari, S. Nagarajan, V.P. Sarvothaman, A.T. Simpson. Hydrodynamic Cavitation: Devices, Design and Applications, John Wiley & Sons, 2022, ISBN 978-3-527-34643-1.
[136] S. Nagarajan, V.V. Ranade, Valorizing waste biomass via hydrodynamic cavitation and anaerobic digestion, Ind. Eng. Chem. Res. 60 (2021) 16577–16598, https://doi.org/10.1021/acs.iecr.1c03177.
[137] R. Terán Hilares, L. Ramos, S.S. da Silva, G. Dragone, S.I. Mussatto, J.C. dos Santos, Hydrodynamic cavitation as a strategy to enhance the efficiency of lignocellulosic biomass pretreatment, Crit. Rev. Biotechnol. 38 (2018) 483–493, https://doi.org/10.1080/07388551.2017.1369932.
[138] Z. Wu, D.F. Ferreira, D. Crudo, V. Bosco, L. Stevanato, A. Costale, G. Cravotto, Plant and biomass extraction and valorisation under hydrodynamic cavitation, Processes 7 (2019) 965, https://doi.org/10.3390/PR7120965.
[139] X. Sun, S. Liu, X. Zhang, Y. Tao, G. Boczkaj, J.Y. Yoon, X. Xuan, Recent advances in hydrodynamic cavitation-based pretreatments of lignocellulosic biomass for valorization, Bioresour Technol. 345 (2022) 126251, https://doi.org/10.1016/J.BIORTECH.2021.126251.
[140] R. Mittal, V. Ranade, Bioactives from microalgae: A review on process intensification using hydrodynamic cavitation, J. Applied Phycology, 2023 35:3 1129–1161. 10.1007/S10811-023-02945-W.
[141] S. Nagarajan, V.V. Ranade, Pre-treatment of distillery spent wash (vinasse) with vortex based cavitation and its influence on biogas generation, Bioresour Technol. Rep 11 (2020) 100480, https://doi.org/10.1016/J.BITEB.2020.100480.
[142] T. Garoma, D. Pappaterra, An investigation of ultrasound effect on digestate solubilization and methane yield, Waste Manag. 71 (2018) 728–733, https://doi.org/10.1016/J.WASMAN.2017.03.021.
[143] C. Deng, X. Kang, R. Lin, J.D. Murphy, Microwave assisted low-temperature hydrothermal treatment of solid anaerobic digestate for optimising hydrochar and energy recovery, Chem. Eng. J. 395 (2020) 124999, https://doi.org/10.1016/J.CEJ.2020.124999.
[144] A. Serrano, J.A. Siles, M.A. Martín, A.F. Chica, F.S. Estévez-Pastor, E. Toro-Baptista, Improvement of anaerobic digestion of sewage sludge through microwave pre-treatment, J. Environ. Manage 177 (2016) 231–239, https://doi.org/10.1016/J.JENVMAN.2016.03.048.
[145] X. Li, Y. Shi, W. Kong, J. Wei, W. Song, S. Wang, Improving enzymatic hydrolysis of lignocellulosic biomass by bio-coordinated physicochemical pretreatment—A review, Energy Reports 8 (2022) 696–709, https://doi.org/10.1016/J.EGYR.2021.12.015.
[146] A. Musatti, E. Ficara, C. Mapelli, C. Sambusiti, M. Rollini, Use of solid digestate for lignocellulolytic enzymes production through submerged fungal fermentation, J Environ. Manage (2017) 1–6, https://doi.org/10.1016/J.JENVMAN.2017.05.022, 199.
[147] C. Arce, L. Kratky, Mechanical pretreatment of lignocellulosic biomass toward enzymatic/fermentative valorization, IScience 25 (2022) 104610, https://doi.org/10.1016/J.ISCI.2022.104610.
[148] T. Steinbrecher, F. Bonk, M. Scherzinger, O. Lüdtke, M. Kaltschmitt, Fractionation of lignocellulosic fibrous straw digestate by combined hydrothermal and enzymatic treatment, Energies 15 (2022) 6111, https://doi.org/10.3390/EN15176111.
[149] Capitalizing On Digester Coproducts | BioCycle, (2014). https://www.biocycle.net/capitalizing-on-digester-coproducts/ (accessed July 31, 2024).
[150] E. Abouee Mehrizi, A.A. Ebrahimi, H. Saadati, A. Zahedi, M. Ghorbanian, Z. Soltanizadeh, K. Salemi, Investigating the effectiveness of anaerobic digestion in the treatment of sugarcane industry wastewater: A systematic review and meta-analysis, Case Stud. Chem. Environ. Eng. 8 (2023) 100414, https://doi.org/10.1016/J.CSCEE.2023.100414.
[151] S. Menardo, F. Gioelli, P. Balsari, The methane yield of digestate: Effect of organic loading rate, hydraulic retention time, and plant feeding, Bioresour Technol. 102 (2011) 2348–2351, https://doi.org/10.1016/J.BIORTECH.2010.10.094.
[152] F. Gioelli, E. Dinuccio, P. Balsari, Residual biogas potential from the storage tanks of non-separated digestate and digested liquid fraction, Bioresour Technol. 102 (2011) 10248–10251, https://doi.org/10.1016/j.biortech.2011.08.076.
[153] C. Rico, J.L. Rico, I. Tejero, N. Muñoz, B. Gómez, Anaerobic digestion of the liquid fraction of dairy manure in pilot plant for biogas production: Residual methane yield of digestate, Waste Manag. 31 (2011) 2167–2173, https://doi.org/10.1016/J.WASMAN.2011.04.018.
[154] O. Thygesen, S.G. Sommer, S.G. Shin, J.M. Triolo, Residual biochemical methane potential (BMP) of concentrated digestate from full-scale biogas plants, Fuel 132 (2014) 44–46, https://doi.org/10.1016/J.FUEL.2014.04.062.
[155] F. Monlau, P. Kaparaju, E. Trably, J.P. Steyer, H. Carrere, Alkaline pretreatment to enhance one-stage CH4 and two-stage H2/CH4 production from sunflower stalks: Mass, energy and economical balances, Chem. Eng. J. 260 (2015) 377–385, https://doi.org/10.1016/J.CEJ.2014.08.108.
[156] G. Antonopoulou, K. Stamatelatou, N. Venetsaneas, M. Kornaros, G. Lyberatos, Biohydrogen and methane production from cheese whey in a two-stage anaerobic process, Ind. Eng. Chem. Res. 47 (2008) 5227–5233, https://doi.org/10.1021/ie071622x.
[157] A.K. Patel, N. Vaisnav, A. Mathur, R. Gupta, D.K. Tuli, Whey waste as potential feedstock for biohydrogen production, Renew Energy 98 (2016) 221–225, https://doi.org/10.1016/J.RENENE.2016.02.039.
[158] A. Ghimire, L. Frunzo, L. Pontoni, G. d'Antonio, P.N.L. Lens, G. Esposito, F. Pirozzi, Dark fermentation of complex waste biomass for biohydrogen production by pretreated thermophilic anaerobic digestate, J. Environ. Manage. 152 (2015) 43–48, https://doi.org/10.1016/j.jenvman.2014.12.049.
[159] W. Li, T. Cai, X. Lu, Y. Han, D. kudisi, G. Chang, K. Dong, G. Zhen, Two-Phase improves Bio-hydrogen and Bio-methane production of anaerobic membrane bioreactor from waste activated sludge with digestate recirculation, Chemic. Eng. J. 452 (2023) 139547, https://doi.org/10.1016/J.CEJ.2022.139547.
[160] G. Chinellato, C. Cavinato, D. Bolzonella, S. Heaven, C.J. Banks, Biohydrogen production from food waste in batch and semi-continuous conditions: Evaluation of a two-phase approach with digestate recirculation for pH control, Int. J. Hydrogen Energy 38 (2013) 4351–4360, https://doi.org/10.1016/J.IJHYDENE.2013.01.078.
[161] K. Tsigkou, E. Sventzouri, C. Zafiri, M. Kornaros, Digestate recirculation rate optimization for the enhancement of hydrogen production: The case of disposable nappies and fruit/vegetable waste valorization in a mesophilic two-stage anaerobic digestion system, Renew. Energy 215 (2023) 119010, https://doi.org/10.1016/J.RENENE.2023.119010.
[162] B.E. Logan, B. Hamelers, R. Rozendal, U. Schröder, J. Keller, S. Freguia, P. Aelterman, W. Verstraete, K. Rabaey, Microbial fuel cells, methodology and technology, Environ Sci. Technol. 40 (2006) 5181–5192, https://doi.org/10.1021/es0605016.
[163] T. Pepè Sciarria, G. Vacca, F. Tambone, L. Trombino, F. Adani, Nutrient recovery and energy production from digestate using microbial electrochemical technologies (METs), J. Clean Prod. 208 (2019) 1022–1029, https://doi.org/10.1016/j.jclepro.2018.10.152.
[164] N. Antoniou, F. Monlau, C. Sambusiti, E. Ficara, A. Barakat, A. Zabaniotou, 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 (2019) 505–514, https://doi.org/10.1016/j.jclepro.2018.10.055.
[165] G. Chen, X. Guo, Z. Cheng, B. Yan, Z. Dan, W. Ma, Air gasification of biogas-derived digestate in a downdraft fixed bed gasifier, Waste Manag. 69 (2017) 162–169, https://doi.org/10.1016/J.WASMAN.2017.08.001.
[166] S.S. Timofeeva, J.V. Karaeva, A.A. Kovalev, D.A. Kovalev, Y.V. Litti, 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 (2023) 7559–7568, https://doi.org/10.1016/j.ijhydene.2022.11.260.
[167] T. Hübner, J. Mumme, Integration of pyrolysis and anaerobic digestion – Use of aqueous liquor from digestate pyrolysis for biogas production, Bioresour Technol. 183 (2015) 86–92, https://doi.org/10.1016/J.BIORTECH.2015.02.037.
[168] Z. Yao, W. Li, X. Kan, Y. Dai, Y.W. Tong, C.H. Wang, Anaerobic digestion and gasification hybrid system for potential energy recovery from yard waste and woody biomass, Energy 124 (2017) 133–145, https://doi.org/10.1016/j.energy.2017.02.035.
[169] M. Barbanera, C. Pelosi, A.R. Taddei, F. Cotana, Optimization of bio-oil production from solid digestate by microwave-assisted liquefaction, Energy Convers. Manag. 171 (2018) 1263–1272, https://doi.org/10.1016/j.enconman.2018.06.066.
[170] U.K. Roy, T. Radu, J. Wagner, Hydrothermal carbonisation of anaerobic digestate for hydro-char production and nutrient recovery, J. Environ. Chem. Eng. 10 (2022) 107027, https://doi.org/10.1016/J.JECE.2021.107027.
[171] Z. Fu, J. Zhao, D. Guan, Y. Wang, J. Xie, H. Zhang, Y. Sun, J. Zhu, L. Guo, A comprehensive review on the preparation of biochar from digestate sources and its application in environmental pollution remediation, Sci. Total Env. 912 (2024) 168822, https://doi.org/10.1016/J.SCITOTENV.2023.168822.
[172] Y. Yang, P. Xiao, M. Wen, T. Liu, J. Yang, S. Dai, Y. Zhao, Q. Huang, Z. Liu, B. Li, A review on the modified red mud for biomass catalytic pyrolysis: Preparation, mechanisms and perspectives, J. Anal. Appl. Pyrolysis 178 (2024) 106430, https://doi.org/10.1016/J.JAAP.2024.106430.
[173] Z. Yang, Y. Liu, J. Zhang, K. Mao, M. Kurbonova, G. Liu, R. Zhang, W. Wang, Improvement of biofuel recovery from food waste by integration of anaerobic digestion, digestate pyrolysis and syngas biomethanation under mesophilic and thermophilic conditions, J. Clean Prod. 256 (2020) 120594, https://doi.org/10.1016/J.JCLEPRO.2020.120594.
[174] R. Bedoić, V.O. Bulatović, L. Čuček, B. Ćosić, A. Špehar, T. Pukšec, N. Duić, A kinetic study of roadside grass pyrolysis and digestate from anaerobic mono-digestion, Bioresour Technol. 292 (2019) 121935, https://doi.org/10.1016/J.BIORTECH.2019.121935.
[175] J. González-Arias, M.V. Gil, R.Á. Fernández, E.J. Martínez, C. Fernández, G. Papaharalabos, X. Gómez, Integrating anaerobic digestion and pyrolysis for

treating digestates derived from sewage sludge and fat wastes, Environ. Sci. Pollut. Res. 27 (2020) 32603–32614, https://doi.org/10.1007/s11356-020-09461-1.
[176] M.A. Wahab, K. Kebelmann, B. Schartel, G. Griffiths, Valorization of macroalgae digestate into aromatic rich bio-oil and lipid rich microalgal biomass for enhanced algal biorefinery performance, J. Clean Prod. 341 (2022) 130925, https://doi.org/10.1016/J.JCLEPRO.2022.130925.
[177] S. Wang, Y. Wen, Z. Shi, L. Niedzwiecki, M. Baranowski, M. Czerep, W. Mu, H. P. Kruczek, P.G. Jönsson, W. Yang, Effect of hydrothermal carbonization pretreatment on the pyrolysis behavior of the digestate of agricultural waste: A view on kinetics and thermodynamics, Chem. Eng. J. 431 (2022) 133881, https://doi.org/10.1016/J.CEJ.2021.133881.
[178] M.Z. Hossain, M.M. Bahar, B. Sarkar, S.W. Donne, Y.S. Ok, K.N. Palansooriya, M. B. Kirkham, S. Chowdhury, N. Bolan, Biochar and its importance on nutrient dynamics in soil and plant, Biochar 2020 2:4 2 (2020) 379–420. 10.1007/S42773-020-00065-Z.
[179] Y. Feng, T. Bu, Q. Zhang, M. Han, Z. Tang, G. Yuan, D. Chen, Y. Hu, Pyrolysis characteristics of anaerobic digestate from kitchen waste and availability of Phosphorus in pyrochar, J. Anal. Appl. Pyrolysis 168 (2022) 105729, https://doi.org/10.1016/J.JAAP.2022.105729.
[180] H. Tan, M. Yang, Y. Chen, X. Chen, F. Fantozzi, P. Bartocci, R. Tschentscher, F. Barontini, H. Yang, H. Chen, Preparation of aromatic hydrocarbons from catalytic pyrolysis of digestate, Chin J. Chem. Eng. 57 (2023) 1–9, https://doi.org/10.1016/J.CJCHE.2022.09.002.
[181] Biomass Gasification Market Size, Report | Industry Growth 2032, (n.d.). https://www.imarcgroup.com/biomass-gasification-plant (accessed July 31, 2024).
[182] F. Nanna, A. Villone, C. Freda, D. Barisano, R. Agostini, G. Braccio, G. Cornacchia, S. Brandani, Gasification of anaerobic digestate from mix of biomass residues, manures and MSW to, combined heat and power production, Europe. Biomass Conf. Exhibition Proceed. (2017) 435–438, https://doi.org/10.5071/25THEUBCE2017-2BO.6.2.
[183] C. Freda, F. Nanna, A. Villone, D. Barisano, S. Brandani, G. Cornacchia, Air gasification of digestate and its co-gasification with residual biomass in a pilot scale rotary kiln, Int J. Energy Environ. Eng. 10 (2019) 335–346, https://doi.org/10.1007/s40095-019-0310-3.
[184] M.O. Doyeni, U. Stulpinaite, A. Baksinskaite, S. Suproniene, V. Tilvikiene, The effectiveness of digestate use for fertilization in an agricultural cropping system, Plants 10 (2021) 1734, https://doi.org/10.3390/PLANTS10081734.
[185] M.E. Lee, M.W. Steiman, S.K. St. Angelo, Biogas digestate as a renewable fertilizer: effects of digestate application on crop growth and nutrient composition, Renew. Agricul. Food Sys. 36 (2021) 173–181, https://doi.org/10.1017/S1742170520000186.
[186] A. Slepetiene, J. Volungevicius, L. Jurgutis, I. Liaudanskiene, K. Amaleviciute-Volunge, J. Slepetys, J. Ceseviciene, The potential of digestate as a biofertilizer in eroded soils of Lithuania, Waste Manag. 102 (2020) 441–451, https://doi.org/10.1016/J.WASMAN.2019.11.008.
[187] S. Song, J.W. Lim, J.T.E. Lee, J.C. Cheong, S.H. Hoy, Q. Hu, J.K.N. Tan, Z. Chiam, S. Arora, T.Q.H. Lum, E.Y. Lim, C.H. Wang, H.T.W. Tan, Y.W. Tong, Food-waste anaerobic digestate as a fertilizer: The agronomic properties of untreated digestate and biochar-filtered digestate residue, Waste Manag. 136 (2021) 143–152, https://doi.org/10.1016/J.WASMAN.2021.10.011.
[188] M. Odlare, M. Pell, K. Svensson, Changes in soil chemical and microbiological properties during 4 years of application of various organic residues, Waste Manag. 28 (2008) 1246–1253, https://doi.org/10.1016/J.WASMAN.2007.06.005.
[189] M.R. Panuccio, C. Mallamaci, E. Attinà, A. Muscolo, Using digestate as fertilizer for a sustainable tomato cultivation, Sustainability 13 (2021) 1574, https://doi.org/10.3390/SU13031574.
[190] Y.W. Tiong, P. Sharma, S. Xu, J. Bu, S. An, J.B.L. Foo, B.K. Wee, Y. Wang, J.T. E. Lee, J. Zhang, Y. He, Y.W. Tong, Enhancing sustainable crop cultivation: The impact of renewable soil amendments and digestate fertilizer on crop growth and nutrient composition, Environ. Poll. 342 (2024) 123132, https://doi.org/10.1016/J.ENVPOL.2023.123132.
[191] O. Pelayo Lind, M. Hultberg, K.-J. Bergstrand, H. Larsson-Jönsson, S. Caspersen, H. Asp, Biogas digestate in vegetable hydroponic production: pH dynamics and pH management by controlled nitrification, Waste Biomass Valor. 12 (2021) 123–133, https://doi.org/10.1007/s12649-020-00965-y.
[192] C.A. Brebbia, H. (Hideaki) Itoh, Waste management and the environment VIII, (2014) 550. https://books.google.com/books/about/Waste_Management_and_the_Environment_VII.html?id=L-ahDAAAQBAJ (accessed June 1, 2024).
[193] D. Bolzonella, F. Fatone, M. Gottardo, N. Frison, Nutrients recovery from anaerobic digestate of agro-waste: Techno-economic assessment of full scale applications, J Environ. Manage 216 (2018) 111–119, https://doi.org/10.1016/J.JENVMAN.2017.08.026.
[194] E.M. Barampouti, S. Mai, D. Malamis, K. Moustakas, M. Loizidou, Exploring technological alternatives of nutrient recovery from digestate as a secondary resource, Renew. Sustain. Energy Rev. 134 (2020) 110379, https://doi.org/10.1016/J.RSER.2020.110379.
[195] Q. Chen, D. Yang, X. Chen, X. Wang, B. Dong, X. Dai, Vacuum ammonia stripping from liquid digestate: Effects of pH, alkalinity, temperature, negative pressure and process optimization, J. Environ. Sci. 149 (2025) 638–650, https://doi.org/10.1016/J.JES.2024.03.010.
[196] F.E. Kutlar, I. Engin, Y.D. Yilmazel, Nutrient recovery from manure digestate by using waste magnesite powder and bone meal as sustainable substitutes for struvite precipitation, J. Chem. Techn. Biotech. 99 (2024) 1671–1682, https://doi.org/10.1002/JCTB.7661.
[197] M. Sena, M. Seib, D.R. Noguera, A. Hicks, Environmental impacts of phosphorus recovery through struvite precipitation in wastewater treatment, J. Clean Prod. 280 (2021) 124222, https://doi.org/10.1016/J.JCLEPRO.2020.124222.
[198] R. Cabeza, B. Steingrobe, W. Römer, N. Claassen, Effectiveness of recycled P products as P fertilizers, as evaluated in pot experiments, Nutr. Cycl. Agroecosyst. 91 (2011) 173–184, https://doi.org/10.1007/s10705-011-9454-0.
[199] S. Trotta, F. Adani, M. Fedele, M. Salvatori, Nitrogen and phosphorus recovery from cow digestate by struvite precipitation: Process optimization to maximize phosphorus recovery, Results in, Engineering 20 (2023) 101478, https://doi.org/10.1016/J.RINENG.2023.101478.
[200] R.D. Cusick, M.L. Ullery, B.A. Dempsey, B.E. Logan, Electrochemical struvite precipitation from digestate with a fluidized bed cathode microbial electrolysis cell, Water Res. 54 (2014) 297–306, https://doi.org/10.1016/J.WATRES.2014.01.051.
[201] M.A. Bustamante, J.A. Alburquerque, A.P. Restrepo, C. de la Fuente, C. Paredes, R. Moral, M.P. Bernal, Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture, Biomass Bioenergy 43 (2012) 26–35, https://doi.org/10.1016/J.BIOMBIOE.2012.04.010.
[202] G. Arab, V. Razaviarani, D. McCartney, Effects of digestate co-composting on curing phase of composting, Bioresour Technol. Rep. 19 (2022) 101121, https://doi.org/10.1016/J.BITEB.2022.101121.
[203] I.G. Ezemagu, M.I. Ejimofor, M.C. Menkiti, C. Diyoke, Biofertilizer production via composting of digestate obtained from anaerobic digestion of post biocoagulation sludge blended with saw dust: Physiochemical characterization and kinetic study, Environ. Challang. 5 (2021) 100288, https://doi.org/10.1016/J.ENVC.2021.100288.
[204] L. Bauer, K. Ranglová, J. Masojídek, B. Drosg, K. Meixner, Digestate as sustainable nutrient source for microalgae—challenges and prospects, Appl. Sci. 11 (2021) 1056, https://doi.org/10.3390/APP11031056.
[205] M. Altun, Polyhydroxyalkanoate production using waste vegetable oil and filtered digestate liquor of chicken manure, Prep. Biochem. Biotechnol 49 (2019) 493–500, https://doi.org/10.1080/10826068.2019.1587626.
[206] L. Mejias, M. Estrada, R. Barrena, T. Gea, A novel two-stage aeration strategy for Bacillus thuringiensis biopesticide production from biowaste digestate through solid-state fermentation, Biochem Eng. J. 161 (2020) 107644, https://doi.org/10.1016/J.BEJ.2020.107644.
[207] L. Mejias, A. Cerda, R. Barrena, T. Gea, A. Sánchez, Microbial Strategies for Cellulase and Xylanase Production through Solid-State Fermentation of Digestate from Biowaste, Sustainability 10 (2018) 2433, https://doi.org/10.3390/SU10072433.
[208] V. Dolganyuk, D. Belova, O. Babich, A. Prosekov, S. Ivanova, D. Katserov, N. Patyukov, S. Sukhikh, Microalgae: A promising source of valuable bioproducts, Biomolecules 10 (2020) 1153, https://doi.org/10.3390/BIOM10081153.
[209] C.C. Chong, Y.W. Cheng, S. Ishak, M.K. Lam, J.W. Lim, I.S. Tan, P.L. Show, K. T. Lee, Anaerobic digestate as a low-cost nutrient source for sustainable microalgae cultivation: A way forward through waste valorization approach, Sci. Total Environ. 803 (2022) 150070, https://doi.org/10.1016/J.SCITOTENV.2021.150070.
[210] E. Sobolewska, S. Borowski, P. Nowicka-Krawczyk, Effect of solar and artificial lighting on microalgae cultivation and treatment of liquid digestate, J. Environ. Manage 344 (2023) 118445, https://doi.org/10.1016/J.JENVMAN.2023.118445.
[211] T.J. Barzee, C. Yothers, A. Edalati, K. Rude, A. Chio, H.M. El Mashad, A. Franz, R. Zhang, Pilot microalgae cultivation using food waste digestate with minimal resource inputs, Bioresour Technol. Rep. 19 (2022) 101200, https://doi.org/10.1016/J.BITEB.2022.101200.
[212] J. Al-Mallahi, K. Ishii, M. Sato, S. Ochiai, Static supply of different simulated flue gases for native microalgae cultivation in diluted cow manure digestate, J. Environ. Manage 335 (2023) 117557, https://doi.org/10.1016/J.JENVMAN.2023.117557.
[213] T. Bongiorno, L. Foglio, L. Proietti, M. Vasconi, A. Lopez, A. Pizzera, D. Carminati, A. Tava, A.J. Vizcaíno, F.J. Alarcón, E. Ficara, K. Parati, Microalgae from Biorefinery as Potential Protein Source for Siberian Sturgeon (A. baerii) Aquafeed, Sustainability 12 (2020) 8779, https://doi.org/10.3390/SU12218779.
[214] R. Lu, H. Yan, Y. Liu, Y. Wang, X. Cui, X. Wu, Z. Yu, R. Ruan, Q. Zhang, Enhancement of nutrients recovery and cell metabolism in piggery anaerobic digestate by the co-cultivation of indigenous microalgae and bacteria, J. Clean. Prod. 375 (2022) 134193, https://doi.org/10.1016/J.JCLEPRO.2022.134193.
[215] M.L. Thi Nguyen, C.Y. Lin, C.H. Lay, Microalgae cultivation using biogas and digestate carbon sources, Biomass Bioenergy 122 (2019) 426–432, https://doi.org/10.1016/J.BIOMBIOE.2019.01.050.
[216] Y. Collos, P.J. Harrison, Acclimation and toxicity of high ammonium concentrations to unicellular algae, Mar. Pollut. Bull. 80 (2014) 8–23, https://doi.org/10.1016/J.MARPOLBUL.2014.01.006.
[217] F. Marazzi, C. Sambusiti, F. Monlau, S.E. Cecere, D. Scaglione, A. Barakat, V. Mezzanotte, E. Ficara, A novel option for reducing the optical density of liquid digestate to achieve a more productive microalgal culturing, Algal. Res. 24 (2017) 19–28, https://doi.org/10.1016/J.ALGAL.2017.03.014.
[218] M. Zielińska, P. Rusanowska, M. Zieliński, M. Dudek, J. Kazimierowicz, P. Quattrocelli, M. Dębowski, Liquid fraction of digestate pretreated with membrane filtration for cultivation of Chlorella vulgaris, Waste Manag. 146 (2022) 1–10, https://doi.org/10.1016/J.WASMAN.2022.04.043.
[219] C.C. Chong, Y.W. Cheng, S. Ishak, M.K. Lam, J.W. Lim, I.S. Tan, P.L. Show, K. T. Lee, Anaerobic digestate as a low-cost nutrient source for sustainable microalgae cultivation: A way forward through waste valorization approach, Sci.

Total. Environ. 803 (2022) 150070, https://doi.org/10.1016/J.SCITOTENV.2021.150070.
[220] P. Praveen, Y. Guo, H. Kang, C. Lefebvre, K.C. Loh, Enhancing microalgae cultivation in anaerobic digestate through nitrification, Chem. Eng. J. 354 (2018) 905–912, https://doi.org/10.1016/J.CEJ.2018.08.099.
[221] X. Chen, Z. Li, N. He, Y. Zheng, H. Li, H. Wang, Y. Wang, Y. Lu, Q. Li, Y. Peng, Nitrogen and phosphorus removal from anaerobically digested wastewater by microalgae cultured in a novel membrane photobioreactor, Biotechnol. Biofuels 11 (2018), https://doi.org/10.1186/s13068-018-1190-0.
[222] V. Proskynitopoulou, A. Vourros, I. Garagounis, P. Dimopoulos Toursidis, S. Lorentzou, A. Zouboulis, K. Panopoulos, Enhancing nutrient and water recovery from liquid digestate: A comparative study of selective electrodialysis and conventional treatment methods, J. Environ. Chem. Eng. 12 (2024) 112675, https://doi.org/10.1016/J.JECE.2024.112675.
[223] M. Alrbai, S. Al-Dahidi, B. Shboul, M. Abusorra, H. Hayajneh, Techno-economic feasibility study of ammonia recovery from sewage sludge digestate in wastewater treatment plants, Clean. Environ. Syst. 15 (2024) 100235, https://doi.org/10.1016/J.CESYS.2024.100235.
[224] A. Petrovič, M. Simonič, L. Čuček, 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 (2021) 112593, https://doi.org/10.1016/J.JENVMAN.2021.112593.
[225] B. Riaño, B. Molinuevo-Salces, M.B. Vanotti, M.C. García-González, Ammonia recovery from digestate using gas-permeable membranes: A pilot-scale study, Environments 8 (2021) 133, https://doi.org/10.3390/ENVIRONMENTS8120133.
[226] N. Değermenci, E. Yildiz, Ammonia stripping using a continuous flow jet loop reactor: mass transfer of ammonia and effect on stripping performance of influent ammonia concentration, hydraulic retention time, temperature, and air flow rate, Environ. Sci. Pollut. Res. 28 (2021) 31462–31469, https://doi.org/10.1007/S11356-021-13005-6.
[227] A. Bonmatí, X. Flotats, Air stripping of ammonia from pig slurry: characterisation and feasibility as a pre- or post-treatment to mesophilic anaerobic digestion, Waste Manag. 23 (2003) 261–272, https://doi.org/10.1016/S0956-053X(02)00144-7.
[228] G. Provolo, F. Perazzolo, G. Mattachini, A. Finzi, E. Naldi, E. Riva, Nitrogen removal from digested slurries using a simplified ammonia stripping technique, Waste Manag. 69 (2017) 154–161, https://doi.org/10.1016/J.WASMAN.2017.07.047.
[229] D. Wang, Y. Xin, H. Shi, P. Ai, L. Yu, X. Li, S. Chen, Closing ammonia loop in efficient biogas production: Recycling ammonia pretreatment of wheat straw, Biosyst. Eng. 180 (2019) 182–190, https://doi.org/10.1016/J.BIOSYSTEMSENG.2019.02.010.
[230] J. Yan, L. Wu, W. Ye, J. Zhou, Q. Ji, M. Alberto Gomez, Y. Hong, J.G. Lin, H. Zhang, Ferric and sulfate coupled ammonium oxidation enhanced nitrogen removal in two-stage partial nitrification - Anammox/denitrification process for food waste liquid digestate treatment, Bioresour. Technol. 398 (2024) 130533, https://doi.org/10.1016/J.BIORTECH.2024.130533.
[231] A.T. Ukwuani, W. Tao, Developing a vacuum thermal stripping – acid absorption process for ammonia recovery from anaerobic digester effluent, Water Res. 106 (2016) 108–115, https://doi.org/10.1016/J.WATRES.2016.09.054.
[232] D.V. Arellano-Yasaca, C.Y. Chu, I. Ríos-García, W.N.L. Wan Jusoh, Process optimization for ammonium removal from municipal food waste treatment plant liquid digestate using natural rocks and volcanic ash, Biomass Bioenergy 193 (2025) 107581, https://doi.org/10.1016/J.BIOMBIOE.2024.107581.
[233] Biomethane - European Commission, (2022). https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biomethane_en (accessed June 22, 2024).
[234] J. Dahlin, C. Herbes, M. Nelles, Biogas digestate marketing: Qualitative insights into the supply side, Resour. Conserv. Recycl. 104 (2015) 152–161, https://doi.org/10.1016/J.RESCONREC.2015.08.013.
[235] Economic aspects of digestate processing and use - SAF Ukraine, (2020). https://saf.org.ua/en/news/1053/ (accessed September 27, 2025).
[236] M. Wendland, New fertilizer regulation in Bavaria—influence on agriculture and water management, From Milk Lakes to Butter Shortages. What ... (2018). https://raumberg-gumpenstein.at/jdownloads/Tagungen/Wintertagung/Wintertagung_2018/2w_2018_wendland.pdf (accessed June 13, 2024).
[237] K. Golkowska, I. Vázquez-Rowe, V. Lebuf, F. Accoe, D. Koster, Assessing the treatment costs and the fertilizing value of the output products in digestate treatment systems, Water Sci. Technol. 69 (2014) 656–662, https://doi.org/10.2166/WST.2013.742.
[238] C. Herbes, U. Roth, S. Wulf, J. Dahlin, Economic assessment of different biogas digestate processing technologies: A scenario-based analysis, J. Clean Prod. 255 (2020) 120282, https://doi.org/10.1016/J.JCLEPRO.2020.120282.
[239] J. Dahlin, C. Beuthner, V. Halbherr, P. Kurz, M. Nelles, C. Herbes, Sustainable compost and potting soil marketing: Private gardener preferences, J. Clean Prod. 208 (2019) 1603–1612, https://doi.org/10.1016/J.JCLEPRO.2018.10.068.
[240] J. Dahlin, M. Nelles, C. Herbes, Biogas digestate management: Evaluating the attitudes and perceptions of German gardeners towards digestate-based soil amendments, Resour. Conserv. Recycl. 118 (2017) 27–38, https://doi.org/10.1016/J.RESCONREC.2016.11.020.
[241] Nitrates - European Commission, (2024). https://environment.ec.europa.eu/topics/water/nitrates_en (accessed June 13, 2024).
[242] B. Stürmer, E. Pfundtner, F. Kirchmeyr, S. Uschnig, Legal requirements for digestate as fertilizer in Austria and the European Union compared to actual technical parameters, J. Environ. Manage 253 (2020) 109756, https://doi.org/10.1016/J.JENVMAN.2019.109756.
[243] National Organic Standards Board (NOSB) | Agricultural Marketing Service, (2012). https://www.ams.usda.gov/rules-regulations/organic/nosb (accessed June 13, 2024).
[244] Fermented organic liquid fertiliser recognised by Ministry of Agriculture and Farmer Welfare (MoAFW) - Industrial Outlook, (2021). https://industrialoutlook.in/biogas/press-release-2/ (accessed September 27, 2024).