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Current and prognostic overview on the strategic exploitation of anaerobic digestion and digestate: A review

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ABSTRACT

The depletion of fossil fuels and increasing demand for energy are encountered by generating renewable biogas. Anaerobic digestion (AD) produces not only biogas, also other value-added products from the digestate using various organic, municipal and industrial wastes which have several benefits like remediating waste, reduces greenhouse gas emissions, renewable energy generation and securing socio-economic status of bio-based industries. This review work critically analyzes the biorefinery approaches on AD process for the production of biogas and digestate, and their direct and indirect utilization. The left-out residue obtained from AD is called 'digestate' which enriched with organic matter, nitrogen, heavy metals and other valuable micronutrients. However, the direct disposal of digestate to the land as fertilizer/landfills creates various environmental issues. Keeping this view, the digestate should be upgraded or transformed into high valued products such as biofertilizer, pyrochar, biodiesel, syngas and soil conditioner that can aid to enrich the soil nutrients and ensures the safe environment as well. In this context, the present review focused to illustrate the current techniques and different strategic exploitations on AD proper management of digestate products for storage and further applications. Such a technology transfer provides a proven strategic mechanism towards the enhancement of the sustainability of bio-based industries, attaining the energy demand, safest waste management, protection of environment and reduces the socio-economic issues of the industrial sector.

1. Introduction

Currently, 80% of the energy demands are met by fossil fuels which could results in various environmental concerns like air pollution, greenhouse gas emission, climate change and other public health hazards (Hosseinzadeh-Bandbafha et al., 2018; Tabatabaei et al., 2020). Undeniably, the rapid development of population and simultaneous depletion of fossil fuels are the primary determinants that trigger to focus on the alternate renewable energy (Jayakumar et al., 2021, 2022). In response to address the aforementioned major challenges, the research communities still focus to develop a sustainable technology for more reliable, cost-effective, clean and renewable energy (Tabatabaei et al., 2019). In such a way, biogas and biofuel, which are exploited from the biomass, can be potential alternative renewable energy sources that could reduce the dependence of fossil fuels. Furthermore, these are comparatively better than the existing renewable energy sources such as hydro, wind and solar with respect to the exergy efficiency (Pazuch et al., 2017). However, among the other renewable energies from biomass, biogas offers a superior energy balance compared to biofuels and is expected to cover 25% of consumption in the future energy demand (Budzianowski, 2016). In addition, the biogas possesses high energy yield that can produced from various renewable feedstock's such as agricultural residues, municipal waste, food waste and industrial wastes (Shirzad et al., 2019).

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The competitive nature of biogas production via anaerobic digestion (AD) looks a promising strategy for sustainable development of bio-based industries (Atelge et al., 2020). Biogas produced from AD is composed with more than 50% methane which cannot be achieved by aerobic digestion. AD can protect human and animal health by minimizing the pathogens. AD process can also reduce odors from livestock manure. In general, AD treatment is widely applied for wastewater treatment due to this process can tolerate the higher organic loading (COD >4000 mg/L). Also, there are several advantages over aerobic digestion such as, faster mass flow rate, stable and accurate flow of CO_2 and CH_4. It provides energy to the local grid to meet the rapid growing energy demand with locally sourced renewable energy. The common processes involved in the AD cycle and digestate utilization are depicted in Fig. 1. Accordingly, the organic materials are digested through various biochemical reactions by the consortia of different bacteria and each stage are sequentially ordered process as hydrolysis, acidogenesis, acetogenesis and methanogenesis, as illustrated in Fig. 2. Acidogenesis process converts soluble monomers into organic compound acids [formic, propionic, lactic, succinic, butyric acids (reactions 1), ketones (acetone and glycerol), and alcohols (methanol and ethanol as give in reaction 2)].

$$C_6H_{12}O_6 \rightarrow 2CO_2 + 2CH_3CH_2OH \quad (1)$$

$$2H_2 + C_6H_{12}O_6 \rightarrow 2H_2O + 2CH_3CH_2COOH \quad (2)$$

During acidogenesis, acetogenic bacteria are the responsible for the products. The possible reactions are given in 3–6 which show acetogenesis representation.

$$2H_2O + CH_3CH_2OH \rightarrow 2H_2 + CH_3COO^- + H^+ \quad (3)$$

$$3H_2O + CH_3CH_2COO^- \rightarrow H^+ + CH_3COO^- + 3H_2 + HCO_3^- \quad (4)$$

$$4H_2 + 2HCO_3^- + H^+ \rightarrow 4H_2O + CH_3COO^- \quad (5)$$

$$2H_2O + C_6H_{12}O_6 \rightarrow 2CO_2 + 2CH_3COOH + 4H_2 \quad (6)$$

Eqs. (7)–(12) are the common reaction occur in methanogenesis with key product being methane.

$$CH_3COOH \rightarrow CO_2 + CH_4 \quad (7)$$

$$CH_3OH \rightarrow H_2O + CH_4 \quad (8)$$

$$4H_2 + CO_2 \rightarrow 2H_2O + CH_4 \quad (9)$$

$$NO^- + CH_3COO^- + H^+ + H_2O \rightarrow NH_4^+ + 2HCO_3 \quad (10)$$

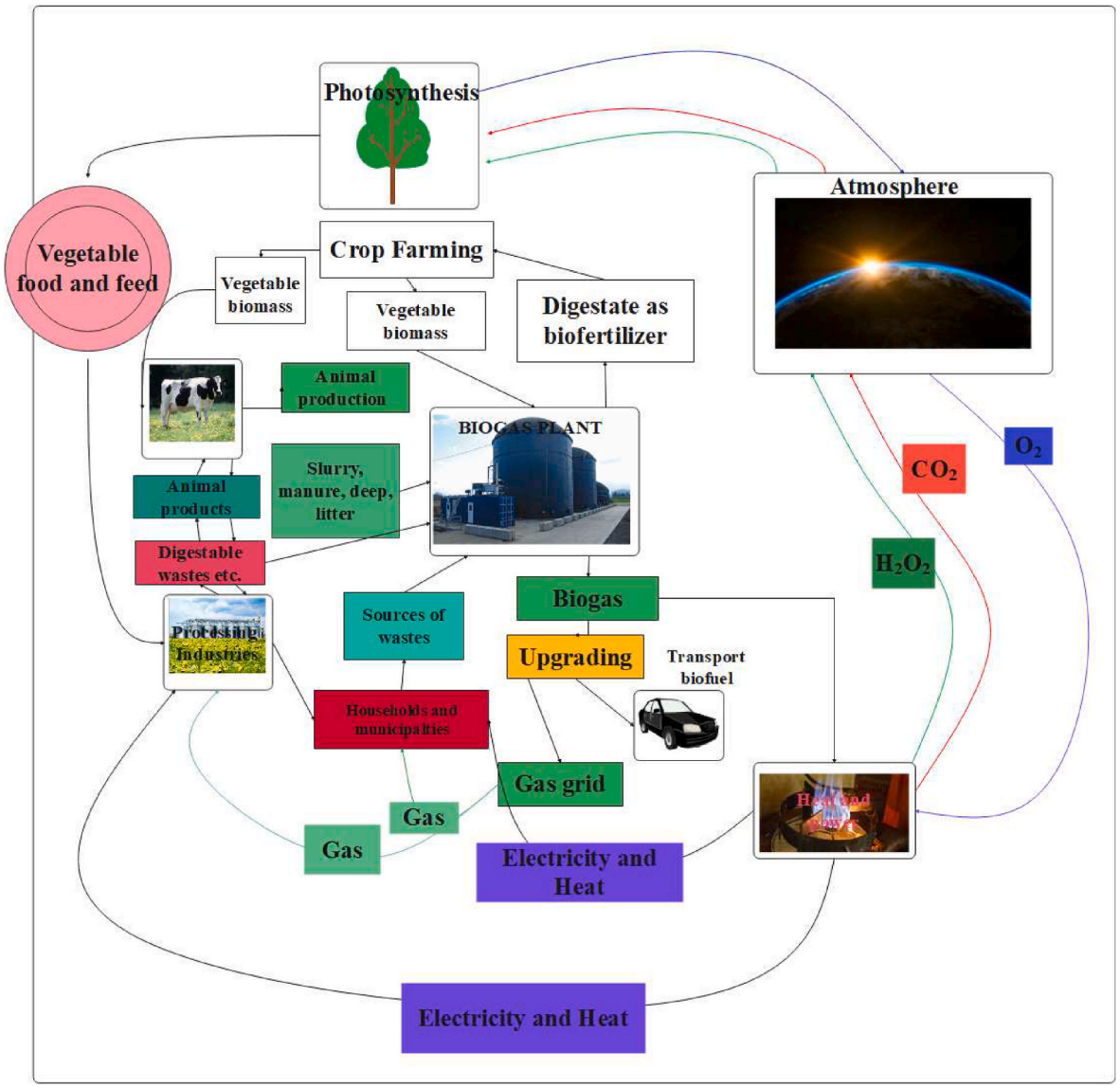


Fig. 1. A modern co-digestion biogas plant exemplifies how it fits into the circular economy.

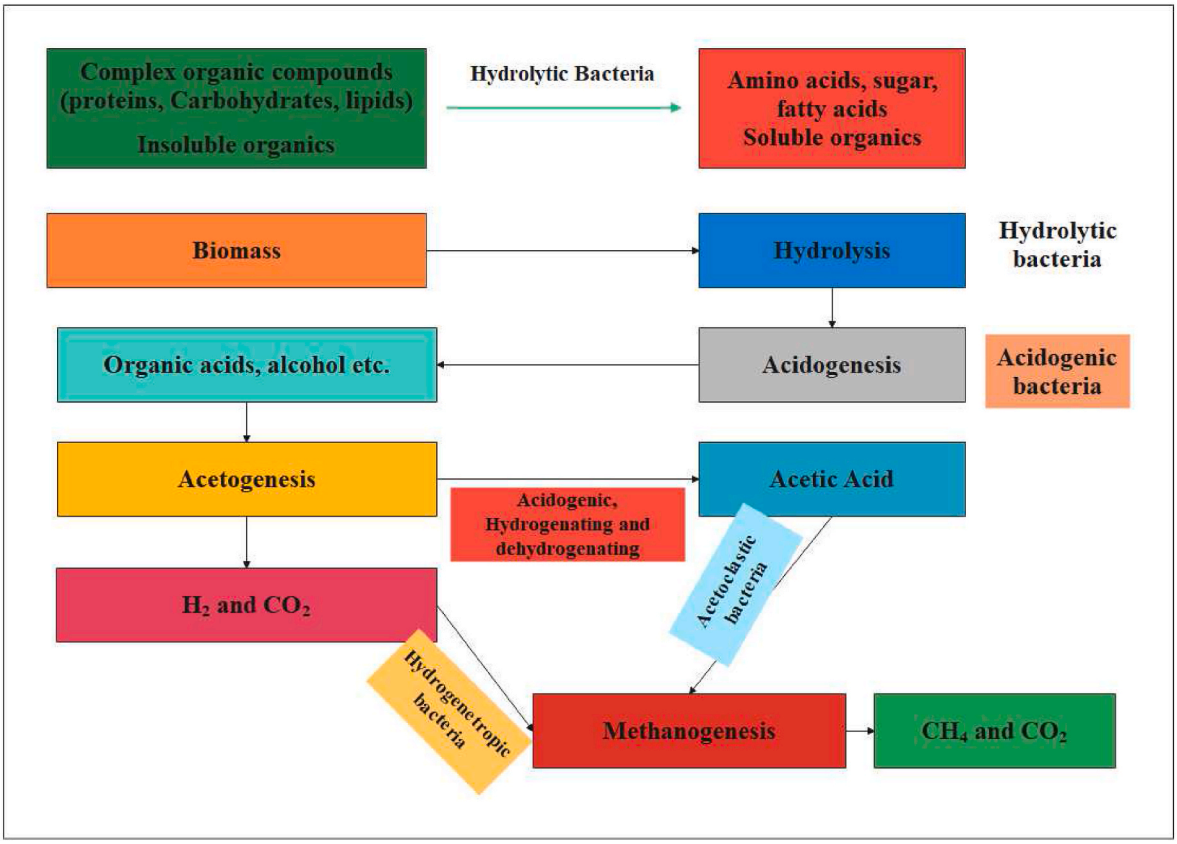


Fig. 2. Anaerobic digestion of complex macromolecules reaction sequence.

$$SO_4^{2-} + CH_3COO^- + H^+ \rightarrow H_2S + 2HCO_3 \quad (11)$$

$$CO_2 + 2CH_3CH_2OH \rightarrow CH_4 + 2CH_3COOH \quad (12)$$

In the first step of hydrolysis, the hydrolytic enzymes produced by certain bacteria decompose the complex organic substrates (proteins, carbohydrates and fats) into amino acids and monomers. The solubilized monomers released from the hydrolysis process are further degraded to short-chain fatty acids, alcohols, and ketones by the acidogenic bacteria in the process called acidogenesis. Followed by, in the third stage of acetogenesis, the products produced in the preceding phase are converted into acetic acid, hydrogen, and carbon dioxide. In the final stage of biogas production, the process called methanogens; methane and CO_2 are produced under the strict anaerobic conditions. In this step, approximately, 70% of methane outcome is originated by the anaerobic digestion of acetate; whereas the remaining is obtained from the conversion of hydrogen and CO_2 (Passos et al., 2017). As a result of biological processes occurred in AD, the complex organic waste substrates are transformed into renewable gaseous and liquid components (Nagarajan et al., 2019). Commonly, these components of gaseous molecules are flammable, colloquially, known as biogas which predominately comprises 50–60% methane, 25–40% carbon dioxide and other trace gases (Atelge et al., 2018). The previous studies report that the biogas obtained agriculture wastes has been characterized as higher composition of CH_4 (49–69%) and CO_2 (30–40%) as major contents and hydrogen sulphide (0.7–13%) as a minor content; whereas the biogas acquired from the landfill wastes composed with 45–55% CH_4 and 30–40% CO_2 which are comparatively lower than the biogas from agriculture wastes. On the other hand, the trace elements of the biogas from landfill wastes, H_2 and N_2 have been found to be 0–5% and 5–15%, respectively, which are comparatively higher than the biogas obtained from the agriculture wastes (0.2–3% and 0–1%), respectively. Notably, the biogas produced from one of the waste sources, sewage sludge, has not shown any significant contents of H_2, N_2 and O_2. Even so, it comprised with 55–65% CH_4 and 35–45% CO_2. It is well-proven that the AD is one of the most persuasive biological processes for converting the biomass feedstock's into biogas and CO_2, simultaneously, AD generates the high-valued digestate as a residue by-product (Ghosh et al., 2020). So far, different options exist to create value-added product such as, biocontrol products, soil amendments, mineral fertilizers, bio-stimulants, organo-mineral fertilizers from the AD digestate. Recently, a global milestone has been achieved as the European Union has acquainted with a new fertilizer regulation (CE, 2019/1009) that can lead to commercialization of digestate-based products from AD in the global market. Keeping the view on significance of AD, the present study addresses the direct and indirect utilization of biogas, CO_2 and AD digestate. Apart from the gaseous products, the left unattended portion of AD, that is digestate, are less economically important due to the presence of copious amount of impurities. A complex system of anaerobic digestion provides various environmental benefits. The present review emphasis to address recent techniques for proper management and treatment of AD digestate to enrich the nutrients content and to find its appropriate applications towards biofuel, biochar, syngas and bio-fertilizers and subsequent storage and handling of the products.

2. Anaerobic digestion and utilization

Beyond the waste management process of land filling and incineration, AD could be a sustainable technology for the conversion of waste sources to energy (Bhatt and Tao, 2020). In such a way, biogas is a renewable and eco-friendly fuel produced by the AD of organic substrates tends to reduce greenhouse gas emissions, eventually, mitigate the climate change (Kapoor et al., 2020a). Table 1 provides the typical components and composition of biogas produced from various

Table 1
Component and composition of biogas produced from various substrates.

Component/Composition	Methane (CH_4) %	Carbon dioxide (CO_2) %	Hydrogen sulphide (H_2S) %	Hydrogen (H_2) %	Nitrogen (N_2) %	Oxygen (O_2) %	Reference
Typical Composition	50–80	30–50	0–1	0–1	0–10	0–2	Chozhavendhan et al. (2020a)
Agricultural Waste	49–69	30–40	0.7–13	0.2–3	0–1	0–1	Calbry-Muzyka et al. (2022)
Landfill	45–55	30–40	0–0.10	0–5	5–15	0–1	Rasi et al. (2007)
Sewage waste	55–65	35–45	0	–	<1%	–	Calbry-Muzyka et al. (2022)
Sour cabbage	–	–	–	0–20	–	2–8	Sołowski (2022)
Sheep and cow dung	65.34	22.81	–	7.49	3.39	0.95	Adamu (2015)
Cow dung	92	6.68	–	–	–	–	Diagi et al. (2019)
Poultry	90	6.56	–	–	–	–	Diagi et al. (2019)
Cow dung	54.50	44.25	–	–	–	–	Obileke et al. (2020)
Floral waste	57	–	–	–	–	–	Kulkarni and Ghanegaonkar (2019)
Cow manure	54.7	–	–	–	–	–	
Untreated wheat straw on 13th day of HRT	48.90	19.50	–	–	–	–	Chandra et al. (2012)
Pretreated wheat straw (4%NaOH) on 10th day of HRT	61.20	19.00	–	–	–	–	Chandra et al. (2012)
Primary sludge and biological sludge.	47%	48%		0.0055%			Kushkevych et al. (2018)
Textile industries wastes	52–56%	42–47%	–	0.251%	–	–	Kumar et al. (2020)
Whiskey distillers' byproducts	60–62%	31–33%	–	–	–	–	Jackson et al. (2020)
Microalgae	75%	21%	–	6.9	2.6	0.15	Yukesh Kannah et al. (2021)

substrates. In AD processes, the complex organic feedstocks are segregated by various types of anaerobic microorganisms. Many varieties of feedstocks such as agricultural (energy crops, harvest residues), industrial (sludge) and municipal waste are used as a substrate for the AD process. Each substrate has a different composition of carbohydrate and protein contents which result in the production of different qualities of biogas. The composition of biogas depends on several parameters such as volatile solids, particle size distribution, sludge retention time, up flow velocity, total solids, temperature, pH, hydraulic retention time and organic loading rate and so on. A documentation made by (Awad et al., 2014) provide the details of process parameters, characteristics, and inner components of anaerobic bioreactors. Recently, a study reported by (Ajayi-Banji and Rahman, 2022) showed the influence of the parameters for solid-state anaerobic digestion in terms of stability thresholds. A comprehensive review made by (Janesch et al., 2021) reveals the impotence of phase separation during AD processing. In yet another recent study, the challenges and optimization of the parametric operation have been discussed by (Uddin and Wright, 2022). (Kainthola et al., 2020) have investigated to optimize the process towards the acceleration of methane production during the co-digestion of food waste and rice straw. They reported that the significant interaction has been found at the optimum condition (pH 7.32, C/N 30, F/M 1.87) which showed an improved methane yield of 323.78 mL/g. The biogas produced by AD process primarily comprises with methane, carbon dioxide and traces of hydrogen sulfide, nitrogen and water vapor. The complex composition nature and the presence of traces amount of impurities lead to reduce the calorific value of the biogas and increase the corrosiveness, clogging mechanical wear and unwanted emission which hinder its successful utilization (Kapoor et al., 2019; Sahota et al., 2018). Hence, it becomes mandatory to give special concern for upgrading the quality of the biogas (improving the biomethane content >90%). This can be achieved by separating the CO_2 stream (80–90%) as a byproduct with the aim to widen the scope of biogas production processes (Kapoor et al., 2020a).

However, the raw biogas can be used directly as an alternative to natural gas from the digester for cooking and lightning of the site. The calorific value of the typical biogas (methane - 60% and CO_2 - 40%) provides 5.5 to 6.5 kWh/m^3 whereas the calorific value of the natural gas ranges from 5.8 to 7.8 kWh/m^3 (Yu et al., 2010). But in case of indirect utilization, it requires various approaches like water scrubbing, pressure swing adsorption, membrane separation and cryogenic separation to enhance the quality of biogas (Chozhavendhan et al., 2020b).

2.1. Biogas and AD digestate based biorefinery model

It is undeniable that the biomass is considered as a neutral, renewable and sustainable carbon source derived from the live or dead organism with high energy content (Fusi et al., 2016). Exploitation of biomass through AD is the most effective biological process in converting the diverse of substrates such as food waste, agricultural residues, municipal waste, and palm oil mill effluent with high carbon content into renewable bioenergy (biogas). Unfortunately, it is believed that the bio-based industries indulge the method of biorefinery to develop the business and economic efficiency on the sustainability in biomass over fossil fuels (Sauvée and Viaggi, 2016). Nevertheless, the production of biogas by AD provides a center piece of sustainability on performing the greater energy production (electricity or transportation fuel) with lesser waste generation (Chozhavendhan et al., 2020a). The unattended nutrient rich effluent named AD digestate in biogas plant can serve as feedstock for the production of high valued bio-chemicals (Hagman et al., 2018), biofuels and bio-fertilizers (Mirmohamadsadeghi et al., 2019). The incorporation of biorefinery in biogas plants can aid to attain numerous benefits like complete utilization of feedstock, zero-waste discharge, and avoids illegal dumping of waste, thereby, protects the environment with co-generation of high valued bio-based chemicals that promotes sustainable economic development. An integrated biorefinery aims at maximizing the utilization of biomass with low demand for a substrate quality and composition, infrastructure facility, and to convert them into sustainable high valued bio-based products through thermochemical, biochemical and chemical conversion technologies (Ferreira, 2017). Further, the generation waste from different biogas plants increases from year to year, as displayed in Fig. 3.

2.2. Direct utilization of biogas

Direct combustion of biogas is commonly employed which is an affordable route of utilization without the removal of impurities. It is simple, low cost and maintenance technology and does not require the

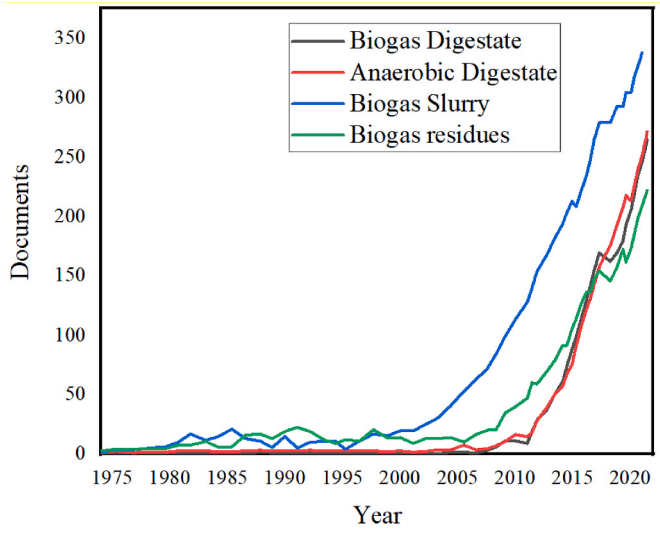


Fig. 3. Biogas digestate publications from various years.

removal of impurities. While burning with a blue flame that indicates as a clean energy which emits lesser pollutants (Kadam and Panwar, 2017). It was observed that the consumption time for cooking is less with biogas when compared to other conventional fuels, also, the conversion efficiency of biogas to heat in a gas stove can be achieved about 80–90% (Nevzorova and Kutcherov, 2019).

2.3. Indirect utilization of biogas

In recent times, biogas can replace the natural gas with proper advanced treatment technologies and potentially utilized in man synthetic applications. Accordingly, upgrading the biogas by separating CO_2 to obtain the purified biogas is known as biomethane. Such a biogas upgradation in the form of biomethane is well-identified by reaching the maximum market value. Literally, upgrading process improves the calorific value of raw biogas from 20 to 35.8 MJ/m^3 and quality of the biogas (Sahota et al., 2018). Many industries around the globe are already customized to the application of natural gas for various applications. Since the upgraded biomethane possess the properties of natural gas, it can be used as a substitute for heat energy in boilers and Combined Heat and Power plants (CHPs), fuel cells, transport fuel and so on (Browne et al., 2011). In addition, biomethane is effectively used as a transport fuel or blended with vehicular fuel in the transport sector. The utilization of biomethane as a transport fuel has attracted and received an overwhelming response in many countries around the globe. In recent times, the commercial use of biomethane gas in the form of bio-compressed natural gas is gaining a huge interest in many European nations. Approximately, 27.4 million of natural gas vehicles are conveniently operated in worldwide using the natural gas with dual fuel mode (Daniela Thrän et al., 2014; NGV Global, 2019). The upgraded biogas can be stored as compact biomethane or liquefied biomethane. The liquefied biomethane is observed to be more convenient when compared to compressed biomethane with respect to volume and energy density basis (Cucchiella et al., 2017; Sun et al., 2015). In recent times, there are some emerging upgradation techniques are followed to improve the biogas quality, such as, desulfurization, H_2S removal by organic solvent scrubbing, adsorption on a solid surface, chemoautotrophic upgrading, upgrading by photosynthetic, and biogas upgrading by microbial electrolysis cells.

Recently, the scope of utilization for biomethane is significantly increased by injecting it into the natural gas grid. The upgraded biogas exhibits an unlimited storage space when it introduced into the natural gas grid system which provides the more practical convenient for transportation, distribution and utilization in term of biomethane. The injected gas can be taken out at a place of the gas grid that can be used for potential utilization of renewable energy production. Such a system provides a diverse and flexible spectrum of applications, particularly, in the areas of power generation, heat provision and mobility that creates a broad base of potential consumers. During AD, organic wastes are subjected to break down to produces biogas. CH_4 and CO_2 are the key components of resulted biogas. However, unwanted impurities such as N_2, NH_3, O_2, H_2S and H_2 are found to present in the acquired biogas. In order to produce a much higher pure CH_4 there a need for feasible technologies to clean up the raw biogas. There are different common methods are used to clean up the raw biogas. Accordingly, water scrubbing, adsorption by pressure swing, chemical absorption, membrane permeation, and cryogenic process are the most important techniques. Such a need for purification is generally carried out for the high energy demand. However, the technique that to be selected for upgrading and cleaning on CH_4 is based on the requirements of CH_4 purity, especially, for large-scale processing. The key factor, biogas composition can be the controlled by the available resources. This fact can be used evaluated for achieving successful practice.

Another one of the prominent biofuels, the syngas, consists of hydrogen (25–30%), carbon monoxide (CO) (30–60%) and carbon dioxide (CO_2) (5–15%). It is produced by the gasification or pyrolysis of carbonaceous materials (Vieira da Rosa and Ordonez, 2022). The syngas is used for the industrial production of ethanol, methanol, several aldehydes and olefins. Apart from its heating value, biomethane can be utilized for producing high-value platform chemicals like hydrogen, methanol, chloroform, and ethylene. At present, the demand for chemicals produced from the carbon source is very low but expected to grow when received acceptability by the consumers from the developing nations.

2.4. Carbon dioxide (CO_2) generation and utilization

During the biogas production, CO_2 is generated as a co-product. Further, it is separated while upgrading the biogas that can be reused and liquefied. Normally, the concentration of CO_2 stream is improved up to 80–90% after the upgradation process from the initial concentration of 40–50%. It is well-known that such a pure CO_2 is non-hazardous and non-flammable which offers an interesting additional source of revenue to the bio-based industries (Kamyab et al., 2019). Besides, the carbon dioxide liberated with biogas digestate is prevalently utilized in the chemical process industries as a raw material for the production of chemicals, including urea, methanol, dimethyl ether (DME), and synthetic fuels. Under ambient physico-chemical conditions, carbon dioxide with slow chemical reactivity is activated with suitable catalysts for chemical transformations. Carbon dioxide can be upgraded into chemicals and fuels through the use of carboxylation and/or reduction reactions involving the addition of hydrogen or electrons (Kapoor et al., 2020b). Furthermore, the chemicals produced from carbon dioxide of biogas digestate can be used in a variety of industries, especially, in the production of algae (Kamyab et al., 2019), gas and chemical industries (Alper and Yuksel Orhan, 2017), and food processing factory (Huang et al., 2020). Carbon dioxide (CO_2) is widely employed in the chemical industry as a feedstock for the industrial production of urea, methanol and synthetic fuels.

Annually, the industrial utilization of CO_2 reaches 130 million tons for the production of high valued chemicals like urea, salicylic acid, carbonates and polycarbonates. CO_2 is one of the major reactants for the production of urea. Urea is produced by reacting CO_2 with ammonia at elevated temperature and pressure (190 °C and 2.027×10^7 Pa) is widely used as fertilizer, explosive, and chemical industries (Alper and Yuksel Orhan, 2017). Solid CO_2, colloquially, dry ice, is well-recognized as a common refrigerant for frozen food transportation. Similarly, high purity CO_2 is popularly used in all beverage industries for producing carbonated drinks. CO_2 is an important element to enhance growth and the productivity level of plant via, photosynthesis process (Lim et al.,

2016; Lokman et al., 2021). In an overview, integrated biorefinery model, the algae convert CO_2 into carbon-rich lipids, protein and carbohydrates which can be further fermented or anaerobically digested or pyrolyzed to produce ethanol, biogas or biochar, respectively (Thi Nguyen et al., 2019).

2.5. Utilization of anaerobic digestate

As discussed earlier, anaerobic digestion (AD) is the most powerful biological technique which converts biomass into biofuels. Herewith, the digestate comes out as a final output either in the form of solid or liquid digested effluent which consists of feedstock materials and other suspended materials. The composition of the digestate mainly depends on the quality of the feedstock and various processing stages. A copious amount of carbon source from the feedstock remains unutilized in the digestate which can also act as a promising sustainable substrate for the production of high-valued products (Dahlin et al., 2015; Wang et al., 2020). However, improper handling of digestate creates a serious environmental problem and legal issues while disposing without proper treatment. The digestate has the flexibility for producing diverse products economically when the oil prices are more volatile. Recently, various studies have been made on effective utilization of digestate to reach the refined shape of the biorefinery in the integrated biogas production plant. The biological feedstock are converted into biogas through the process of AD and the left-out carbon-rich digestate can be used as a substrate for the effective production of high-valued bio-based chemicals (Kim et al., 2016). There are various factors that significantly affect the effective utilization of digestate, hence, it should be properly characterized and treated before utilizing it as a substrate for the effective production of value-added products.

3. Characterization and importance of digestate processing

As stated earlier, the resulted digestate from biogas plants contains solid, liquid and gaseous phases. Studies elsewhere reveal that digestate also contains nutrient-rich undigested materials residue of the feedstock processed (Schneider and Gerber, 2020). The left-out residues are nutrient rich organic waste, usually called as digestate. The digestate is found to be rich in nutrients such as carbon, nitrogen and phosphorous and other micronutrients like Na, K, Ca, Mg, Fe, Al, and Si (Rahimi and Shafiei, 2019; Wang and Lee, 2021). Significantly, the carbon, nitrogen and phosphorous content in the distillate are observed to be 15–55%, 0–8% and 1–4%, respectively. Generally, the carbon content is found to be low in the feedstock's like animal manure, organic fraction of municipal solid waste and sewage sludge that are used (Li et al., 2020; Pecchi et al., 2020) except agricultural residues (lignocellulosic biomass) are for feedstock. Similarly, the nitrogen in the form of ammonia is present in the range of 1–3% from animal manure, food waste (Luo et al., 2020) except sewage sludge which consists of 7% (Nisticò et al., 2019). The fruits and vegetable wastes and sewage sludge comprises around 2.5% whereas the swine manure digestate contains 4.5% of phosphorus (Parmar and Ross, 2019).

The quality of digestate depends on the feedstock, microbial community and the operational condition of the AD process (Logan and Visvanathan, 2019). The soluble digestate requires further appropriate treatment before the disposal or the introduction of new technology for the effective utilization of organic waste for the production of value bio-based products from it (Peng et al., 2020). Digestate processing purely depends on the expiration use. The digestate is further processed to use either as biofertilizer or the removal of all nutrient content from the digestate that led to be used as usual effluent water treatment. The quality protocols are already accomplished with the clear standard point for the digestate usage which is acceptable for digestate management to protect human's health and environments. These constrains could provide the impurity free (plastic, glass, and stone) hygiene and pathogenic free digestate to avoid chemical (organic and inorganic) and biological pollution (spreading of communicable disease). For the comfortable storage and further applications, the digestate must comply with the volume reduction, separation of valuable nutrients using decanter, centrifugation and filtration. The digestion time and amount of the digestate depend on the soil properties and the crops utilized. The nutrients present in the digestate are concentrated for reducing transportation and storage cost. Eventually, some fraction of digestate with poor quality is unfit for any process, hence, it dumps for landfills if it is produced from municipal solid waste.

4. Digestate treatment technologies

The high volume with low nutrient content of resultant digestate from the AD makes too expensive for transportation and tough for the direct replacement to mineral fertilizers. The economy of the digestate depends on the costs for collection, transportation, storage of digestate and the end products. Eventually, the ultimate aim for involving treatment technologies is to improve the quality and marketability of the digestate and to ensure the secured disposal of effluent after recovering the nutrients. In recent times, various treatment technologies are outlined by different researchers such as physical, chemical and biological process to acquire the quality digestate. The treatment of digestate may also be carried out as solid/liquid fractionation or partial/complete refining of digestate (Dahlin et al., 2019). The different technologies employed for valorization of digestate are depicted in Table 2.

4.1. Physical methods

A variety of physical methods are employed for the solid-liquid separation of digestate like drying, screw press separators, stripping, vacuum evaporation, and decanter centrifuge. The physical method aims to separate the solids from the liquid phase.

4.1.1. Screw press

Separation using screw press is the common physical method that employed for separation of solids from the medium or large scale biogas plants which are operated with high fiber digestate (Guilayn et al., 2019). In general, screw presses are slowly rotating at 5 rpm. The horizontal axis is inclined to 20 °C to drain the water during the process for dewatering. Solids are separated into two phases as solid and liquid phases further comprising the dry matter of 20% and 3% in each phase, respectively (Fuchs and Drosg, 2013). Generally, the solid phase is known as press cake. The presence of solid content in this cake is inversely proportional to volatile solids of the feedstock. During the screw press operation, the average pressure ranging between 0.58 and 2.91Mpa is normally applied. However, several studies revealed that there is no significant effect on dewatering was found when the pressure applied above 1.74 Mpa in the digestate, hence, does not cause any notable decrease in the moisture level. Bauer et al. (2009) stated that the accumulation of solid separation and the separation efficiency always depends on the dry matter and fiber content present in the digestate. The merit of screw press separator involves low investment cost and energy consumption when compared to other methods. The mesh size of the screen plays a vital role in the degree of separation as small size particles (0.25–0.5 mm radius) remains in the liquid. The limitation of this process is that it cannot separate the small sludge fraction from digestate.

4.1.2. Drying

The drying process aims at improving the nutrient concentration and stabilizes the digestate that reduces the total mass. The moisture content is reduced for easy storage and transportation process. Solid digestate can be dried using commercially available technologies in the market like Belt dryer, drum dryer, fluidized bed dryer, apart from solar radiation (Awiszus et al., 2018). Utilizing the solar energy reduces the operational cost of drying and reduces the moisture content of the solid digestate. In few instances, high heat energy is required for drying

Table 2
Technologies utilized in digestate valorization.

Digestate origin	Technologies utilized	Operation	Nutrient Recovered	Nutrient recovered efficiency	Remarks	End product	Reference
Chicken slurry	Pyrolysis	–	Nitrogen	N_2- 93.9%	The precipitation of struvite is increased by 10% on pyrochar seeding	Biochar, Struvite precipitation	Wang and Lee (2021)
Synthetic digestate	Membrane separation	–	Ammonia	NH_3 – 94.3%	A PTFE- 0.22 membrane operated under optimal conditions supported ammonia recoveries of 71.6% and 84.6% after only 3.5 h using real and synthetic digestates, respectively.	Ammonia for fertilizer	Rivera et al. (2022)
Maize & grass silage, liquid cattle manure	HTC & acid leaching	Batch	Phosphorus	P - 90%	The HTC shows good sorption efficiency with better microporosity.	Soil conditioner	Zhao et al. (2018)
Swine manure	Hydrothermal conversion	–	Nitrogen	N_2 - 45%	Solubilization and sorption efficiency increased	Hydrochar and Soil conditioner	Zhang et al. (2020)
Pig manure	Membrane separation	Fed batch	Nitrogen, Phosphorus	N_2 - 92.7%, P - 100%	Increased algal growth for biodiesel production	Biodiesel production	Ji et al. (2015)
Livestock waste	Ultraviolet, Filtration	Batch	Nitrogen, Phosphorus, Carbon dioxide	N_2 - 76.0%, P - 63.2%, CO_2 - 62%	Purification and up gradation of biogas	Biogas	Zhao et al. (2015)
Swine manure	Autoclave Mixed with municipal wastewater	Batch	Nitrogen, Phosphorus	P - 95%, N_2 - 95%	Increased algal growth	Bioremediation	Dickinson et al. (2015)
Food waste	Stripping	Continuous	Nitrogen	N_2 - 20%	34% methane yield increased	Biogas	Bi et al. (2020)
Food waste	Membrane separation	Fed batch	Nitrogen	–	Enriched biogas production	Biogas	Shi et al. (2019)
Cattle manure	Bipolar bioelectrodialysis	Batch	Nitrogen	N_2 - 90%	Enriched bioenergy production	Bioenergy	Zhang and Angelidaki (2015)
Municipal wastewater	Pyrochar adsorption	–	Phosphorus	P - 65%	Iron rich prepared at pyrochar is prepared at 300 °C with highest P intake	Pyrochar	Wang et al. (2020)
Piggery manure	Pyrochar adsorption	–	Nitrogen	N_2 - 45.2–66.64%	Sorption efficiency increased by 85.6%	Biochar	Ding et al. (2020)
Food waste	Hydrothermal conversion	–	–	Organic matter removal	Effectively removed organic pollutants	Biochar	Huang et al. (2020)
Sewage sludge	HTC & acid leaching	–	–	P- 25.3%	The energy recovery efficiency is increased due to reduced ash content in hydrochar process	Hydrochar	Marin-Batista et al. (2020)

digestate and the heat energy produced in the biogas plant are utilized for the drying. The exhaust digestate may contain dust, ammonia, heavy pollutants and other volatile components. The high concentration of ammonia reduces the market value of fertilizer and hence ammonia is to be scrubbed to be reduced in the scrubber unit to reduce its effect on the environment (Maurer and Müller, 2019). The dried digestate can be pelletized for better market towards waste-based digestate products (Dutta et al., 2021).

4.1.3. Stripping

Stripping is generally applied to the liquid phase after the digestate is separated. In this process, the more volatile compound is removed from the liquid by flowing against the gas at enhanced temperature and pH (Hidalgo et al., 2016; Tampio et al., 2016). The aim of the stripping process is to remove nitrogen rather than reducing the volume or concentrating the nutrient in the digestate. The removal of nitrogen from digestate in the form of ammonia is carried out by contacting either with air or water. The gaseous ammonia is then treated counter currently with sulphuric acid in the scrubbing unit to get an ammonium sulphate as commercial fertilizer (Ma et al., 2018). The process of stripping involves physio-chemical technology when compared to other methods as it removes 88% of ammonia. Bi et al. (2020) stated that in his studies on chicken manure the nitrogen content and volatile fatty acid was reduced 20% and 30% respectively with increased methane yield of about 34%. It does not require expensive chemicals for the production of pure nitrogen fertilizer, avoids environmental hazards and other expensive effluent treatment process (Sigurnjak et al., 2019). The major limitations in this process are high maintenance and more cleaning effort for clogging part in the packing column.

Other common physical methods are the process of membrane separation, decanter centrifuge and vacuum evaporation. The process of membrane separation is an alternative process of physical separation for the liquid digestate and depends on the pore size of the membrane. Based on the filter size and action the process is defined as reverse osmosis, microfiltration and nanofiltration and so on. The purified materials pass through the filters and the larger particles are remains retained by the filter. The advantage of the process of membrane separation aids to reduce the volume of the liquid phase, the transportation cost, does not require heat energy and chemicals. The limitations of these processes are fouling smell, clogging and need adequate cleaning process. Decanter centrifuge are the more frequently used technologies for separating small particles, colloids and phosphorous from the digestate. The fed digestate is fed at the center of the centrifuge and the particles are separated on the basis of the size, shape and density on applying centrifugal force. The particles are attached to the wall of the centrifuge are separated further. The clarified liquids are separated from digestate and leave the decanter. Vacuum evaporation is applied to the liquid phase of the digestate where it is heated under negative pressure. As like as stripping process, the process of evaporation is aimed at removing the nitrogen-rich concentrate form the digestate (Li et al., 2019). (Leverenz et al., 2021) have reported the continuous thermal stripping of ammonium from digestate which showed a potential result for the land fill application. During the process, green ammonium was produced effectively (Baldi et al., 2018). have examined using the alternative stripping reactor consists of a packed column followed by a vibrating mesh screen. During their study, liquid digestate derived from

AD of livestock manure showed comparatively high ammonia removal yields (77%) when it works in a continuous mode. Struvite crystallization and ammonia stripping is another route to recover the N_2 and P (Hidalgo et al., 2016). reported that the ammonia has been recovered effectively more than 80% using this technique. Also, the crystallization simultaneously removed P and N up to 90%. Yet another study was carried out by (Kang et al., 2017) to optimize packed tower aerators for anaerobic digestate stripping to recover CO_2. The diffused aerator removed 82.1% of dissolved CO_2 and 13.7% of inorganic carbon.

4.2. Chemical methods

4.2.1. Precipitation

In the solid-liquid separation process, precipitating agents are added to enhance the separation efficiency of suspended solids and phosphorous. This method is most suitable for the treatment of municipal and industrial wastewaters. In general, ferric chloride, lime, and ammonium sulphate are widely employed for the precipitation process. During precipitation, the presence of positive ions significantly aggregates with the negative ion particles which leads the digestate to form precipitation and thus aids for the further separation process. The combined effect of precipitation and sedimentation can ameliorate the efficiency of solid-phase separation above 90% for the solid-liquid separation (Meixner et al., 2015). Accordingly, struvite is the most common precipitated solid material which is used as a base stock for inorganic fertilizer production (Numviyimana et al., 2022).

4.2.2. Flocculation/coagulation and other methods

Flocculation/coagulation is another chemical method utilized to treat the digestate generated from biogas plants. Flocculation is the process used in biogas plants to treat the digestate in which the colloidal substances are combined to form larger particles. Thus, larger particles formed by flocculation can be easily separated from the digestate. In this process, organic acids (acrylamide) are likely added to increase the progression of flocculation. However, the usage of flocculation is limited due to environmental impacts created by the polymer in the farmlands as it is not degraded easily. Stabilization is one of the other chemical methods, in which, acidification and alkaline are added to the digestate for improvisation of separation process. The supplementation of acid or alkali to the digestate can increase or decrease the pH shift, kills the pathogen and neutralize the offensive smell. Sulphuric acid/lime is added to digestate for the acid/alkali treatment (Lin et al., 2009). In this regards, coagulation-flocculation has been extensively used throughout biogas digestate treatment to minimize total suspended solids, color, and organic content such as dissolved organic matter and recalcitrant compounds in order to enhance treatment effectiveness and prevent fouling of biogas digestate plants after treatment. The potential benefits of using coagulation-flocculation are that it is a controllable, economically feasible, excellent color removal and simple physical-chemical treatment of stabilized and old landfill leachate of biogas digestate waste (Zahrim et al., 2019). The process of coagulation/flocculation can be affected by a lot of parameters, including the type and dosage of coagulant/flocculant, pH, mixing speed, time, temperature, and retention time. The formation of coagulant, destabilization of colloid/particle, and particle aggregation are the three types of successive stages in the coagulation process. The two preceding steps, coagulant formation and colloid/particle destabilization, are stimulated as a result of rapid mixing rate. Particle aggregation occurs throughout the flocculation process. At this point, the inter-particle collisions form large flocs particles that can be separated from the treated biogas digestate (Aziz and Ramli, 2014).

The research conducted by Ritigala et al. (2021) revealed that magnetic seed (MS) flocculation/coagulation is an efficient pre-treatment method of high strength digestate of food waste an efficient high strength digestate of food waste. The coagulation process was enhanced by assessing the effectiveness of removing turbidity, total suspended solids (TSS), total chemical oxygen demand (tCOD), and total phosphorus (TP) phosphate utilizing highly stable Keggin Al_{30} nanocluster (PAC_{30}), magnetic seeds, and polyacrylamide. PAC_{30} exhibited improved removals of 98.93% turbidity, 98.04% TSS, 58.28% tCOD, 99.98% TP, and 99.50% dissolved phosphates at the optimum dosage of 4.82 g/L.

4.3. Biological methods

4.3.1. Composting

The separated solids from the solid-liquid phase of the digestate are subjected to the further process, is known as, composting, which is usually carried out with the supplementation of additional organic materials (woodchips and green waste). Normally, composting is carried out under aerobic conditions with the use of microorganisms through different methods, like static pile and windrow in vessel composting (Ayilara et al., 2020). Typically, improvisation of composting can be done through the appropriate implementation of pH, carbon, nitrogen, other nutrients concentration (magnesium, iron) as well as the presence of moisture in the solid fraction. Hence, the compost becomes an ideal biofertilizer which slowly releases to enrich the soil nutrients to improve the yield. The compost obtained by this process is proven to be a stable and possess good ratio of C: N (<10) with appreciable nutrient properties to stimulate the growth of crops. Another method of composting for effective utilization of digestate into value added products is vermicomposting where the earthworms process and enhance the quality of end product. Literature reveals that the earthworms can convert several kinds of organic substrates, including the organic wastes with toxic components into enriched vermicompost with reduced toxicity (Yuvaraj et al., 2021; Karmegam et al., 2021; Jayakumar et al., 2022). Rıdvan and his coauthors have studies on the vermicomposting of anaerobically digested sludge by earthworm *Eisenia foetida*. The found that good earthworm biomass can be attained in feed mixture of 20% sewage sludge +40% cow manure +40% hazelnut husk. During the vermicomposting period, heavy metals concentration (Zn, Cu, Cd, Pb, Ni and Cr) in all feed mixtures were decreased with the increasing vermicomposting time (Kızılkaya et al., 2021). An improved anaerobic digestion technique has been introduced. They found the acidification of substrates using biochar derived from vermicompost can be improved the compost quality (Wang et al., 2017). In study elsewhere, the feasibility of composting and anaerobic digestion in community scale level has been investigated by (Leow et al., 2020). In most recently, a comprehensive documentation for fate and bioavailability of heavy metals during anaerobic digestion and composting of animal manure has been reported by (Zheng et al., 2022) which provide a wide range information on the composting outdome from the AD. The digestate can be added with the earthworms, *Perionyx excavatus* and *Perionyx sansibaricus* to produce earthworm biomass which can be used as additive for animal feed (Logan and Visvanathan, 2019). The nutrients in the digestate ensure the suitable environment for the earthworm and other microbes (*Azotobacter chroococcum, Bacillus megaterium and Rhizobium legumin Sarum*) to grow and produce high quality biofertilizer with high phyto stimulant properties (Raja Sekar and Karmegam, 2010). There are some notable merits of the composting process which make this technique as a thriven process that improve marketability towards low-cost fertilizer, easy transportation, and stability. On other hand, large footprints with huge nitrogen emissions are considered as some of the demerits of composting. During the AD process, it is needed to deactivate viable pathogens, including virus, parasite, and the pathogens harboring antibiotic resistance genes. Such a deactivation of sludge-associated pathogens is a serious concern that should be made towards sludge pathogens control. Also, during the deactivation mechanisms, the key affecting factors, pathogen-associated model with design aspects processing are considered. In addition, the incorporation of proper the risk assessment should be proposed for evaluating the reliability of AD-based pathogen deactivation.

4.3.1.1. Biofertilizer. The biogas digestate can be used as a promising biofertilizer where the nutrients are readily assessable to roots of the crops by increasing the uptake. The use of such biofertilizers reduces the surface and underwater pollution and thus protecting the environment. The digestate has nutrient content like carbon, nitrogen, phosphorous, potassium and other micronutrients. The raw digestate can be applied to the seasonal crops with a certain condition like rainy season, high humidity. Since the dry and hot sunny reduces the nutrient level of nitrogen considerably. The direct application of digestate reduces 70% of the nitrogen content due to ammonia oxidation and however high ammonium nitrogen are phytotoxic to plant growth (Manu et al., 2021). The stored digestate has to be properly sheltered and protected away from wind and proper stirring has to be carried out before application. The advanced treatment technology improves the quality of digestate with increased content of nutrients as bio-fertilizers. The application of high dose of digestate decreases the pH value of soil to 4.5. At low pH (>5) the availability less than macronutrients (N, P, K, Ca, Mg) and micronutrients (Mo, B) are reduced and however trace element (Fe, Mn, Zn, Cu) intake is increased (Głowacka et al., 2020). The mass reduction of digestate increases the nutrient content with an increased C/N ratio (<10 and usually < 8) (Guilayn et al., 2019). Decreasing pH value of the digestate by the process of acidification may lead to the limiting volatility of ammonia. Several studies revealed that the addition of digestate directly or as co-combusted product for increasing the quality and yield of the crops (Dietrich et al., 2020; Ronga et al., 2020). Nesse et al. (2019) experimented in tomato and lettuce using digestate as growth media and produced a significant biomass growth when compared to synthetic fertilizers. However, the issues for accumulated heavy metal should be considered in applications as fertilizer. Struvite is an alternate promising fertilizer containing better agronomic value when compared to other phosphorous containing fertilizers (Zhang et al., 2020). Struvite is a potential orthophosphate biofertilizer produced when NH^{4+}, PO_4^{3-} and Mg^{2+} are available in equal molar concentration in digestate (Knoop et al., 2018).

4.3.2. Algae growth

Growing of algae in the biogas plants led to the introduction of the integrated the approach of biorefinery via direct utilization, transesterification, biochemical and thermochemical conversion (Thanigaivel et al., 2022). Microalgae refineries can produce sustainable biofuels (bioethanol, biodiesel) and high-value products (lipids, pigment, protein) under the perception of waste to wealth (Chew et al., 2017). Microalgae can effectively utilize the CO_2 released from the biogas unit and the carbon source from the liquid phase of the digestate to produce many commercial products (Bavarella et al., 2020). The utilization of bio-CO_2 produced during the production of biogas for microalgal cultivation would ultimately reduce the carbon footprint in the anaerobic digester (Bacenetti and Fiala, 2015). Thi Nguyen et al. (2019) investigated the microbial biomass growth and CO_2 reduction efficiency on utilizing digestate by *Chlorella* and *Scenedesmus* species and observed that *Scenedesmus* species are more efficient biomass accumulation and higher CO_2 reduction when compared to *Chlorella*. Ji et al. (2015) stated that *Desmodesmus* species could effectively remove 268.238 and 6.427 mg/L of ammonium nitrogen and phosphorous from anaerobic digested waste water and similarly shows highest lipid production of 261.8 mg/L. The algae can easily blend with animal feed and thus provide more nutrition when compared to grains. Another added advantage is that microalgae utilize nutrients like nitrogen, phosphorous apart from carbon and other nutrients in the digestate which instantaneously reduces the cultivation cost and environmental impacts. Nuchdang et al. (2018) stated that the algal growth increases 4 folds of biodigestability of digestate when compared to untreated digest. The microalgal cultivation in digestate will help to avoid the effluent treatment process, avoid legal sanctioning of effluent disposal and suggests eco-friendliness process to provide additional income to bio-based industries (Chozhavendhan et al., 2022).

Over the decade, nutrition management and environment protection play a major role in digestate processing technologies. The nutrient content in the digestate can be concentrated or the volume is reduced by physical, chemical or biological process as discussed before. Sometimes the combination of the technologies achieves substantial reduction in volume, nutrient-rich product and may accelerate the cost of treatment processes. Advancement in the treatment process results in refined products from the digestate however it may require high chemicals and additional investment in energy input, operational and maintenance costs.

5. Merits and demerits of digestate treatment technologies

Anaerobic digestion is frequently used to convert and valorize organic waste, waste water, and other biomass sources as renewable energy and biofuel in the form of biomethane as presented in Table 3. The composition of the material left over after digestion, or digestate, is heavily influenced by the processed feedstocks. Because this by-product is often high in nutrients such as nitrogen and phosphorus, it has the potential to be reused in agricultural systems as fertilizer or nourishing broth (Magrí, 2018). The application of digestate to agricultural soils as a nutrient supply in accordance with local regulations is both financially and ecologically appealing due to the recommended replacement of mineral fertilizers. The use of digestate in semi-natural grass biomass production on low-fertility soils near biogas plants might be an alternate technique for diversifying the feedstock portfolio of biogas plants (Jurgutis et al., 2021). However, considerations such as transportation requirements, water content, and the presence of heavy metals, organic micro-pollutants, or pathogens may make this management technique ineffective. Additional digestate treatment, beyond soil application, may be required to increase the digestate's capacity to transport essential elements, protect human health, and avoid negative effects on recipient agricultural ecosystems, aquatic bodies, and the environment. Under the wrong conditions, storage, land application, or post-treatment can result in nutrient leaching and runoff, as well as gaseous nitrogen emissions as ammonia (NH3) and nitrous oxide (N2O) (Vázquez-Rowe et al., 2015).

6. Utilization of digestate for value added products

As discussed, the digestates are rich in nutrients and the undigested suspend particles exist in solid and liquid forms. The composition of digestate purely depends on the feedstock selected, microorganism involved and process adopted for the biogas production (Manasa et al., 2020; Wang and Lee, 2021). The availability of nutrients from the digestate is transformed into high-value products and to protect the environment (Elalami et al., 2020). Propionibacterium acnes, *Escherichia coli,* Mycobacterium bovis, Streptococcus salivarius, Collinsella aerofaciens are the prevalent microorganism present in the AD digestate are remove by harboring antibiotic resistance gene in digestate. The presence of pathogenic microorganism and their deactivation of pathogenic process are closely monitored for the use of digestate (Zhao and Liu, 2019). Including the aforementioned applications, the digestate is used to produce environmentally friendly renewable biopolymer. The biopolymers are widely used in water purification, food and pharmaceutical industries. The digestate can also employ as fish, animal and poultry feed. During the AD, methane-utilizing mixed cultures which having the capability for producing Polyhydroxybutyrate (PHB) have been explored by (Fergala et al., 2018). While operating with a fed-batch reactor, they found the mixed culture that can accumulate up to 51 ± 2% PHB within 70 days (Fergala et al., 2018). Most recently, bioplastics were collected during the bio-waste treatment, which is often composed of anaerobic digestion composting of the digestates (Bandini et al., 2022). have examined the degradability of polylactic acid obtained from the AD operation under industrial conditions. In study elsewhere, waste paper was used as resource for polyhydroxyalkanoate production through anaerobic digestion (Al Battashi et al., 2021). Such an economic

Table 3
Digestate treatment technologies with merits and demerits.

Technologies	Digestate Phase	Significance outcome or percentage of separation	Merits	Demerits	Reference
Screw press	Liquid phase	Solid fraction - 10% Liquid fraction - 90%	Good odor containment Low power consumption Low maintenance cost Easy start-up	Low cake formation Required further processing	Zhang et al. (2018)
Drying	Solid phase	Solid fraction - 98% Liquid fraction - 2%	Volume reduction Improves nutrient concentration Creates a marketable product	Heat cost Electricity cost	Pell Frischmann Consultants Ltd (2012)
Stripping	Liquid phase	25–35% ammonia recovery	Production of nitrogen fertilizers Avoids environmental hazard	Heat cost Cost for chemicals	Logan and Visvanathan (2019)
Membrane technology	Liquid phase	25-30 nutrient concentration	No chemicals used Volume reduction, no heat energy requirement Low solid waste generation	Fouling and offensive smell Clogging of materials Requires adequate cleaning	Fuchs and Drosg (2013)
Decanter centrifuge	Liquid phase	Solid fraction - 92% Liquid fraction - 8%	Low labors cost Compact size Process adaptability	Power requirement Noise and vibration Close specific gravity particles cannot be separated easily	Popovic et al. (2017)
Precipitation	Liquid phase	Combined with sedimentation 90% of solid-liquid separation was achieved	Creates pure homogeneous material Simple technology, low cost	Generates large volume of salt Ineffective in removing metal ions	Numviyimana et al. (2022)
Flocculation	Liquid phase	Removal efficiency of dry matter and organic matter was 32.00% and 39.39%.	Limited investment Simple process	High operational cost Non-reusable chemical	Chuda and Ziemiński (2021)
Composting	Solid phase	Provides stable nutrients to activate the plant growth	Low-cost fertilizers Improves the soil quality Maintains good C:N ratio	Huge emission of nitrogen	Logan and Visvanathan (2019)
Algal growth	Liquid phase	4-fold increased biodigestability of digestate	Production of high-value commodities Carbon dioxide reduction emission	Harvesting of algae is tough, slow growth	Nuchdang et al. (2018)
Biological demand	Liquid phase	Reduces Biological oxygen demand, ammonia concentration	The biological sludge is produced as a by-product that can be returned as a feedstock for AD digester.	High operating cost	Logan and Visvanathan (2019)

way to produce bioplastic can be a one of the significant constituents of municipal solid waste that can be utilized as a feedstock for poly-hydroxyalkanoate (PHA) production. There are multiple benefits in the utilization of digestate in both economic and environmental aspects like production of biofertilizer, production of renewable biofuels, utilization of organic waste sustainably, improvement in the local economy, reduced impact on environment on releasing reduced greenhouse gas emissions like CH_4, CO_2, NO_x (Seadi et al., 2018). For maintaining sustainability and to ensure long term sustainability, an integrated approach of biorefinery is introduced to the biogas plant. The integrated approaches have made biogas as self-sustained and it opened a potential nascent market for the utilization of digestate.

6.1. Biochar/hydrochar/Pyrochar

In particular, digestate is a by-product of biodegradable agricultural biogas waste that could be used straightforwardly as bio-fertilizer or, after separation of the solid and liquid-solid phases, thermochemically (pyrolysis like slow, fast, and flash pyrolysis; gasification; and hydrothermal carbonization) transmogrified to biochar/hydrochar/pyrochar (Radawiec et al., 2015). Like most other adsorbents, biochar (BC)/pyrochar (PC)/hydrochar (HC) is a highly flexible material that can be produced by carbonization of organic (carbonaceous) materials such as biomass and wastes in accordance with Circular Economic Principles (CEP) and “tailor-made” for specific applications (Chiappero et al., 2020). Biochar is manufactured from biodegradable waste that can be utilized as a carbon biosequestrant, a biofuel, and in agriculture as a soil improver that decomposes slowly and improves soil fertility, the number of biogenic components, and physical and water properties (Ravindran et al., 2022). The digestate produced by biogas anaerobic digestion and other biomass wastes are converted into biochar/hydrochar and other biofuels through the thermochemical conversion technologies, such as pyrolysis (slow, fast, and flash pyrolysis), gasification, and hydrothermal carbonization (HTC) (Hung et al., 2017).

Depending on the process conditions, such as temperature, heating rate, reaction time, and biomass utilized, the pyrolysis and gasification mechanisms are frequently employed to generate bio-oil and synthetic gas (syngas), respectively, as well as biochar. Biochar has extraordinary properties such as high porosity, high sorption capacity, potential bulking agent, improved aeration and can serve as a habitat for nitrifying bacteria that could breakdown organic matter with reduced emission of greenhouse gases (GHGs) and also improve the biodigestate/compost quality (Chew et al., 2017). In point of view for global warming (GW), AD of different bio-waste materials and further use of the digestate can effective reduce the greenhouse gas (GHG) emissions that are useful for calculation of global warming factors (GWFs), this can be determine the contribution to GW measured in CO_2-equivalents per tonne of wet waste.

On the other hand, hydrochar (HC) is the solid by-product generated from the hydrothermal carbonization (HTC) process (Codignole Luz et al., 2018). Hydrothermal carbonization (HTC) reaction occurs in an aqueous system, and feedstock moisture is not an issue, as it is in the pyrolysis and gasification of biochar production. The HTC temperatures range from 180 to 350 °C, which is lower than the temperatures employed in the previously stated thermochemical processes. Throughout the HTC, depending on the reaction conditions, small amount of gas and an effluent are produced. Hydrolysis, dehydration, decarboxylation, condensation-polymerization, and aromatization are all reaction entangled in HTC. Hydrochar seems to have advantageous features over biochar (BC), such as soil remediation, carbon capture and storage, and improved plant growth (Cavali et al., 2022).

The biogas and biogas digestates are generated from the wet organic waste through the anaerobic digestion (AD) and the byproducts or digestates from AD can be utilized to regulate the natural ecosystems, such as soil. This digestates can be used as a raw material for the production of biochar, hydrochar, or pyrochar, and the aforesaid products

can be employed for the application of adsorbing pollutants. The biochar and hydrochar obtained have the potential to improve the biogas products by utilizing the digestates. It has been revealed that introducing biochar or hydrochar to anaerobic digestion positively affects biochemical reactions and microbial growth by increasing buffer capacity and facilitating direct interspecies electron transfer (DIET), resulting in higher methane yields. Carbon dioxide (CO_2), hydrogen sulfide (H_2S), ammonia (NH_3), and siloxanes are all undesired compounds available in biogas products that can be adsorbed by hydrochar and biochar (Jin et al., 2018).

Various studies revealed that digestate derived biochar is produced below the temperature of 300–800 °C with 30–120 min residence time shows the characteristics of reduced specific surface area of the product (Opatokun et al., 2016; Tsai et al., 2018). Biochar gained its fame on removing heavy metals, high porosity, high sorption capacity, improving the soil quality and sequestering atmospheric carbon (Inyang et al., 2012). Biochar contains 40–60% of ashes and has wide application as a soil improver and adsorbent (Neumann et al., 2016). The adsorbent capacity of the biochar is dependent on porosity and surface chemical properties, which are influenced by feedstock quality and quantity, and pyrolysis conditions (Chojnacka et al., 2020). Hydrothermal conversion (HTC) processes produce hydrochar as slurry from solid digestates with a 27.6 MJ/kg heating value of volatile solid. The production of hydrochar slurry is similar to the pyrolysis process (Deng et al., 2020). The activated carbon produced from the HTC process combined with acid leaching shows a better porosity of 1762 m^2/g when compared with the non-leached one (Zhao et al., 2018). The HTC conversion (180 °C) of sewage sludge converts organic phosphorous into inorganic phosphorous and the total phosphorous in the hydrocars is leached as a low-grade phosphorous ore (Marin-Batista et al., 2020). Qin et al. (2017) investigated magnetic rice straw biochar for enhancing methane production from the municipal solid waste organic fraction. In this analysis, throughout the selective enrichment of microorganisms participating in an AD on magnetic rice straw biochar, methane production increased by 11.69% in AD treatment with magnetic biochar fabricated at 3.2 g $FeCl_3$:100 g rice-straw ratio compared to control treatment without biochar addition.

Besides, the high energy demand for drying the digestate is met out by heat and combined heat and powers (CHPs) from biogas processing plant. The pyro char is a stable organic compound produced from the different types of biogas digestate by the thermal process between 300 and 700 °C under low oxygen concentration. Sometimes, the gasification temperature was increased up to 850 °C (Chang et al., 2020). The conversion of digestate to pyro char/biochar aptly suits for soil conservation and amendment of the land. The application of digestate along with pyro char helps to retain the organic matter in the soil which was eroded by the process of erosion. The digestate can be applied as solid or liquid form along with pyro char which significantly increases growth performance of the plant (Greenberg et al., 2019; Peng et al., 2020). Hydro char/biochar production from waste biomass and its application in energy and environment is depicted in Fig. 4.

6.2. Biofuel

Integration of digestate for the biofuel production via fermentation process is very effective in utilizing the carbon and other nutrients present in it. The solid digestate obtained from the lignocellulose materials is found to be rich in fiber. It is commonly considered as low-valued product that can be used as animal feed. Recent studies stated that the fiber rich digestate can be used as a potential feedstock for the production of biofuel (MacLellan et al., 2013). Accordance with that report, 1.67 billion gallons of bioethanol are produced annually from 63 million tons of solid digestate. In some instances, bio-butanol can also produce due to its specific nature using various species of clostridium using glucose derived from digestate fiber (Bramono et al., 2011). Teater et al. (2011) accomplished the production of ethanol by anaerobic digestion of solid digestate feedstock in stirred tank reactor. Likewise, the nutrients available in the liquid phase of the digestate are used for cultivating the algae to recover the nutrient and to treat the effluents for production of biofuel (Van Den Hende et al., 2015).

The digestate is high in ammonia toxicity and turbidity and hence it is diluted in the ratio of 1:5 to 1:50 to avoid the substrate inhibition on microalgal growth (Koutra et al., 2017). The enzymatic digestibility of digestate enhances glucose yield and biofuel yield. Lipids from the algal biomass are converted into biodiesel via transesterification process and produce glycerol as a byproduct (Chozhavendhan et al., 2019). In addition, glycerol obtained as product that can be used as a co-substrate for the production of high platform chemicals (Sivasankaran et al.,

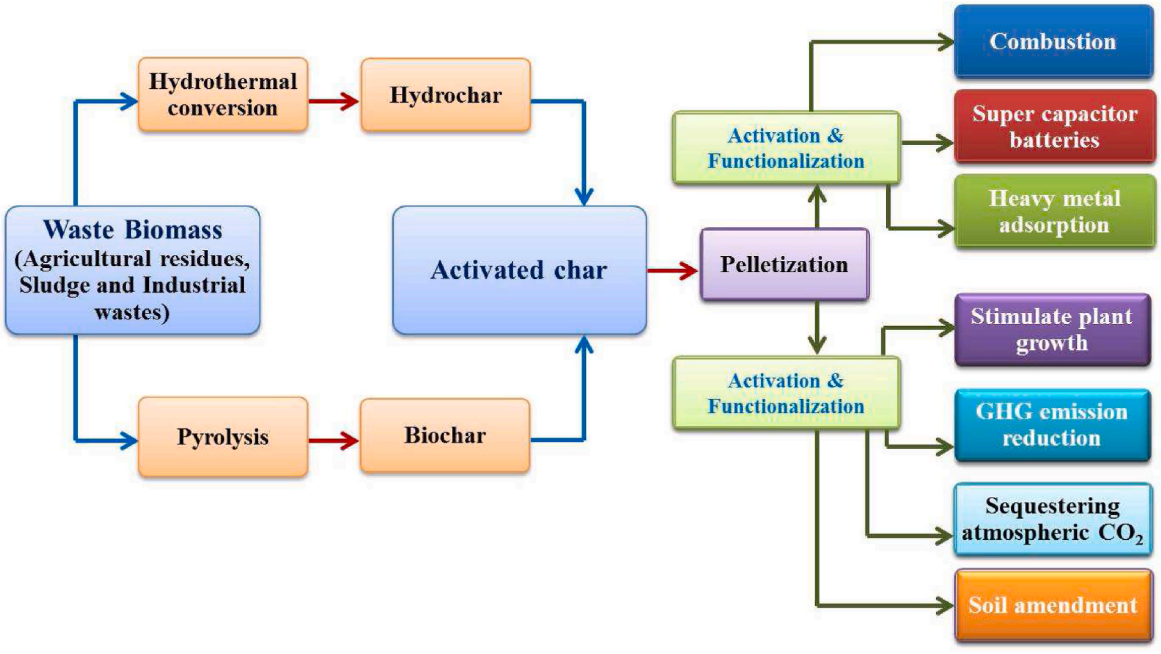


Fig. 4. Hydrochar/biochar production from waste biomass and its application in energy and environment.

2016). Axelsson et al. (2012) observed that the presence of heavy metals, competitive and pathogenic microorganism and volatile fatty acids also influences the utilization of digestate by microalgae. The quality of biofuel produced depends on the feedstock of the digestate, process and route of the production of biofuel. The production of ethanol forms the anaerobic digestion digestate is in early stage and still more studies is to be carried out for improving the production process and yield. Fig. 5 shows the prognostic assessment of anaerobic digestion and digestate for biofuel application.

Innovatively, the influence of Fe_3O_4 nanoparticles was investigated by (Boscaro et al., 2022) on the microbial development for anaerobic digestion. They have observed that the citrate-coated Fe_3O_4 nanoparticles of 20 nm have synthetized a considerable amount of biogas production in an economic way. A documentation by (Ferraz et al., 2022) have provided the recent advancements in AD of sugarcane vinasse towards struggle free production biogas as end-use product (Hassan et al., 2021). have examined on production of biofuels, CH_4 and H_2 via dual-stage AD of food leftovers. They identified that the microbe, *Bacillus amyloliquefaciens*, has been observed to be acted more predominant on the biofuel production. As a recent finding, the use of white-rot fungi was studied by (Zhang et al., 2022) for the H_2 production via anaerobic digestion of coal. The studty showed that the pretreated coal by white-rot fungi showed an improved production by 20.28 times. The diverse application of digestate led to zero wastage discharge from biogas plants and helps for the sustainable development of bio-based industries economically.

7. Biocircular economy of biogas and digestate

Digestate is a component of the biogas chain, which is an excellent example of a circular economy, which is a closed-cycle system in which all products are resources and none are trash as shown in Fig. 1. The digestate is a potential biofertilizer and a source of income for many biogas facilities across the world. The chemical composition and fertilizing capacity of digestates from eight agricultural biogas facilities were investigated. The findings of the digestate chemical analysis show that the digestate biomass included a high concentration of nitrogen (up to 73 g kg^{-1} fresh mass) and potassium (up to 25 g kg^{-1} fresh mass). The digestate was valued at 2.88–7.89 EUR mg^{-1} for liquid digestate and 7.62–13.61 EUR mg^{-1} for solid digestate based on commercial fertilizer market prices for nitrogen, potassium phosphorus, organic carbon, Cu, Zn, Fe, and Mg. In addition to energy sales revenue, the digestate produced by the 1 MW biogas plant is worth EUR 941–2095 per day (Jurgutis et al., 2021).

8. Current scenario, challenges and techno-economic assessment

Of course, there is a crucial need of technologies for waste to wealth using different integrated approaches to address the wastes from agricultural, industrial, and outcomes from municipal waste treatments and utilization. However, there are still implementation challenges such as lack of awareness and clarity among people persists towards the portability of biogas production and utilization. Still some managing issues need to focus for successful AD implementation. Based on microbiological and technological process, the major managing issues are removal of anaerobic nitrogen and treatment of chlorinated organics. In recent researches have shown some serendipities for sulphur and calcium removal by coupling of AD process with microbial fuel cells. Yet another crucial importance is CO_2-emission abatement with respect to the impetus of AD. Hence, there should be given a keen focus on the production of green energy and clean nutrients, thus, the future of AD will be assured. The biogases produced by the microbial process are utilized directly for the cooking and lighting process. Studies reveal that the NO_x emissions are observed as critical point with regard to environmental impact of biogas plants (Paolini et al., 2018). In general, NO_x emissions from the biogas was found to be higher than the natural gas engines. The averaged emission factor is 540 g NOx gJ^{-1}, which is more than three times of rate from natural gas engines. While comparing the emission factor to methane consumption, an emission factor of 0.63 and 11.6 g NOx/m^3 of CH4 were observed for flaring and combined heat and power applications, respectively. The importance of controlling this pollutant was demonstrated by (Cornejo and Wilkie, 2010). The effective usage of biogas has various bottlenecks and comprehensive technology development is required in the field (Ullah Khan et al., 2017). Beyond the conventional usage, biogas from the AD can be used to produce many biological products from the byproduct digestate. However, the valorization of digestate may influenced by the collection, conversion, transportation and storage. The direct disposal and utilization of digestate are simple, inexpensive, but, creates environmental

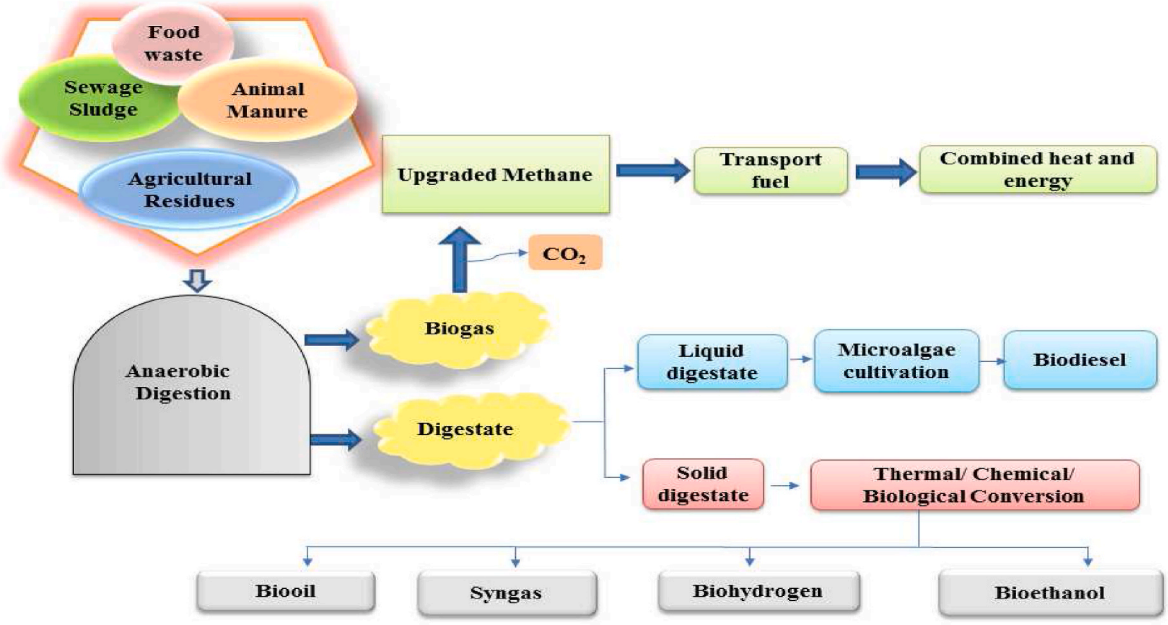


Fig. 5. Prognostic assessment of anaerobic digestion and digestate for biofuel production.

impacts. In this view, the presence of competitive pathogenic microorganism, unutilized carbon, nitrogen, heavy metals and other microelements significantly influence the direct utilization of the digestate (Kumar et al., 2022). There are some indicators that can be generally used to ascertain the sustainability of the AD process. They are material in and output, emission output, circular economy (CE) for water, CE for biogas, CO_2 emissions, and CE efficiency for energy use of biogas. The use of anaerobic digestion for biogas production needs sophisticated systems. In order to maintain the appropriate process and optimization of anaerobic digester, the standards and permit information provided by environmental protection agency (EPA), USA can be followed which has adequate details for Anaerobic digestion guidelines, Interconnection guidelines, co-digestion guidelines, and permitting license guidelines. However, Anaerobic digesters may be subject to local government permit requirements with respect to a range of municipal issues, such as zoning, construction and storm water management.

On other hand, in order to ensure the sustainability of the biogas plant, the nutrient rich organic matter present in the digestate should be properly recovered and recycled (Barampouti et al., 2020; Verdi et al., 2019). The biogas produced is composed with CH_4 and CO_2, hydrogen sulfide, ammonia, and other gases. For ensuring the AD operations and its biosafety, these gases should be handled with safety issues. In overall, biogas risks include disease, asphyxiation, explosion, and poisoning of hydrogen sulfide. In such a way, a significant caution is required while working with biogas. Hence, proper ventilation, more precautions, adequate work places, sophisticated control, personal protective equipment can minimize the risk associated with biogas and AD processing. In addition, systems should be perfectly designed to confine the space entry to perform better maintenance.

Hence, the digestate should be processed for various treatment technologies to produce promising renewable products, such as biofuels, biofertilizer and other value-added products. The integrated approach of biorefinery helps to ameliorate the market value of bio-products in a more competitive way with their economic sustainability. The attempts are made by the government to educate and empower the farmers, industrialists and other stakeholders about the AD process and its direct and indirect utilization (Kapoor et al., 2020a). The technological revolution has been made to set stout economic development along with employment generation (Maina et al., 2017). However, the new policies advertising the technological implementation can ensure the sustainable development of biogas plant and other bio-based industries. The British Standards Institution (BSI), UK, has framed the Publicly Available Specification (PAS) for the end-use of anaerobic digestate. According to BSI, PAS 100 should be followed for the compost pollicization. For the biofertilizer application, the regulation PAS 110 should be covered. Accordingly, these regulations are applicable to input materials, source of biowaste, and digestate quality. However, output and processes are need to get certification by independently audited schemes with respect to the country.

9. Conclusions

The production of biogas via AD using the different bio-based wastes provides the interesting techno-economic solution for the aspects of product valorization, recycling of material, economic and environmental sustainability. The biogas can be utilized directly and the left-over residue, digestate, is addressed for effective utilization. On the basis of biorefinery approach, the anaerobic digestion offers a technology platform for improving the process stability and increases the wide applications. The technology transfer from small scale to large scale requires understanding the feasibility, technology involved, and marketability. The presence of impurities like heavy metal, ammonia and excess water inhibit the direct application of digestate to the land which impacts the environmental safety. The valorization of anaerobic digestion and the digestate produce the high-value added products like biogas, biochar, biofertilizer, biodiesel and animal feed. The valorization of digestate closes the loops of AD process towards recovery and recycles the unutilized nutrients present in it. The resource recovery and generating value-added products from digestate maintains a challenge to secure and enhance the socio-economic benefits by providing a sustainable development of bio-based industries. The development of the integrated biorefinery approach to the AD and digestate provide zero wastage discharge from the anaerobic digestion plant and embellishments on the economy and sustainability.

Author contribution statement

Dr. Sivasankaran Chozhavendhan: Conceptualization, Writing-Original draft preparation, **Dr. Guruviah Karthigadevi:** Writing-Original draft preparation. **Mr. Balasubramanian Bharathiraja:** Review and Editing. **Mr. Ramanujam Praveen Kumar:** Review and Editing. **Mr. Lata Deso Abo:** Review and Editing. **Dr. Sundramurthy Venkatesa Prabhu:** Visualization, Investigation. Supervision and Editing. **Dr. Ramalingam Balachandar:** Review and Editing. **Dr. Mani Jayakumar:** Visualization, Investigation. Supervision and Editing.

Declaration of competing interest

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

Data availability

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

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