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Emerging technologies for biogas production: A critical review on recent progress, challenges and future perspectives

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ABSTRACT

Biogas is a resource of renewable energy with the highest significance to development in many countries due to the great accessibility to biomass. It is mostly produced by the anaerobic digestion of various feedstocks, but technologies such as landfilling, aerobic composting and incineration are also being used. The current novel review aimed to present emerging technologies for biogas pretreatment, production and upgrading process. Furthermore, various applications together with a current and future perspectives of biogas have been covered. It was found that pretreatment technologies such as chemical, physical, thermochemical and oxidative are increasing biomethane and biogas yield. Hence, extrusion pretreatment has increased biomethane production by 190 %. The novel technologies for biogas upgrading, such as photosynthetic biofixation of CO_2 by microalgae have shown that upgraded CH_4 have maximum CO_2 content in the biogas ranging from 2 to 6 %. Microbial electrolysis cell technology is sustainable and effective for biogas upgrading with a low requirement of energy. Thus, it was found that bioelectromethanogenesis leads to the uptake of 13.2 gCO_2/d. In addition, nanobubble technology is in recent studies extensively investigated for the improvement of methane yield. In Europe around 70 % of biogas plants are utilising the feedstocks from agriculture sectors. In 2022 global combined production of biogas and biomethane has reached more than 1.6 EJ which is an increase of 17 % in the last five years. Fossil fuels are the primary global energy source with around 85 % of the world's energy supply. Hence, wider use of biogas could ensure the goals for the implementation of sustainable renewable energy.

1. Introduction

An effective method for reducing one of the most significant greenhouse gases, CO_2 and substitution of fossil fuels with renewable energy sources (RES) is decreasing the consumption of fossil fuels (Lu et al., 2021). The major environmental issues of concern are changing global climate, due to pollutants such as plastic pollution, pesticide accumulation and biowaste (Mishra et al., 2021). Nowadays, renewable energy sources represent a necessary and beneficial part of the system for energy supplying (Ighravwe and Babatunde, 2018). Global development of renewable resources is expanding and usage costs have decreased. Across the globe, the establishment of renewable resources has become very significant for managing global climate change (Lu et al., 2021). Therefore the growth and implementation of the RES have

Abbreviations: AD, Anaerobic digestion; AcoD, Anaerobic co-digestion; AnMBR, Anaerobic membrane bioreactor; APBR, Anaerobic packed bed reactor; ASTBR, Anaerobic structured bed reactor; AFBR, Anaerobic fluidized bed reactor; AHP, Analytical hierarchy process; B, Biological; Bcm, Billion cubic meters; C, Chemical; CHP, Combined heat and power; COD, Chemical oxygen demand; COMB, Combined; CM, Reducing methanogens; CNMs, Carbon-based nanomaterials; CSTR, Continuous stirred tank reactor; EU, European Union; EGSB, Expanded granular sludge bed; FB, Fermenting bacteria; FBR, fixed bed reactor; FW, Food waste; FSTR, Fully stirred tank anaerobic reactor; GHG, Greenhouse gas; HAIB, Horizontal anaerobic immobilized biomass reactor; HAR, Hybrid anaerobic reactor; HRT, Hydraulic retention time; MDEA, Methyldiethanolamine; MCDM, Multi-criteria decision-making; NB, Nanobubble; NPs, Nanoparticles; OA, Organic acids; OM, Organics matter; OLR, Organic loading rate; P, Physical; P2G, Power to gas; RES, Renewable energy sources; SSAD, Small-scale AD systems; SRT, Solid retention time; TS, Total solids; UAFR, Up-flow anaerobic filter; UASB, Up-flow anaerobic sludge blanket reactor; VFAs, Volatile fatty acids; VS, Volatile solids.

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become one of the main priorities for every country (Li et al., 2024). The major reason for this is that renewable energy sources are a primary, clean and inexhaustible source of energy. The renewable energy most common sources include hydro, wind and solar energy, but they also include geothermal energy and biomass. Currently, these sources are responsible for the production of 28 % of the total demand regarding energy usage in the world (Zhao et al., 2022).

In accordance with EU policies towards the utilization of renewable energy and overcoming climate changes, their attention is directed to promoting the renewable resources that have spurred the uprising of biogas plants for the production of cleaner energy (Scarlat et al., 2018). Biogas as renewable energy enables the sequestration of CO_2, thus enhancing the quality of air (François et al., 2023c). Anaerobic digestion (AD) exploits the potential of biogas to be used for electricity and heat production, as well as fuel with further environmental, economic and climate interests (Mancini et al., 2024). After AD, produced biogas is composed of CH_4 (55–70 %) and CO_2 (30–45 %) by volume and small amounts of O_2, H_2S, H_2O and trace hydrocarbons (Zabed et al., 2020). Of great significant for the environment is obtaining biogas through AD by utilizing agricultural and livestock biowaste, which is then utilized for the production of electricity (Shirzad et al., 2019). Currently, the largest biogas production is represented in US, Germany and China, respectively (Molla et al., 2024).

According to REPowerEU plan the annual biogas production should reach the 35 billion cubic meters (bcm). Currently, it is only 3 bcm for produced biomethane and 15 bcm for produced biogas in EU-27 IAE) (IAE, 2023). The value of produced biogas could be enhanced through processes of purification and upgrading that involve the removal of CO_2 from biogas that further increases the energy density by biomethane concentration increase (Mulu et al., 2021). Studies have revealed the utilization of modern technologies in the purification and upgrading of biogas such as cryogenic separation (Tamilselvan and Selwynraj, 2024), chemical absorption (Lv et al., 2024) and bioconversion process (Huang et al., 2024). The main deficiency of the mentioned technologies is their very high costs of operation and capital of investment (Archana et al., 2024).

Hence, the current study has covered the most crucial selected segments for biogas production technology. The main objective of this review is to provide detailed status on current emerging technologies for biogas production, pretreatment as well as upgrading. The upgrading technologies include an overview of physicochemical, biochemical, nanotechnology as well as green current technologies. The main feedstocks for biogas production are being discussed, evaluated and compared. Furthermore, since the leading technology for biogas production is still anaerobic digestion in this review main reactor designs and operational parameters have been summarized. Ultimately this review facilitates various applications of biogas utilization as well as current scenarios and future perspectives of biogas production worldwide. Energy generation from renewables (biomass and biowaste) is crucial for achieving low-carbon emissions due to its numerous advantages involving low-cost energy provision for purposes of heating and generation of power, access to easy off-grid energy as well as decreasing the costs for fossil energy.

2. Sources for biogas production

On the global level, climate and energy change policies as well as more and more usage of renewable resources, have motivated researchers and the enlargement of plants to produce biogas (Sica et al., 2023). The main basis for this is the rapid price increase of energy sources, uncontrolled depletion of fossil fuels, the variability of stability of supply and the trustworthiness of purchasing (Kucher et al., 2022). Biomass as a source of energy that is an alternative presents a chance and an opportunity to overcome environmental issues such as restrained depletion of various resources from nature and pollution (Koryś et al., 2019) and could be described as a generic description of a group of highly diverse products that meet the common criteria of being organic (Wiselogel et al., 2018). The categorization of biomass could be done by its origin. Thus, renewable sources could be described as woody and agricultural biomass (residues of crops, trees, energy crops and stalks), industrial waste, biomass from marine (reed, waterweed, water hyacinth and algae), poultry waste, animal husbandry (Fernandes et al., 2023) and all the land and organic waste and vegetation that is water-based by origin (Yaqoob et al., 2021). Every biomass that consists of proteins, carbohydrates, fats, hemicelluloses and cellulose as the major components has the prospective to be utilized as a substrate in the system process of biogas production. The expected CH_4 yield and the biogas composition depend on the system for digestion, feedstock type and time of retention and due to that there is a need for the optimization of the system (Ghosh et al., 2020). Primary feedstocks for biogas production are presented in Fig. 1.

2.1. Food waste as feedstock

One of the main global issues presents a generation of food waste which is a consequence of rising demands for food supplements because of the continuing growth in population number (Mishra et al., 2021). Every year, about 1.3×10^9 tons of different foods are treated as waste around the world. Places such as homes, restaurants, grocery stores, company cafeterias and bars are places where this type of waste could be generated (Chew et al., 2021). The main components of food waste are organic matter like carbohydrates, proteins and lipids, which decompose into compounds such as fatty acids, glucose, organic amino acids, etc. (Mishra et al., 2021). In recent years, anaerobic digestion has become the first method of choice for waste treatment as it is the most widely used method for biogas production. In comparison with other methods of treatment such as gasification, pyrolysis and incineration, pollution of the air and solid waste caused by the method of anaerobic digestion is minimal (Chew et al., 2021).

2.2. Industrial feedstock

Various industries processing different raw materials produce a high quantity of residues, by-products, and waste that could be utilised for the production of biogas. The content of waste could include different pathogens, impurities and heavy metals that depend on techniques that industries use in their production process. All these wastes could change the biological environment in a bioreactor and slow down or even stop the process of anaerobic digestion. In addition, using digestate as a fertilizer could cause health risks for people and animals and lead to environmental pollution. Therefore, a lot of countries already have committed to environmental legislation for the reduction of waste utilization. Generally waste from industries represents waste such as waste from textile industrial sectors, petrochemical waste, pulp and paper industrial wastes, agro-industrial wastes etc. (Atelge et al., 2020). The usage of agro-industrial waste and its degradation process are also followed by different characteristics such as chemical composition and physical, as well as thermal properties (Devi et al., 2022). The AD process of industrial waste is affected by parameters such as type of feedstocks, pH, organic loading rate and temperature. Hence in the study of Kiani et al. (Kiani et al., 2022) was found that bioreactor performance was enhanced by utilizing a digestion consisting of two-stage and maximum uptake of COD (greater than 80 %) and CH_4 production with the value of 0.329 L_{CH4}/kg COD with utilizing APBR and ASTBR reactor configurations was obtained with a high loading rate of 30 kg COD/m^3d.

In recent years there has been an increase in the pulp and paper industry production. Hence great amounts of waste are generated from these industries such as sludge, fly ash and lime mud (Gupta and Shukla, 2020). Fig. 2 gives various technologies for the usage of waste from the pulp and paper industry. Hence, generated waste could be used in biohydrogen production, energy generation (biogas and biochar), biorefinery integration (fuel and energy), clinker preparation (brick and

Fig. 1. Different feedstocks that could be used for the production of biogas as a renewable energy source.

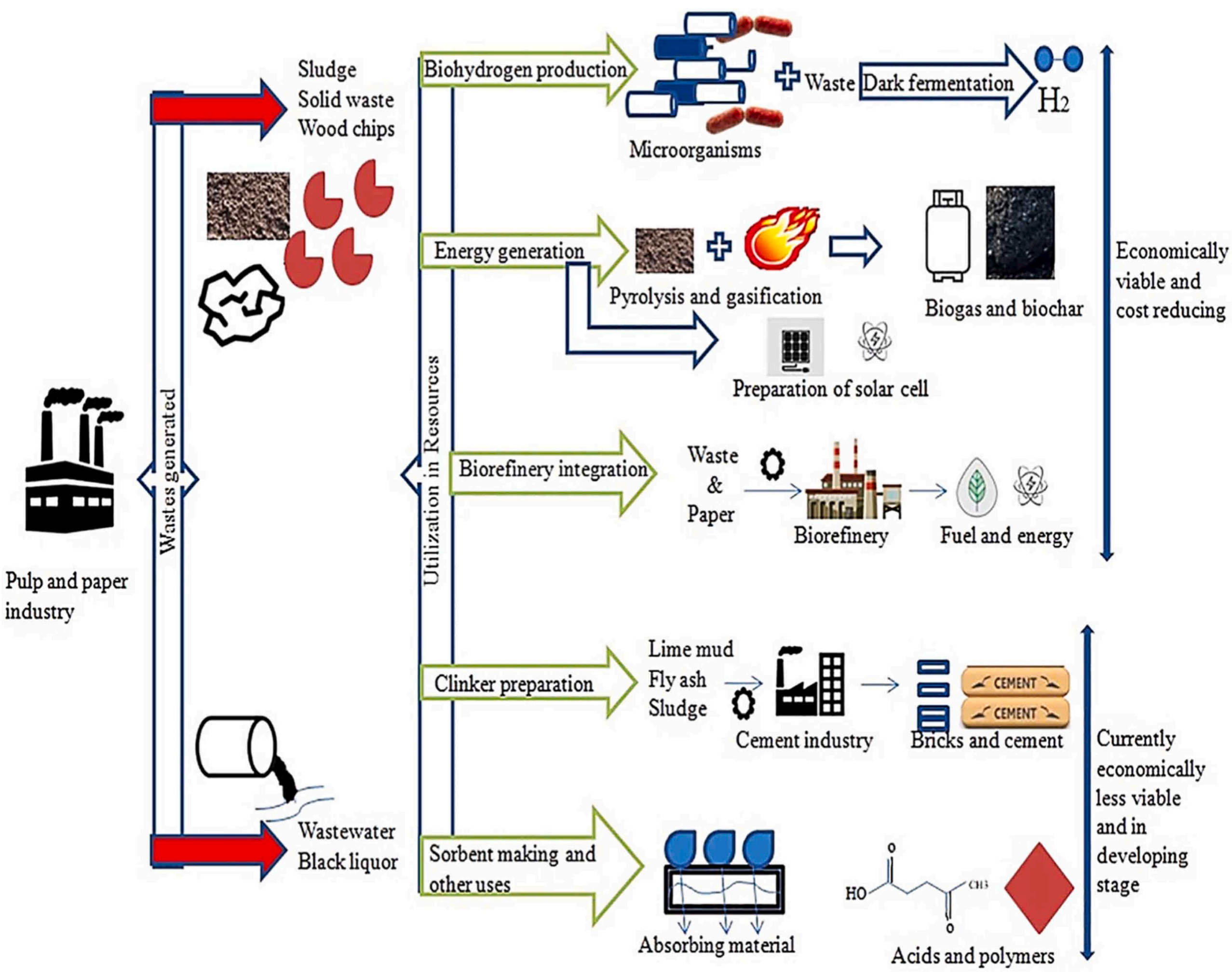

Fig. 2. Representation of various techniques for waste valorization from pulp and paper industry (Gupta and Shukla, 2020).

cement), sorbents preparation (acids and polymers), etc. (Gupta and Shukla, 2020). Among the mentioned technologies, special attention is directed towards biohydrogen production (Yellezuome et al., 2024). The production of biohydrogen from various biowaste is a sustainable approach for the development of products, decreased cost of biowaste disposal and environmental regulations consideration (Yellezuome et al., 2024). Its production considers reaction of an anaerobic fermentation process without any light for breaking down complex carbohydrates and to form H_2 and other products. This process of H_2 production is also called a dark fermentation process. The by-product of biohydrogen production is water vapour and hence it is a clean energy source without any pollution (Tagne et al., 2024).

2.3. Activated sludge from wastewater treatment plants

Waste activated sludge is generated in high quantities from the process of activated sludge which is utilized in treatment plants for wastewater. In Europe, there was around 9×10^6 metric tons of waste activated sludge produced and discharged in 2020. The main producer was Germany with 1.8×10^6 metric tons of activated sludge followed by Spain and France with 1.2×10^6 metric tons. Since waste activated sludge has great amounts of organics it could be utilized as a substrate for energy production (biogas). Per ton of sludge from the wastewater industry, there is around 120 m^3 of biogas produced and by further optimization of the process of anaerobic digestion regarding CH_4 production, biogas from this source could be a significant source of energy (Kanellos et al., 2024). The schematic illustration of biogas production from wastewater treatment plants is given in Fig. 3. Biogas could fulfil the energy demands of wastewater treatment plants or it could be utilized in the infrastructure of existing grids for the production of heating and electricity (Gas for climate 2050, 2022). There are currently many studies directed toward enhancing biogas production from activated sludge by using various pretreatment techniques such as; ultrasonication (Zhao et al., 2023), enzymatic and thermal pretreatment (Moreira et al., 2023), utilization of natural zeolites (Tang et al., 2023a), etc.

Food residues and organic household (Chew et al., 2021) waste are the major constituents of municipal solid waste. In global meaning, this waste comes from end-users of products from commercial, medical, trade activities and households and carries a significant amount of organic nutrients (Mishra et al., 2021). On the basis, it contains 10 % plastic, 17 % paper, 46 % scraps from food and waste from grade and 27 % other waste. Anaerobic digestion is one of the most utilized methods in the management of food biowaste by process of biogas production. Co-digestion together with substrates such as lignocellulosic waste and biowaste from slaughterhouses could be effectively utilized for the process enhancement, thus obtaining greater yield for biogas. In addition, methods of pretreatment could increase the production of CH_4 in AD process of food waste (Chew et al., 2021). Biogas production using municipal solid waste is influenced by the fraction of organic (Parvez and Ahammed, 2024) that could be utilized for the AD process of biogas production (Mittal et al., 2019). The latest data show that the production of this waste amounts to about 1.7 billion tons per year with a constant trend of increase as the population grows. Unfortunately, with poor management, municipal solid waste could pose a danger to the health of humans and impose many negative impacts on the environment such as contaminated soil, water, and air. Therefore, the primary option to reduce municipal solid waste and create better management practices is to use it as a primary substrate for bioenergy production with good sustainable and economic practices (Mishra et al., 2021).

2.4. Livestock manure as a feedstock

Livestock manure is comprised of organic matter that could be utilized as a feed in a process of bioenergy production (Wang et al., 2021). In the EU27 and UK up to 1.4 billion tons of livestock manure from farms is being yearly produced and only a small fraction of this biowaste is being collected (Köninger et al., 2021). Plant, animal and human waste are organic materials which are biodegradable and with parts that could be utilized for the production of biogas. Any wet organic matter is suitable for usage in the process of anaerobic digestion. Generally, livestock wastes such as plant wastes (forage and straw), manure and fodder wastes, and household wastes are types of biomasses that are appropriate for biogas production. Transformation and use of livestock manure waste for biogas production are important from different aspects. Some of them are protecting the environment and human health and heating value - because they could be utilized as a substitute for fossil fuels (Zareei, 2018). Hence, there are many studies conducted for the enhancement of livestock manure properties for improved

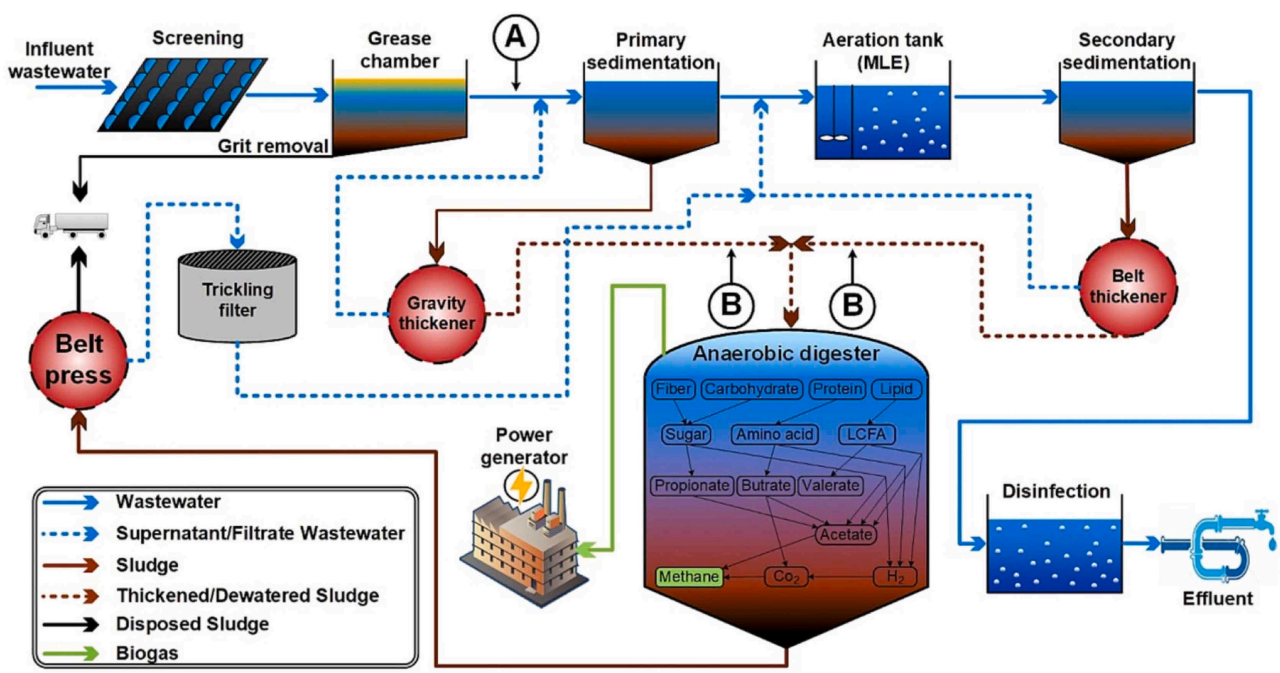

Fig. 3. Process flow diagram for biogas production from wastewater treatment plant by AD process (Salamattalab et al., 2024).

production of biogas. Hence, in the study of Chen et al. (2023) alkaline pretreatment was found to enhance the yield of biogas and CH_4 production.

2.5. Microalgae as feedstock

Another feedstock for the production of biogas is microalgae. The biomass from algae has a small quantity of lignin and cellulose in its content, thus making them a great source of feedstock for biogas production by the process of AD. Microalgae is considered as very effective source for the production of biogas due to their high lipids and polysaccharides content. Furthermore, they are easy to cultivate, grow fast, easy to harvest as well as easily transformed into biogas. However, the obtained yield of biogas is in accordance with the used algal strains and operating conditions (Ahmad et al., 2022). In the conducted study by Kowthaman et al. (2021) *Spirulina platensis* microalgae was utilized as a feedstock for the production of biogas. The study revealed that maximum yield of obtained biogas was 740 mL/gVS at 70 °C and a reaction time of 4 h utilizing 6 % NaOH for the alkaline pretreatment. Furthermore, in the study of Kumari et al. (2021) obtained yield of biogas was 479 mL and CH_4 yield was 147 mL/VS (g) for untreated *Chlorella pyrenoidosa* biomass.

Different feedstock wastes with their CH_4 yield are given in Table 1. This shows different substrate types, their comparative amount of methane yield and energy potential that could be generated from the biogas production process. Furthermore, it could be noticed that methane yield for different substrate types is in the range from 0.0178 to 0.501 m^3/kg. Regarding the obtained fresh matter, values ranged from 96 to 409.6 kWh/t. As found in the study of Bharathiraja et al. (Bharathiraja et al., 2018) the highest yield for energy production was determined for maize silage. Furthermore, the second highest obtained methane yield was found for kitchen waste as determined in the study of Nwokolo et al. (Nwokolo et al., 2020) with a value of 0.501 m^3/kg. Moreover, as given in Table 1 wastewater from the paper and pulp industries and sewage sludge has the lowest yield of methane and energy. Therefore, the most important waste from this category is kitchen waste in terms of biogas production.

Table 1
The amount of methane yield and obtained fresh matter for biogas production using various feedstocks.

Substrate types	Methane yield* (m^3/kg)	Obtained fresh matter (kWh/t)	Reference
Banana skin (*Robusta species*)	0.277	-	(Ji et al., 2017)
Onion skin	0.400	-	(Ji et al., 2017)
Potato skin	0.267	-	(Ji et al., 2017)
Pulp and paper mill sludge	0.429	-	(Atelge et al., 2020)
Pulp and paper industry wastewater	0.078–0.138	-	(Atelge et al., 2020)
Animal manure+ Tomato pulp	0.404	-	(Nwokolo et al., 2020)
Corn stover + Chicken manure	0.219	-	(Nwokolo et al., 2020)
Kitchen waste	0.501	-	(Nwokolo et al., 2020)
Chicken litter/dung	-	257.3	(Bharathiraja et al., 2018)
Horse manure	-	114.3	(Bharathiraja et al., 2018)
Municipal solid waste	-	207.2	(Bharathiraja et al., 2018)
Sewage sludge	-	96.0	(Bharathiraja et al., 2018)
Maize silage	-	409.6	(Bharathiraja et al., 2018)

* **Note:** Presented units are given per mass of volatile solids.

3. Advanced pretreatment technologies for feedstocks

The pretreatment technologies (Fig. 4) of feedstock for biogas production include; physical pretreatments (mechanical, extrusion, microwave irradiation), thermochemical pretreatments (liquid hot water and steam explosion pretreatment), chemical pretreatments (alkali, acidic and organosolv), oxidative pre-treatments (wet oxidation, advanced wet explosion and ozonolysis) (Abraham et al., 2020). In physical pretreatments, the feedstocks are treated without usage of chemicals and microbes. This treatment influences the size of particles, cellulose crystallinity, polymerization range, size of pores and area of biomass surface. In mechanical treatments varieties of milling, grinding and chopping technologies are used for feedstock processing before entering an anaerobic digester. The study of Dell Omo (Dell'Omo and Spena, 2020) evaluated double stage mill on an industrial scale for the pre-treatment of giant reed stems and wheat straw and the study results established that CH_4 yield was upgraded by 137 % in comparison to biomaterial which was not treated.

In pretreatment by microwave irradiation, energy from microwaves is introduced into biomass which ensures its fast heating with a low thermal gradient and due to its fast heating energy costs are reduced (Arpia et al., 2021). In addition to microwave irradiation treatment, there are also studies directed towards combine pretreatment by using microwave irradiation and ultrasonic methods (Yue et al., 2021). The combination of these two methods is found to result in decreased biomass particle size and growth in the area of the exposed surface as well as availableness of oligosaccharides, cellulose and hemicellulose (Sidana and Yadav, 2022). Furthermore, these methods combination accelerates the process of hydrolysis and process of biodegradation of residues from agriculture sectors and sewer sediments which are adopted for the production of biogas. In the study of Hosseinzadeh et al. (Hosseinzadeh et al., 2024) was found that low-frequency ultrasonic pretreatment was feasible in improving the production of biogas from landfill leachate in anaerobic digestion and for recovery of energy.

Extrusion pretreatment is usually combined with the actions of thermal and mechanical operation due to rotation of a screw inside the container that is tight. The study of Karimipour-Fard et al. (Karimipour-Fard et al., 2024) investigated 6 screw designs with shear intensity variations for enhancing the pre-treatment process of biowaste (forestry) for the generation of industrial biogas. It was found increased biomethane production by 190 % by using optimal designs of screws in comparison to benchmark samples. In thermochemical pretreatment marked as liquid hot water pretreatment biowaste is treated at great pressure without any chemicals and by ensuring high pressure water is kept in a state of liquid at a temperature ranging from 140 to 220 °C. When this water under pressure penetrates the biowaste it leads to the hydrolysis of organics (hemicellulose), the area of the surface is increasing and the lignin fraction is removed from biomass (Chen et al., 2022). In the study of Lee et al. (Lee et al., 2020) sunflower stalk was treated at different temperatures for AD and the obtained results showed that hydrothermally treated biomaterial led to an increased yield of methane with 87 %.

In steam explosion (Fig. 4), the pretreatment biomaterial is heated under great pressure for a short time and with steam which is saturated. This process is followed by a fast reduction in pressure and results in lignocellulose material destruction. The pressure is usually from 5 to 50 bars and the temperature ranges from 160 to 250 °C. The hemicellulose hydrolysis occurs during an explosion of steam and lignin fraction is kind of transformed leading to easily degradable lignocellulose material (Yu et al., 2022). In the research of Hashemi et al. (Hashemi et al., 2021) was revealed that steam explosion pre-treatment increased the production of biogas (Table 2) from birch wood with a value of 155 % and that enzymatic treatment further led to an increase in the yield of biogas up to 25 % (Hashemi et al., 2021).

Pretreatments with alkali solutions (NaOH, KOH, urea and $Ca(OH)_2$ etc.) are generally utilized for lignocellulose-based biowaste that results

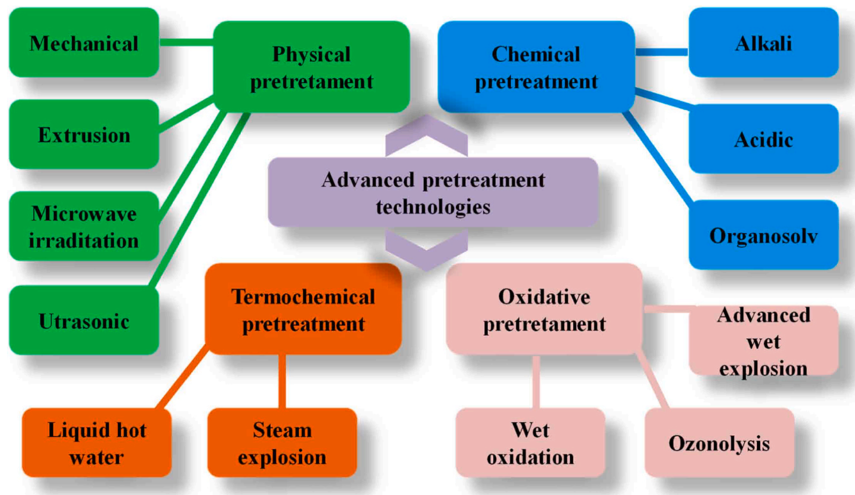

Fig. 4. Classification of different advanced technologies for feedstock treatment used for biogas production.

Table 2
The representation of various feedstocks and its pretreatment or upgrading technology with obtained biogas and methane yields as well as process conditions.

Feedstock	Biogas yield (mL/g VS)	Increase of biogas yield (%)	Methane yield (mL/g VS)	Increase in methane yield (%)	Process conditions	Reactor type	Pretreatment or/ upgrading technology	Reference
Swine manure	-	-	566.1 ± 7.8	49	157 days, 2.5 L of anaerobic inoculum, pH 8	Continuous stirred tank reactor (CSTR)	Membrane-based NH_3 extraction	(Rivera et al., 2022)
Mixed fruit waste	-	-	53.58	10	pH 7, 37 °C, 86 days	Batch digestion	Dilute acetic acid	(Saha et al., 2018)
Biorefinery lignin	-	56.3	-	106.2	Thermophilic conditions (52 °C), HRT: 20 days	Bioreactor	Wet explosion and enzymatic hydrolysis	(Khan and Ahring, 2020)
WWTP mixed sludge	70.3 ± 12.1 L/d		324.7 ± 75.8	91.2 ± 0.7	Mesophilic conditions (35 ± 2 °C), HRT: 20 days	Anaerobic digester at pilot scale	Photosynthetic upgrading	(Méndez et al., 2022)
Birch wood	-	25	566	-	40 °C, 43 days	Batch reactor	Steam explosion and enzymatic	(Hashemi et al., 2021)
Miscanthus	295.50	56.92	135.51	8	35 °C, 90 days	Batch reactor	Hydrothermal and alkaline	(Xue et al., 2020)
Rice straw	-	-	311.7	88.7	37 °C, 50 days.	Batch reactor	Microbial	(Amin et al., 2021)
Organic fraction of municipal solid waste (OFMSW)	-	-	342.66 ± 6.11	41.49	Mesophilic conditions (35 ± 2 °C), 30 days	Batch reactor	Thermal	(Kamali et al., 2023)
Wheat straw	-	-	27.4 Nm^3/ tVS	137	Mesophilic conditions (38 °C), 28 days	Anaerobic reactor	Mechanical	(Dell'Omo and Spena, 2020)
Giant reed stems (*Arundo donax*)	-	-	15.6 Nm^3/ tVS	49.1	Mesophilic conditions (38 °C), 28 days	Anaerobic reactor	Mechanical	(Dell'Omo and Spena, 2020)
Rice straw	29.26	20.79	-	-	37 ± 1 °C, 45 days	Batch reactor	Fungal pretreatment	(Rani and Dhoble, 2023)
Cattle manure	-	-	1.30 ± 0.15 L CH_4/ L_r day	-	Thermophilic conditions (55 ± 1 °C)	Four cylindrical up-flow reactor	Ex-situ biogas upgrading	(Ghofrani-Isfahani et al., 2021)
Algae and corn husk	740	60	-	-	50 °C, pH 7	Batch reactor	Thermochemical pretreatment	(Kowthaman et al., 2021)
Wheat straw	16	-	408	14	37 °C, 10 days	Continuous stirred tank reactor	Fungal and bacterial pretreatment	(Yadav and Vivekanand, 2021)

in the opening of ester bonds in organic fractions of these materials. Fig. 5 gives a schematic representation of three different configurations for alkaline treatment. This kind of treatment improves the process of enzymatic hydrolysis in the AD systems as well as the porosity and area of the surface of biomaterials thus leading to reduced polymerization degree (You et al., 2019). The study by Xue et al. (2020) found enhanced biogas production from miscanthus used as aa feedstock by the combination of alkaline (8 % NaOH) and hydrothermal pretreatment technologies at 175 ℃ (Table 2). The biogas yield was improved by 52.96 % and the time of AD period was reduced by 45.4 % towards the control. The major parameters which affect this process are temperature, time of residence and alkali concentration. On the other side, inorganic acids which are used in the pretreatment process of feedstock include HNO_3, H_3PO_4, H_2SO_4 and HCl (Ilanidis et al., 2021).

This treatment is performed with acids ranging in concentrations from 30 to 70 % and at temperatures under 100 °C or above, depending

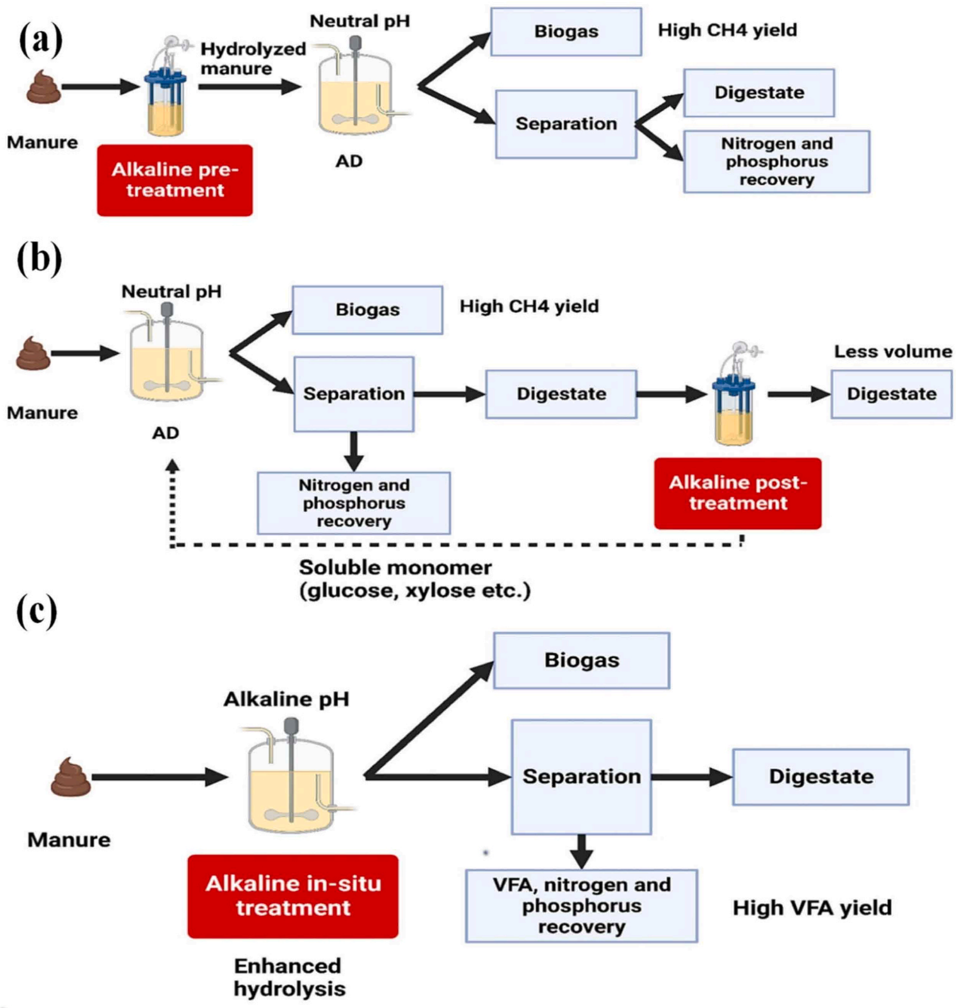

Fig. 5. Different configurations for alkaline anaerobic digestion processes; (a) Pretreatment, (b) Posttreatment and (c) for In-situ usage (Chen et al., 2023).

on acid concentration. These acids are hydrolysing fractions of cel-methane yield fromlulose in the biomaterial (Mishra et al., 2021). Suthar et al. (Suthar et al., 2022) investigated the influence of dilute acid-thermal treatment and the addition of biochar from cattle dung on anaerobic co-digestion of activated waste sludge. The production of biogas was improved by 98.7 % and methane yield by 77.4 %. The treatment with organics is carried out by utilization of various organic solvents in or without the presence of catalysts. The pretreatment with organic solvent of Napier grass and silage was investigated in the study of Jomnonkhaow et al. (Jomnonkhaow et al., 2022). The pretreatment of used biomaterials by organic solvent followed by enzymatic hydrolysis enhanced methane yield 2 times in comparison to untreated biomaterials. In addition, this pretreatment has enhanced the removal of lignin.

In the wet oxidation pretreatment water is added to the feedstock which is then followed by the addition of an oxidizing reagent like H_2O_2 and the biomaterial is heated at temperatures ranging from 125 to 300 °C and pressures from 0.5 to 20 MPa. In the study of Lee et al. (Lee et al., 2021) wet oxidation pretreatment with H_2O_2 for oil palm empty fruit bunches as biogas feedstock has proven to be very effective in improving methane yield from 19.7 to 52.7 %. In the pretreatment called advanced wet explosion, the temperature ranges from 140 to 220 °C and pressure from 0 to 3.5 MPa. When the selected temperature is achieved then O_2 is purged into the selected reactor and feedstock is heated from 5 to 120 min (Wang et al., 2023). When the process is completed, pressure is promptly decreased and biomaterial is removed from the flash tank. Hence, in the study of Dutta et al. (Dutta et al., 2022) sewage sludge was subjected to the advanced wet oxidation and steam explosion pretreatment. Their study revealed a 94 % improved yield of methane under the optimal CH_4 average yield of 183 mL/g VS at 165 °C, 15 min and by using 10 % oxygen.

In the process of ozonolysis, the ozone is used as an oxidizing reagent which influences the fraction of lignin during the pretreatment process. The process effectiveness is dependent on ozone concentration, particle size of biomaterial and amount of biomaterial water. There are no formed inhibitory compounds during the process since biomass is treated at ambient pressure and temperature. The most crucial factor in the process is water due to the solubilization of biomaterial during the pretreatment (Zhou et al., 2023). Perrez-Barragan et al. (Pérez-Barragán et al., 2024) assessed methane and biohydrogen production from two types of biomaterial and used ozonolysis as a pretreatment method. It was revealed that with ozonated enzymatic hydrolysates yield of biohydrogen was improved up to 78.2 % and methane yield was 260 NmL CH_4/g VS.

Table 3 gives various feedstocks for biogas production and their required pretreatment technologies. There is a broad spectrum of wastes that are used as a substrates in anaerobic digestion (AD) in accordance with their origin (source) from one of three main primary kinds of organic waste (Atelge et al., 2020). In addition, the literature indicates that the selection of one or more adequate pretreatment processes could improve the running of a biogas plant increasing the rate of anaerobic digestion or enhancing methane yield (Chandel et al., 2019). However,

Table 3
Feedstock classification and required pretreatment technologies for biogas production.

Origin	Feedstock	Examples	Pretreatment required	Reference
Agriculture	Agricultural residues and waste, Livestock waste, Energy crops, Animal by-products, Manure, Algae; Mosses, Lichens	Herbaceous woody crops, Grasses; Sugar crops, Starch crops, Oilseed crops; Manure (cattle, pig, poultry), Harvest remains; Prokaryotic algae, Eukaryotic algae, Kelps, Bryophyta, Polytrichales, Crustose lichens, Foliose lichens	**P**: (mechanical, thermal), **C**: (oxidative, alkali), **B**:(partial composting, enzymatic, fungi), **COMB**: (nitrogen extraction, extrusion)	(Dahunsi, 2019), (Kamusoko et al., 2019), (Chevalier et al., 2023), (Orlando and Borja, 2020), (Bhushan et al., 2023)
Industry	Industrial wastes and wastewaters	Food/beverage processing; Slaughterhouses waste, Starch industry, Sugar industry, Pharmaceutical industry, Textile industry, Cosmetic industry, Pulp and paper, Biochemical industry	**P**: (thermal, ultrasound, microwave, electrokinetic), **COMB**: (steam explosion)	(Ketsub et al., 2022), (Aliyu Salihu, 2016), (Anacleto et al., 2022), (Yankov, 2022)
Municipal waste	Community bio wastes	Organic fraction from municipal waste, Sewage sludge, Excreta waste, Garden waste, Food remains	**P**:(mechanical), **B**: (precomposting), **COMB**: (steam explosion)	(Mitraka et al., 2022), (Kamali et al., 2023), (Karthikeyan et al., 2018)

Note: **P**- Physical; **C**- Chemical; **B**-Biological; **COMB**- Combined

it must be ensured that the important return in terms of biogas production should be greater than operational and capital costs for pretreatment. In this regard, the process efficiency could be enhanced and the costs involved in pretreatment could be minimized by applying co-digestion (Gontard et al., 2018). Recently, anaerobic co-digestion (AcoD) method has been seen as a more viable technology enhancing biogas yield, in general, compared to AD mono-substrate (Rodríguez-Nuñez and Castillo Baltazar, 2020).

3.1. Emerging technologies for biogas production and upgradation

Under controlled conditions, biogas is produced by the anaerobic activity of selected bacteria and has a calorific value from 21 to 24 MJ/m^3. Biodegradation of organic matter under natural anaerobic conditions delivers about 800×10^6 tons of methane into the atmosphere. The composition of biogas is complex and it is the reason for its limited use (Kapoor et al., 2020b). Biogas represents a mixture of various gases and most of it consists of methane, carbon dioxide and other gases that make up 1–5 % of hydrogen. Methane enables the easy combustion of biogas, whereas CO_2 lowers the calorific value and limits the ability to transport biogas because it does not combust normally. Other biogas constituents such as siloxanes, hydrogen sulphide and water vapour cause corrosion to the mechanical parts that lead to a decrease in the heating value. It is of great significance to ensure the separation of CO_2 due to the calorific biogas value which could increase up to 35.8 MJ/m^3 and other constituents which are corrosive to broaden and increase the usage of biogas (Sahota et al., 2018). The four main biogas production technologies (Table 4) used worldwide are incineration (thermochemical process) and waste disposal, anaerobic digestion and aerobic composting (biological processes) (Tshikovhi and Motaung, 2023).

Selecting the optimal technology is challenging regarding the full complexity of parameters that determine the various (dis)advantages. One of the tools used for the objective assessment is a multi-criteria decision-making (MCDM) such as analytical hierarchy process (AHP) method based on several usually conflicting criteria (Ozgur, 2024). The key is to establish a suitable technology considering the four main criteria (environmental, economic, sustainable and social criteria of energy recovery from used waste) and if necessary, a sub-criteria (identified for pairwise comparison) during the selection process. For instance, Agbejule et al. (2021) found that technology preference follows the order: incineration> anaerobic digestion > aerobic digestion > landfilled gas based on three major criteria and nine sub-criteria are

Table 4
Comparison of main technologies for biogas production.

Process	Landfilling	Aerobic composting	Incineration	Anaerobic digestion
Biomass type	Uncontrollable biomass (mostly organic matter - garbage dump)	Organic waste	Municipal solid waste (MSW)	see Table 3.
Main end products	Gas (CH_4, CO_2)	Gas (NH_3, CO_2), Solid (compost), Heat	Gas (CH_4, CO_2), Heat	Gas (CH_4, CO_2); Digestate
Advantage	Very low cost raw material	Minimizes animal manure quantity and kills microorganisms	Uses almost all types of MWS fraction and can reduce the volume of the waste by 80 % and the solid mass by 70 %.	Economically viable (low capital and operating costs). Low amount of greenhouse gas (GHG) emission. Nutrient-rich substance (digestate) could be further used for fertilizer making it safe for disposal.
Disadvantage	Environmentally problematic (leachate could easily lead to pollution and quality of water and soil)	Causes secondary environmental pollution	Very high initial plant costs, maintenance and operating capital costs, Eventually could lead to air and/or water pollution. Lower energy content	A large area is required for this type of plant installation. Quite difficult management and maintenance. Complex products need additional techniques for processing to become products which are refined. Problems due to storage and product processing.
Reference	(Al-Wahaibi et al., 2020), (Agbejule et al., 2021), (Velasco et al., 2019)	(Lu et al., 2019), (Duan et al., 2022)	(Ouda et al., 2016); (Rasheed et al., 2021), (Beyene et al., 2018)	(Chojnacka et al., 2020), (Holtzapple et al., 2022)

marked for pair-wise comparison and evaluated by 10 experts. This sequence is subject to change on a case-by-case basis concerning the developed capacity integration strategies and institutional capabilities for these processes in the country. However, the main leading technology for biogas production is still considered anaerobic digestion technology since it is in agreement with the new set up targets of the European Union (EU) considering biogas production (Gas for climate 2050, 2022).

3.2. Stages of biogas production by anaerobic digestion

Four basic stages are part of the AD process and make up the biogas production from different organic biomaterials (Livestock, industrial, food and municipal solid waste etc.) that occur in a digester for anaerobic digestion. The stages include hydrolysis, acidogenesis, acetogenesis and methanogenesis (Tang et al., 2023a) as shown in Fig. 6. Hydrolysis is the first stage in which high-molecular and insoluble organic compounds such as carbohydrates, proteins and lipids are subjected to the conversion to low-molecular and simple compounds, such as propionic, formic and butyric acids (volatile fatty acids (VFAs)) as well as to CO_2, H_2 alcohols and aldehydes. This process involves saprophytic bacteria due to the participation of some extracellular enzymes (Koniuszewska et al., 2020). The chemical process that breakdowns the water molecules into anions (OH^-) and cations (H_3O) is called hydrolysis.

For that process, an acidic catalyst to break down the large biopolymers into low-molecular substrates is needed. In the stage of hydrolysis, fermenting bacteria (FB) such as bactericides, clostridia and bifidobacterial represent fermenting bacteria that breakdown mentioned polymers from biomass, i.e., high-molecular carbohydrates and lipids into sugar and fatty acids which are then soluble components of the process (Kour et al., 2019). Acetate and hydrogen are the main products of the hydrolysis phase which are utilised in further stages of anaerobic digestion by the process of methanogens (Begum et al., 2018). Acidogenic bacteria (Kour et al., 2019) convert hydrolysis products and compounds which are water-soluble into components such as CO_2, methanol or ethanol (alcohols), organic acids with H_2 short-chain and aldehydes (Koniuszewska et al., 2020). During acetogenesis, the conversion of the products is mediated by the acetic bacteria, *Syntrophomonas* and *Syntrophobacter.*

In this stage propionate is converted to acetate, glucose is converted to acetate and ethanol is converted to acetate, which then in further stages are used by methanogenic microorganisms as substrate components (Koniuszewska et al., 2020). During the acidogenesis to produce H_2, acetic acid and CO_2 products are subjected to anaerobic digestion. This stage is performed until the point where methanogens can influence acetogenesis products as well as the products from other AD processes to produce CH_4 (Kabeyi and Olanrewaju, 2022). The methanogens which are acetoclastic and CO_2 are reducing methanogens (CM) to produce methane and carbon dioxide (Song et al., 2024). Methanogens are primarily active in a moderately alkaline environment (6.8–7.2) since these microorganisms die if pH $<$ 6. In various stages of AD pH of the suspension goes under changes. In the stage of acidogenesis, the pH value is about 6 and a large quantity of CO_2 is released. In the pH range of 6.6–7.5 that is often buffered in digestate, biodegradation is very effective and microorganisms are very operative (Koniuszewska et al., 2020). Methanogens are categorised as chemolithotrophic microorganisms due to the utilization of carbon dioxide as a resource of carbon (Bharti et al., 2022).

3.3. Physicochemical technologies

There are many technologies which are currently used for biogas and feedstock treatment and pre-treatment process as well as for its upgrading and the first reason is an uptake of impurities such as H_2S, water vapour, ammonia and siloxanes which are not favourable for its applicability, natural gas grind and for end-users. The second reason is an uptake of CO_2 to increase its calorific value and to minimize the density of biogas which was treated to meet the standards of specific Wobble index (upgrading of biogas). In addition, depending on used technology, storage, usage and removal of CO_2 could make biogas a carbon-neutral resource of energy and thus manage emissions of anthropogenic CO_2. After the process of biogas upgrading final product is marked as biomethane and its quality and performance are defined based on the end utilization. Biomethane usually consisted of 95–99 % methane, 1–6 % carbon dioxide and 0.02–0.05 % hydrogen sulphide. Biogas upgrading technologies include scrubbing, membrane separation, pressure swing adsorption and cryogenic technology (Fig. 7). The scrubbing technology includes chemical and organics solvents/physical scrubbing techniques (Nguyen et al., 2021).

Techniques based on the solvent or water scrubbing rely on the

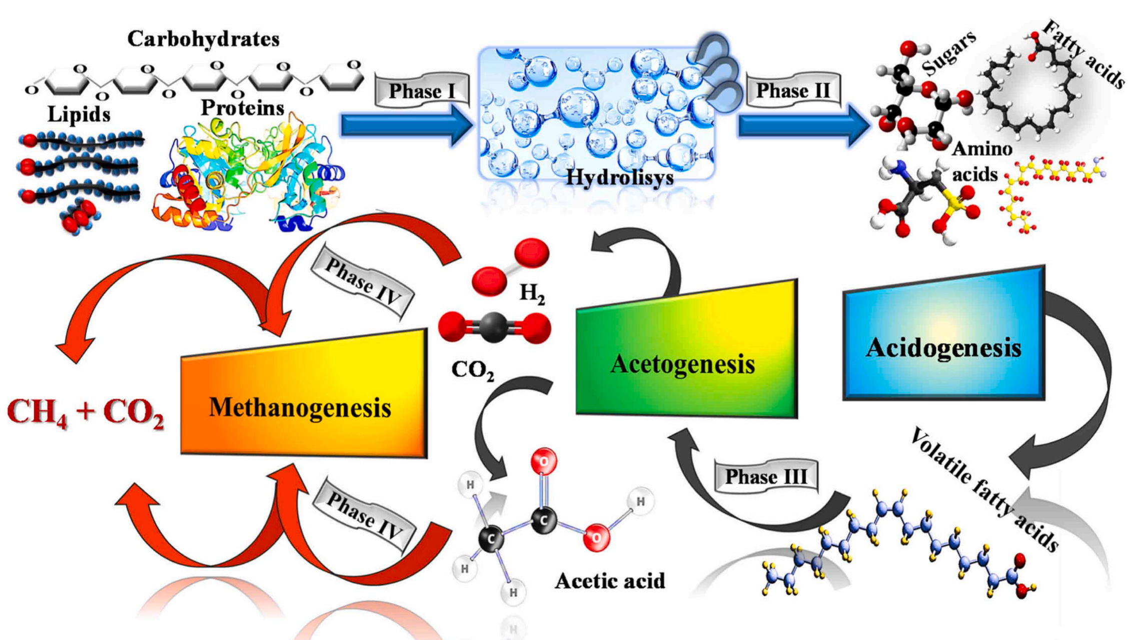

Fig. 6. Anaerobic digestion (AD) stages (hydrolysis, acidogenesis, acetogenesis and methanogenesis) for the process of biogas production from biomass.

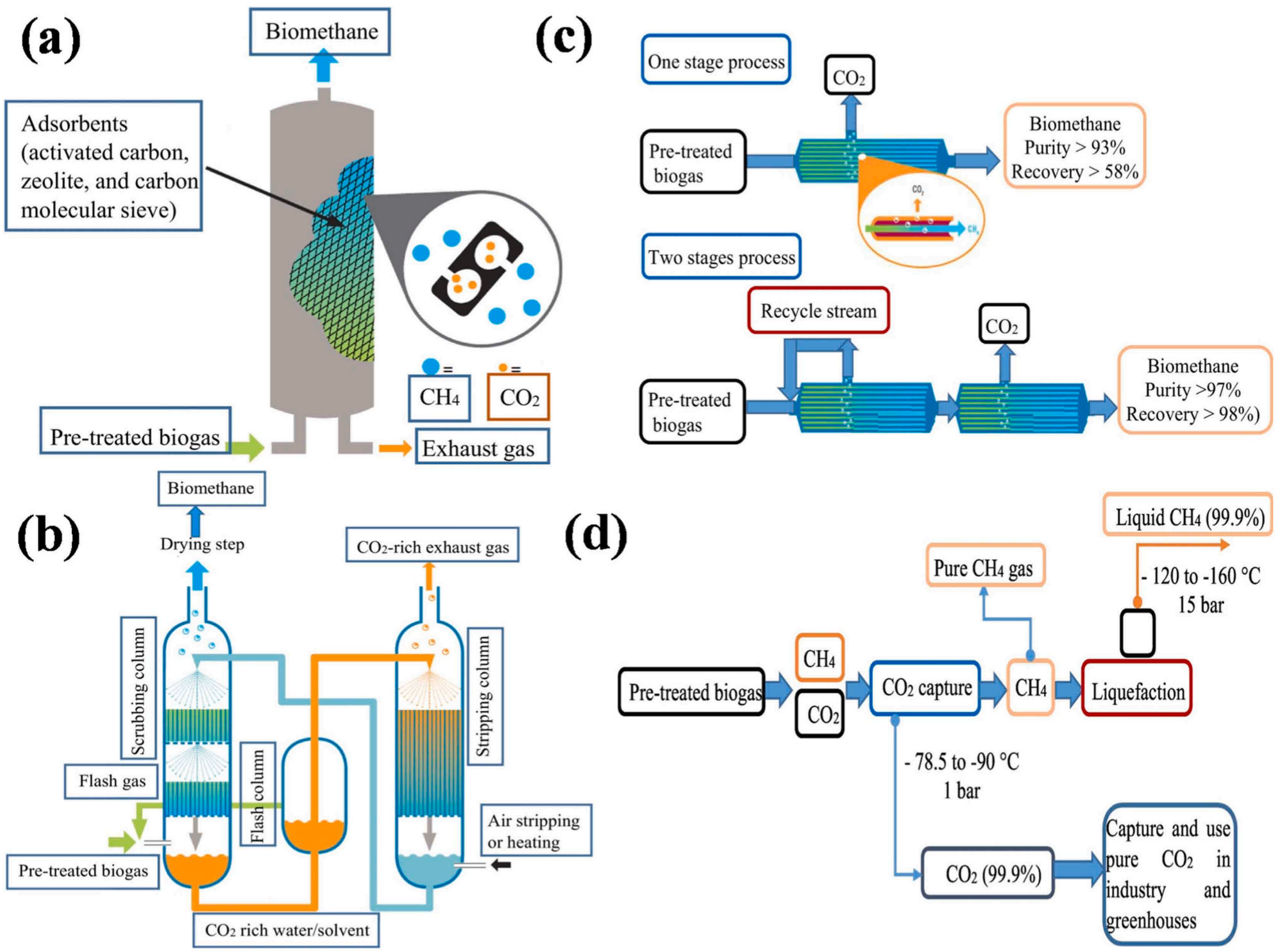

Fig. 7. Biogas upgrading technologies; (a) Pressure swing adsorption, (b) Scrubbing technology for the separation of CH_4 and CO_2, (c) Membrane separation and (d) Cryogenic technology (Nguyen et al., 2021).

solubility difference of CO_2 and CH_4. The used solution could be organic solvent or water. In the process of water scrubbing biogas which is pretreated is maintained at the temperature of 40 °C and the pressure from 6 to 10 bars and introduced into the column for scrubbing (Fig. 7**(b)**). Hence, CO_2 solubility is about 26 times greater compared to the solubility of CH_4. This method requires a great quantity of water with the value of 200 m^3/h for a flow of the gas with 1000 Nm^3/h (Sun et al., 2015). So, regeneration of the water is essential for the economic sustainability of this technique and is favourable for the implementation of this technology into wastewater treatment plants. The process of scrubbing with the organic solvent is similar to one which uses water (Angelidaki et al., 2018). The process with organic solvent is referred also as physical scrubbing. As organic solvents could be used methanol, poly(ethylene glycol) dimethyl ether, propylene carbonate, tributyl phosphate, tetramethylene sulfone, n-methyl-2-pyrrolidone and n-formyl-morpholine (Carranza-Abaid et al., 2021).

In this process, CO_2 has a greater solubility in the organic solvent such as N-methyl-2-pyrrolidone than in the water and a decreased amount of solvent is required as well as scrubbing column size could be decreased. The absorption of CO_2 occurs at pressures ranging from 4 to 8 bars leading to a lower demand for energy in comparison to technology of water scrubbing. In the study of Carranza-Abaid (Carranza-Abaid et al., 2021) was found that solvent performance regarding energetic and economic costs could be arranged in the following order poly (ethylene glycol) dimethyl ether ≈ n-methyl-2-pyrrolidone > n-formyl-morpholine > methanol > water. The disadvantage of organic solvent scrubbing is regeneration of solvent since stripping and pressure of air release are not successful for its regeneration. There are three varieties of the solvent regeneration process; hot process of regeneration, decompression of the solvent or flash desorption and stripping by using an inert gas (Carranza-Abaid et al., 2021).

Another technology for biogas upgrading is chemical scrubbing or chemical absorption (Khan et al., 2021). This technology is based on the chemical adsorbent and CO_2 reaction which is reversible (Fig. 7(b)). Chemical adsorbents could be used in varieties of amine compounds such as methyl diethanolamine (MDEA). The loss of methane in this process is minimal since used adsorbents are reacting only with CO_2. Hence, there are no requirements for lean gas process of post-combustion. In the technology of chemical scrubbing high purity methane (99 %) could be produced (Nguyen et al., 2021). The removal of H_2S from the upstream must be performed due to the H_2S corrosive reaction with the solution of amines. Compared to physical scrubbing technology regeneration of adsorbent compounds is an energy-intensifying process due to the strong bonds between molecules of gas. In general, the regeneration process consumes from 15 to 30 % of the generated energy from bioCH_4 (Sun et al., 2015). The latest studies are directed towards decreasing energy requirements for the adsorbent regeneration process by using a novel solution of amine compounds and by optimizing various process conditions such as rate of gas flow and temperature.

The pressure swing adsorption technology is based on the fact that methane and carbon dioxide are differently adsorbed onto specific adsorbent pores or surfaces. This technology uses differences in selected pressure and temperature since CO_2 adsorption is in proportion to the increased pressure and decreased temperature (Abd et al., 2022). Therefore, separation process is carried by a swing in pressure/temperature. The process basic principle is shown in Fig. 7(a) and its main section is filled with the selected adsorbent (carbon molecular sieve, zeolites, carbon which is activated, silicates, silica gel, etc.). These materials are used because they have great areas of surfaces, are porous and thus will enhance the capacity of adsorption. Since H_2S could be adsorbed onto these materials and lead to producing toxic effects the process of desulphurisation is required before pressure swing adsorption. This technology is operating at various plants for the biogas process of upgrading. The quality of bioCH_4 ranges from 96 % to 98 % and the loss of the CH_4 is between 1.5 % and 2.5 % (Nguyen et al., 2021). Thus, this technology requires exhaust gas post-combustion with the aim of minimising the release of CH_4 into the environment. The requirement of energy for pressure swing adsorption is from 0.15 to 0.35 kWh/Nm^3 of used biogas which makes it a good technology for upgrading biogas (Nguyen et al., 2021).

The technology of membrane separation (Fig. 7(c)) is based on different gas permeability through the pores of the membrane due to their selectivity differences. Hence CO_2 is greatly permeable and CH_4 is impermeable due to their molecule sizes. The used membranes are 20 times less permeable for CH_4 compared to CO_2. The rich exhaust gas of CO_2 from this technology could be utilized for the production of greatly pure CO_2 that could be used in the industry of drinks and food (Esposito et al., 2019). The research of Esposito et al. evaluated this technology and found that high-purity CO_2 with 99.9 % could be obtained after cooling the system to 30 °C with the separation of nitrogen, oxygen and traces of methane. The separation with membranes technology is usually conducted under pressures ranging from 7 to 20 bars and its requirement of energy is ranging from 0.18 to 0.33 kWh/Nm^3 of used biogas. In the study of Baena-Moreno et al. (Baena-Moreno et al., 2020) losses of CH_4 were reported at 2 % at levels of laboratory-scale. In addition, it was reported that the process of pretreatment of biogas is of great importance due to membrane protection and for ensuring great purity of CH_4.

The cryogenic technology (Fig. 7(d)) is based on low temperatures and high pressure conditions for CO_2 condensing while due to the difference of points of boiling CH_4 remains in the gas phase. The process of CO_2 re-sublimation is carried out at a temperature of 78.5 °C and pressure of 1 bar and CO_2 in solid state could be separated from CH_4 by rectification process. Hence, this technology ensures obtaining high purity CH_4 and CO_2 with the value of 99 % by their volumes (Nguyen et al., 2021). The methane loss is more than 1 %. However, cryogenic technology is still developing and the market is not yet ready for it. Disadvantages include high requirements of energy for the compression

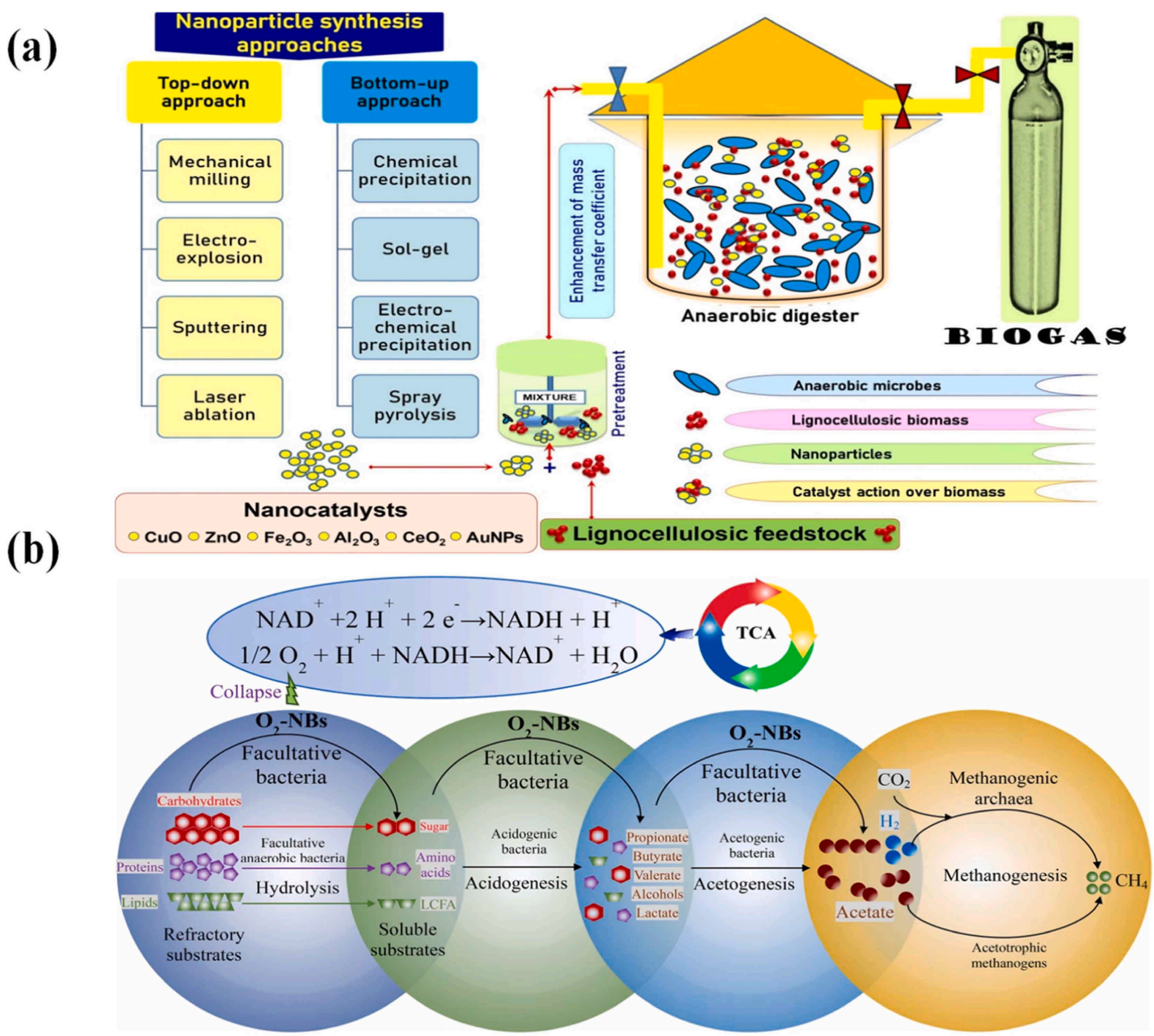

Fig. 8. (a) The mechanism of lignocellulose biomass transformation into biogas mediated by nanocatalyst (Govarthanan et al., 2022) and (b) Nanobubble technology for biogas production by anaerobic digestion (Wang et al., 2021).

and refrigeration of the biogas which is raw and ensuring that frozen carbon dioxide does not lead to equipment clogging in the process of gas refrigeration. The consumption of energy is around 10 % of produced CH_4. Nevertheless, some options for enhancing cryogenic technology are still possible. The utilized energy for condensing of biogas could be recovered by the liquefaction process of produced bioCH_4 and frozen carbon dioxide could be used as a dry ice in selected industries (Esposito et al., 2019).

A lot of the latest studies are directed towards the introduction of nanotechnology for the improvement of the production process of biogas. Fig. 8(a) gives the pathways of lignocellulose biomass conversion into biogas mediated by nanocatalyst. Utilization of NPs is found to decrease contaminants in biogas production and to enhance its production process. In addition, nanoparticles are found effective for decreasing the levels of COD, CO_2 and H_2S removed from the biogas (François et al., 2023a). In the research of Francois et al. (François et al., 2023b) was found that the usage of nanoparticles (NPs) is influenced by the mass and selected feedstock for biogas production, feedstocks biodegradability, pH and variety of used NPs. In another study was reported that carbon-based nanomaterials (CNMs) could be prepared by utilizing different biowastes for enhanced production of biogas. It was found that they had good performance, CH_4 yield as well as good chemical oxygen demand uptake in the anaerobic digestion process (François et al., 2023c).

Another technology called Nanobubble (NB) technology (Fig. 8(b)) has been also explored for upgrading biogas. The nanobubbles are bubbles which have a shape that is spherical and diameter from 50 to 200 nm. These NBs are improving the solubility of the gas with a great charge of surface and a long time of residence. Furthermore, NBs could improve enzymatic activity by promoting the mobility of water, thus acting as carriers marked as Coenzyme F_{420} (Chuenchart et al., 2021). Regarding their mechanism, NBs usage in H_2-NB based systems is quite intriguing. Hence, upgrading of biogas by this technology has been extensively studied in recent years (Wang et al., 2021). In the study of Wang et al. (Wang et al., 2019) was investigated this technology and it was found that NBs have improved methane yield from 14 to 21 % and content of methane was increased by 5 % in comparison to the control used reactor (55 %).

3.4. Biochemical technologies

The biochemical technologies for enhancement of biogas production process include fungal, microorganism and enzymatic pre-treatment. These technologies are greener, eco-friendlier and suitable to foster the performance process. For the enhanced biogas feedstock process of enzymatic hydrolysis during the anaerobic digestion process, it is of great importance to advance the process of microbial growth on utilized biomass which could be done by biochemical technologies. Various enzymes such as xylanases, proteases, cellulases and ligninolytic enzymes have been utilized for the conversion of feedstocks in an anaerobic digestion process into digestible sugars and to improve production of biogas rate under selected operational parameters to avoid inhibitory compounds formation (Fig. 9). In general for the treatment of lignocellulose biomass other technologies must be used before enzymatic liquefaction for getting enhanced production rate of sugars and yield (Deshavath et al., 2021).

There are commercially accessible enzymes utilized in the substrate hydrolysis process which could be further utilized by microorganisms for biogas production and their growth. In the study of Tyagi et al. (Tyagi et al., 2018) was found that prepared manure compost when mixed with the organic fraction of municipal solid biowaste from industry could improve the reduction of organic dissolved carbon with 61 % and volatile solids (VS) by 35 % compared to a control sample, thus enhancing the production of methane yield and increasing the yield of produced biogas by 60 %. In a study by Liew et al. (Liew et al., 2020) was found that selected enzymes have greatly improved biogas

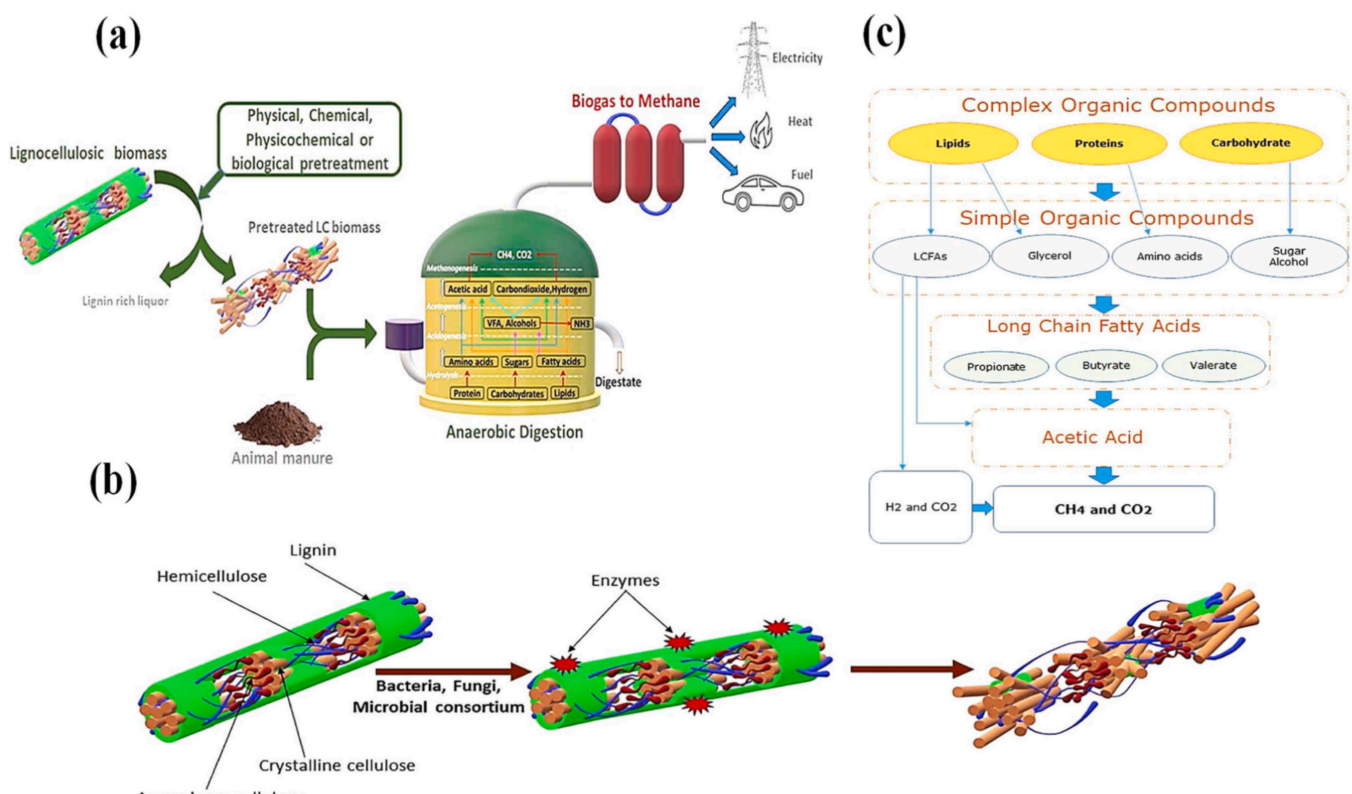

Fig. 9. (a) Production of biogas from lignocellulose biomass by anaerobic digestion process (Abraham et al., 2020), (b) Biological pretreatment process of lignocellulosic biomass (Abraham et al., 2020) and (c) Organic matter pathways for anaerobic degradation (Rasapoor et al., 2020).

production up to 76 %. In the process of enzymatic technology bio-wastes containing various fats and oils usually are utilized bio-surfactants as additives for the stimulation of enzyme activity by leading to increased solubility as well as bioavailability of these compounds of utilized feedstock (Vijayakumar et al., 2022).

The biological fungal pretreatment which could be aerobic of anaerobic is one of the most widely utilized and effective techniques that use types of wood-rotting fungi (*Fusarium*, *Trametes and Phanerochaete*), especially white-rot fungi, for the process of lignocellulose biomass delignification (Fig. 10) at decreased temperatures (Kainthola et al., 2021). These fungi are helping in the degradation process of cellulose, hemicellulose and lignin at equal rates. When the process ends, simple sugars fraction is made and the enzymatic digestibility of utilized lignocellulose feedstocks is improved. During fungal pretreatment degradation effectiveness of lignin is dependent on lininolytic enzymes which are secreted by basidiomycetes like laccase, manganese and lignin peroxidase (Zhao et al., 2019). Even though this process has many advantages, the disadvantages of utilization of white-rot fungi are a long pretreatment period of incubation and significant loss of holocellulose.

Hence for obtaining biomass which is delignified and rich in cellulose a greatly selective type of white-rot fungi is favoured for accelerated production of biogas. Furthermore, parameters for cultivation that influence the performance should be optimized as well (Nurika et al., 2018). The study of Kainthola et al. (Kainthola et al., 2019) found an improved generation of biogas as well as higher methane yield by using fungal pretreatment. Furthermore, in comparison to biomass which was untreated to fungal-treated rice straw increase in methane yield was 1.65 times higher. Albornoz et al. (Albornoz et al., 2018) used the same fungus and biogas yield was enhanced by 25 % by using wheat straw as a feedstock and an incubation time of 15 days. However, the application

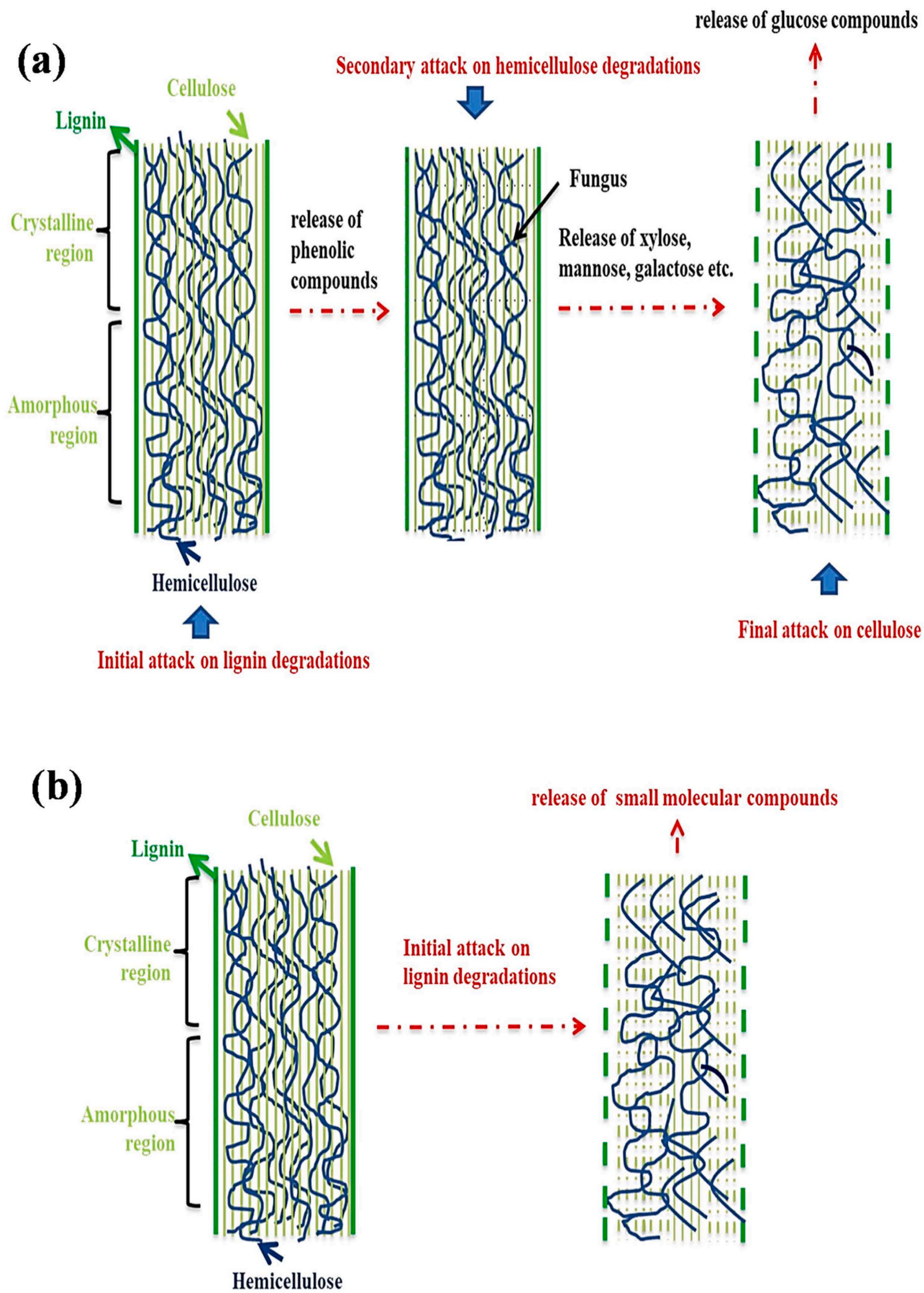

Fig. 10. Substrate degradation pathways of fungi; (a) Selective process and (b) Non- selective process (Kainthola et al., 2021).

of this kind of treatment is of high cost and compared to the general pre-treatment methods from 4 to 15 times higher. In addition, the process of fungal pretreatment still needs to improve its efficiency and this could be performed by optimising the content of moisture and by cultivation media supplementation with selected nutrient elements (Mishra et al., 2021).

Utilization of a specialized microbial consortium (mixture of more strains) has been found to effectively degrade lignocellulose compared to the usage of separate strains (Ali et al., 2024). In comparison with the different fungi whose main target is lignin, pre-treatment with microbial consortium leads to the degradation of cellulose- and hemicellulose (Zhou et al., 2024). The major advantage of this process is the metabolic diversity of microbial consortiums that causes higher adaptability and rate growth, higher consumption yield of substrate and rate, more effective pH control during the process of sugar assimilation and enhanced effectiveness of subsequent enzymatic process of saccharification (Tabatabaei et al., 2020). Hence, Hua et al. (Hua et al., 2022) prepared a micro-aerobic synthetic microbial consortium composed of *Methanosarcina acetivorans* C2A and *Methanosaeta thermophila* NBRC 101360 for anaerobic digestion of cattle manure. It was found that by using these synthetic microbial consortiums at accelerating levels of recovery from decreased inhibition of pH value; biogas production was increased by 44.78 %. Furthermore, the study of Tukanghan (Tukanghan et al., 2021) found enhancement production of biogas and oil palm empty fruit bunches efficiency of degradation by using a consortium consisting of *Bacteroides* and *Clostridium*-rich methanogens. Production of methane increased by 67.2 % and the degradation efficiency of empty fruit bunches by 57.5 %.

3.5. *Green upgrading technologies for biogas production*

Another upgrading biogas technology is bioconversion of carbon dioxide into methane which is done by utilization of hydrogenotrophic methanogens (Fig. 11(b)). Hence, in the process of CO_2 bioconversion by H_2-based chemoautotrophic, CO_2 is sequestrate by its conversion into CH_4 via the usage of hydrogen that is produced from the process of water electrolysis, thus making a new technology which is marked as P2G (Power to gas) (Zabranska and Pokorna, 2018). The used energy for the production of hydrogen via mentioned process is mostly obtained from the energy which is surplus from RES, such as solar and wind. The bioCH_4 which is converted from the reduction of CO_2 would lead to increased content of methane in the final obtained biogas. This process leads to upgraded biogas which is used as a fuel for transportation. Therefore, storage of electricity in the CH_4 could lead to simple storage of energy and its distribution. In this process three types of methanogens could be used; hydrogenotrophic, acetotrophic methanogens and homoacetogens (Wu et al., 2021).

Which methanogens could be used depends on the substrates that are utilized for their metabolism process. Furthermore, following the system configurations in which hydrogen assists the biomethanation of CO_2, the

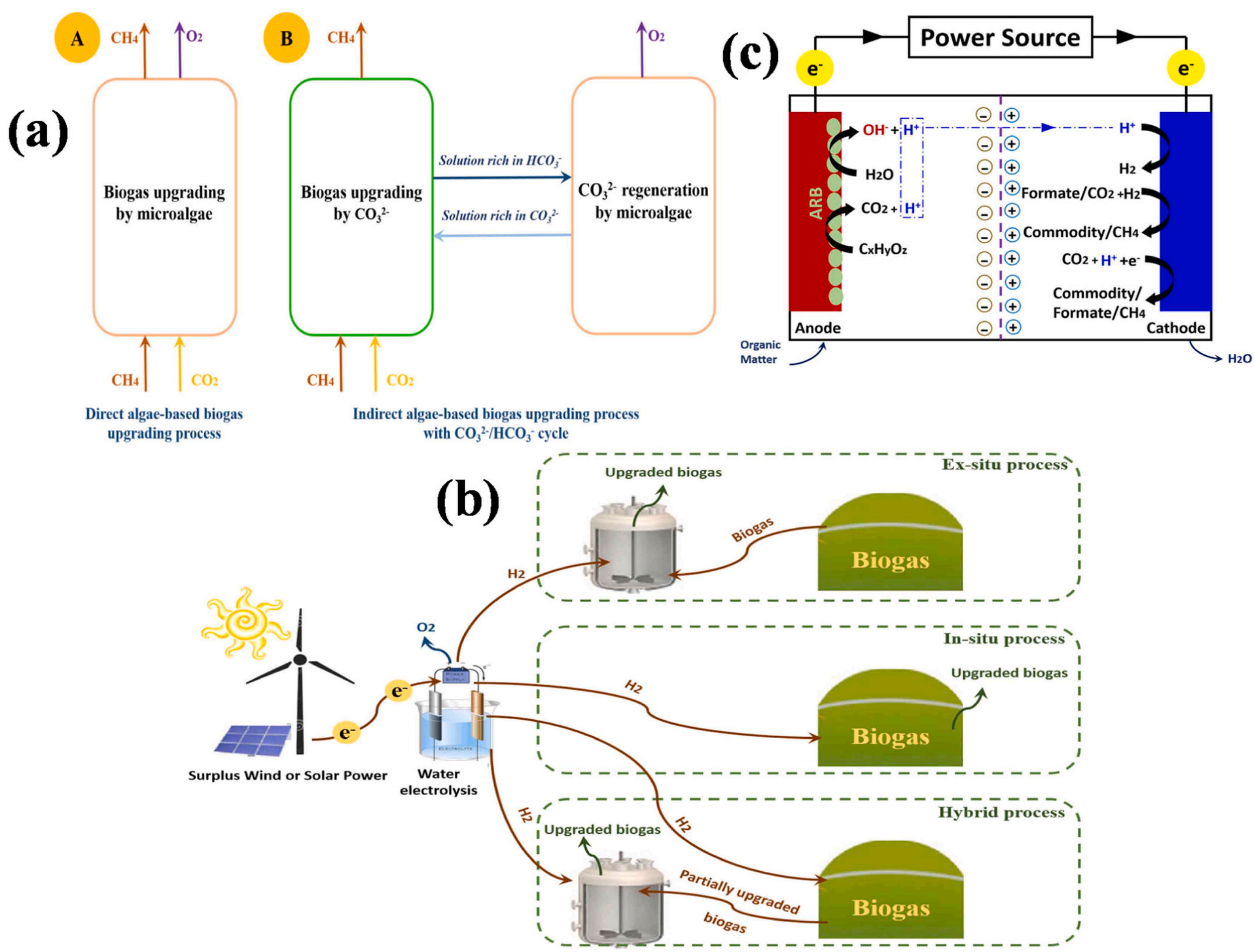

Fig. 11. Biogas upgrading technologies; (a) Utilization of microalgae, (b) Different designs of H_2-based upgrading biogas processes and (c) Microbial electrolysis cell technology (Wu et al., 2021).

upgrading systems for biogas could be divided into the following types; in- and ex-situ and designed hybrid systems which are given in Fig. 11(b) (Wu et al., 2021). In-situ systems for biogas H_2 technology upgrading consist of an anaerobic digester and system for the electrolysis of water for H_2 formation. In this process, H_2 is introduced into AD system and coupled with carbon dioxide which is indigenous and obtained from AD, which is further converted to methane by methanogens. Ex-situ systems have AD unit for the production of biogas which is raw and a second unit of the reactor that is anaerobic for the removal of CO_2 by the biological reaction of hydrogen obtained from the electrolysis of water. In the study of Rafrafi et al. (Rafrafi et al., 2021) CH_4 yield by ex-situ H_2 technology upgrading was found to a value >97 % for a sludge used as a feedstock for biogas production. The hybrid process for biogas upgrading utilizes biomitigation of carbon dioxide to methane in AD system and the process of biomethanation of CO_2 conducted in a reactor which is separate together (Zabranska and Pokorna, 2018).

The microbial electrolysis cell (MEC) for the upgrading of biogas is a sustainable and effective technology with a low requirement of energy (Gao et al., 2021). In this process, H_2 is formed by MEC that is a bioelectrochemical system and CO_2 is converted into CH_4. The bacteria which are anode-respiring could transform organics from wastewater into electrical current and discharge H^+. The H^+ is subsequently transported to cathode and then into H_2 reduced. Thus, this obtained H_2 is then utilized for the CO_2 reduction into CH_4 through hydrogenotrophic methanogens. It also could be used to produce multi-carbon products by the utilization of microorganisms which are acetogenic (Fig. 11(c)) (Wu et al., 2021). In the study of Zeppilli et al. (Zeppilli et al., 2020) bioelectromethanogenesis reaction in a tubular MEC was used for the upgrading of biogas. Thus, it was found that the reaction of bioelectromethanogenesis leads to the uptake of 13.2 gCO_2/d.

The process of photosynthetic biofixation of CO_2 for biogas upgrading is carried out by microalgae. The microalgae could be used due to their high rates of growth, ability to consume nutrients from the various waters and capability for growth under different conditions. There are two proposed configurations (direct or indirect) of this technology shown in Fig. 11(a) (Wu et al., 2021). The CO_2 is fixated via microalgae by the process of photosynthesis. Namely, raw biogas is introduced into the reactor for the biogas photosynthetic system of upgrading. The photoautotrophic microorganisms are responsible for the removal of CO_2 while using as an energy source solar and producing its biomass by the consumption of nutrients (Angeles et al., 2020). The H_2S formed in this process is removed by bacteria in the reactor which are sulphur oxidising or by the reaction with O_2 which is unwanted and obtained from microalgae. In this process, CH_4 is upgraded to have maximum CO_2 content in the biogas ranging from 2 to 6 % (del Rosario Rodero et al., 2020). Overall, this process is a promising technology for commercial uses of the biogas upgrading process. Since it leads to the capture of carbon and its re-use, thus enhancing the sustainability of the biogas production process in a circular system of economy (Bose et al., 2019).

4. Technological challenges for biogas production

The raw biogas is produced from biomass feedstock via a process called anaerobic digestion (AD) which usually consists of four main phases. In this process, organic fractions of biowaste under anaerobic conditions are decomposed into simple molecules mixture containing methane (40–65 %), carbon dioxide (35–55 %), hydrogen sulphide (0.1–3 %), water and other organic volatile compounds (Angelidaki et al., 2018). The value of energy from biogas is 37.3 MJ/m^3 with a calorific value ranging from 5000 to 7500 $kcal/m^3$ (Mishra et al., 2021). Anaerobic digestion (AD) is a process which uses microorganisms in the atmosphere without oxygen that break down high molecular and complex organic components into low-molecular and simpler chemical components. Obtained gas in AD is called biogas and it contains components such as CH_4, CO_2, H_2S, NH_3 and other various gases which are being produced in the plant for anaerobic digestion. The AD process uses different sorts of bacteria (saprophytic bacteria, bactericides, clostridia, bifidobacteria, acidogenic and acetic bacteria) that continuously break down organic components and it comprises the four stages which are previously described (Hosseinzadeh et al., 2024). Microorganisms have a very significant role in the process of AD. Groups of bacteria are different in the hydrolysis phase, acidification and phase of methane production in AD (Wang et al., 2018). Fermentation of methane includes four biological and chemical phases that use mutually interacting groups of microorganisms. In general, AD is not a fast process, since microorganisms need almost a month to adapt to new environmental conditions whenever some of the factors change (substrate type, temperature or other environmental parameters). Microbial relations are very complex and when there is a lack of equilibrium among microorganisms consortia which are responsible for various phases in methane production, the rate of reactions will be affected, which could further lead to the accumulation of inhibitory substances (Koniuszewska et al., 2020).

4.1. *Influencing factors in biogas production*

As mentioned in the previous section, various types of bacteria are involved in the process of anaerobic digestion (AD) (Fig. 9). For the production of biogas from FW in the process that uses bacteria all significant parameters for an adequate environment need to reach equilibrium. Parameters such as volatile fatty acids, temperature, time of retention etc, should be monitored continuously and maintained within their optimum ranges in the process of AD (Zhang et al., 2023). The influence of temperature in the AD process is a significant parameter to monitor. Since temperature influences the production of methane, volatile acid-dependence microorganisms and as well as methanogenic microorganisms. Overall, bacterial fulfilment shows great dependency on temperature effects in AD. There are different temperatures at which AD process occurs and they are divided into the following types: thermophilic (50 and 65 °C), mesophilic (20 and 45 °C) and psychrophilic (10 and 20 °C). The disadvantages of the thermophilic stage are reflected in a greater amount of disproportion and a greater need for energy due to the associated high temperature (Nie et al., 2021).

Overall, bacterial fulfilment shows great dependency on temperature effects in AD. There are different temperatures at which AD process occurs and they are divided into the following types: thermophilic (50 and 65 °C), mesophilic (20 and 45 °C) and psychrophilic (10 and 20 °C). The disadvantages of the thermophilic stage are reflected in a greater amount of disproportion and a greater need for energy due to the associated high temperature (Nie et al., 2021). The use of heat for reactions accelerates the processes, which is also the case with the biogas production process. Thermophiles are microorganisms in AD that undertake mesophilic and thermophilic digestion processes. Thermophiles are effective in the range of 45–80 °C, while mesophilic bacteria are effective at temperatures 25–40 °C (Kabeyi and Olanrewaju, 2022). An optimal temperature of 35 °C is characteristic of mesophilic digestion and 55°C for thermophilic digestion. Improved rate of reaction, reduction of pathogens and less request for microorganism nutrients are all advantages of thermophilic digestion compared to mesophilic digestion. The temperature needs to be regularly monitored, mostly when a change in weather is expected. The temperature (mesophilic or thermophilic) is usually chosen following the variety of end-products (Sawyerr et al., 2019).

The value of pH is the most important parameter (Fig. 12) that not only influences the stability of an AD but also influences its performance. Microorganisms show a high sensitivity to pH, because, for each type of bacteria, the optimal pH range is different and necessary for their growth. For hydrolysis ideal value of pH is 6 and for acetogenesis and methanogenesis, 6–7 and 6.5–7.5, respectively (Leung and Wang, 2016). To ensure the enzymatic activity of enzyme, the required pH value for acid-forming bacteria is > 5.0 and 6.2 for methane-forming bacteria. Methanogenic bacteria showed better performance at pH values 6.8–7.2

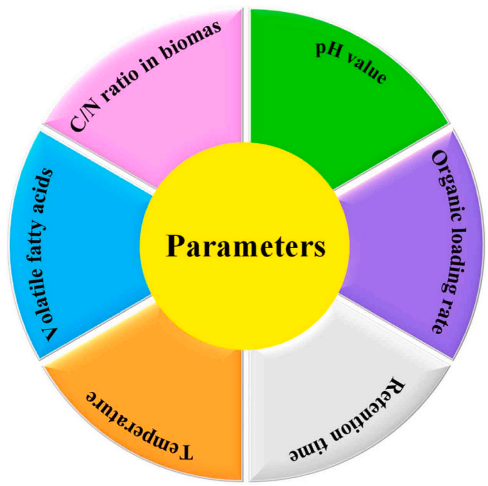

Fig. 12. Different process parameters that can effect anaerobic digestion of biomass.

and the production of CH_4 was established 75 % more efficient at pH> 5.0. It was found that during AD process, the amount of produced CO_2, VFA, bicarbonate concentration (HCO_3) and alkalinity influence the pH variations (Pramanik et al., 2019). pH is also a stability indicator of digestion. The limitation of the methanogenesis process is found to be a result of high pH values as well as some dysfunction of the system or low capacity of buffering could disrupt and stop the process of digestion at lower pH values. To maintain a pH value in the AD system, the relation between HCO_3 and VFA concentration is of great importance (Sawyerr et al., 2019).

Retention time is the time required to complete the degradation process of organics matter (OM) or the average time that OM remains in a digester (Zhang et al., 2023). A longer retention time is usually required (Leite et al., 2023) because it will contribute to better stabilization of the sludge and will provide better contact of the liquid flow and biomass in the treatment process (Sawyerr et al., 2019). In AD system two kinds of retention time are incorporated. The first retention time is called solid retention time (SRT), which is an average time that selected bacteria spend in the digester. The second retention time is called hydraulic retention time (HRT) and it is the average time that sludge in technical condition spends in the digester (Deepanraj et al., 2014). The bacterial rate of development which is linked to time of retention is under the influence of temperature, the composition of the substrate and the loading rate of organics (Zhang et al., 2023). It is usually needed for 10–40 days at mesophilic temperature for the treatment of waste from organics. On the other side, a shorter retention time is usually required at a thermophilic temperature (Bokhary et al., 2022).

The organic loading rate (Fig. 12) represents the quantity of organic solids (dry components), which is used in AD per day per unit volume of capacity of the digester. This parameter highly influences the yield of CH_4 (Zhang et al., 2023). The quantity of substrate referred to biomass used in the reactor unit system is marked as OLR (organic loading rate). It is usually expressed as chemical oxygen demand (COD) in kg/m^3, volatile (VS) of total solids (TS)/ L per day. The increase of OLR in solid waste AD leads to problems, such as insufficient consumption of H_2 and VFA by methanogens that are created by the acidogenic bacteria at the same rate. Growth of OLR and activity of acidogenic (CO_2, H_2 and VFA,) can lead to a decrease in pH value and production of gas, but also to the cumulation of organic acids (Sawyerr et al., 2019). The ratio of carbon and nitrogen (C/N) is a ratio among their quantity in FW. Yang et al. (2023) (Tang et al., 2023b) revealed that this ratio has a great effect on AD process stability. Carbon utilization is 30–35 times faster than nitrogen by microorganisms during the AD process and this could be the reason for the chosen C/N ratio in the substrate of 30–35:1 (Pramanik et al., 2019).

4.2. Operational parameters and reactor design strategies

Bioreactors to produce biogas should have appropriate operation parameters and conditions for utilized communities of microbes which are participating in the process of substrate conversion, with emphasis on methanogens. Since microbes could be inhibited in dependence of applied pH value, this parameter should be strongly monitored. In addition to pH, temperature also should be monitored since it effects the activity and conditions of living for microorganisms. Furthermore, efficient nutrients should be provided, because their deficit as well as the presence of some inhibitors could lead to effective reactor performance (Wu et al., 2021). There are several reactor configurations for anaerobic digester system which could be utilized in dependence on available biowaste and space such as fully stirred tank anaerobic reactor (FSTR), fixed bed reactor (FBR) and its varieties such as anaerobic packed bed reactor (APBR) and up-flow anaerobic filter (UAFR), anaerobic fluidized bed reactor (AFBR) up-flow anaerobic sludge blanket reactor (UASB), expanded granular sludge bed (EGSB), anaerobic membrane bioreactor (AnMBR), anaerobic structured bed reactor (ASTBR), horizontal anaerobic immobilized biomass (HAIB) and hybrid anaerobic reactor (HAR) (Kiani et al., 2022).

The biogas performance depends on various biological, physical and chemical parameters, such as the type of used feedstock, the technology of pre-treatment and the diversity of used anaerobic microorganisms (Kumar et al., 2021). The plants for anaerobic digestion could be categorized as micro-, small-, medium- and large-scale anaerobic digestion systems with the following combined heat and power (CHP) electrical output; < 15, between > 15 and <99, between > 100 and < 299 and > 300 kWe. The small-scale AD systems (SSAD) vary in dependence on geographical position, utilized feedstock, weather conditions and general usage of the reactor. SSAD systems could be further categorized into high- and low-rate systems and passive systems (covered lagoon digester). Low-rate systems are systems in which utilized feedstock is held in a selected digester from 10 to 30 days to increase the obtained yield of biogas. These systems operate in mesophilic (from 25 to 40 °C) and thermophilic (from 50 to 65 °C) ranges of temperature and require utilization of additional heating to maintain selected temperature. The types of low-rate systems are given in Fig. 13. The garage-type AD digester utilizes a process of dry fermentation which usually lasts from 4 to 5 weeks by processing in a batch mode which is usually combined with the tank that contains percolation fluid. The feedstock is added or removed by the batch wise mode and the digester operates in a thermophilic or mesophilic range of temperature. Garage-type AD digester could be used for the stream of feedstock which contains a great amount of total solids (higher than 15 %) (Franca et al., 2022).

In plug-flow reactors (Fig. 13(b)) when new feedstock is being added into the reactor it pushes present biomaterial through the used digester like a "plug", thus the older biomaterial is driven out. In the research of Dong et al. (Dong et al., 2019) was found that plug flow reactors are very good for processing biowaste that contains a high content of total solids (TS>10 %) which decreases the time of start-up, volume of reactor and efficiency of the process. In comparison to a complete mix digester or continuously stirred tank reactor (CSTR) for AD, the plug-flow reactors could handle double more content of total solids and triple the organic loading rate at decreased hydraulic time of retention (Rossi et al., 2022). A complete mix digester (Fig. 13(c)) needs to have a supplementary heating and mixing system with the aim of reaching a microorganism active mass. In this reactor type production of biogas is supported by adjusting the volume of entering into the digester to sustain retention time from 20 to 30 days. The varieties of biowastes could be treated in this type of reactor with TS in the range from 3 to 10 %. The enhancement of CSTR system includes the utilization of two-phase configuration in which used feedstocks are broken down by usage of fermenting bacteria in the phase one with methanogens further in phase two by

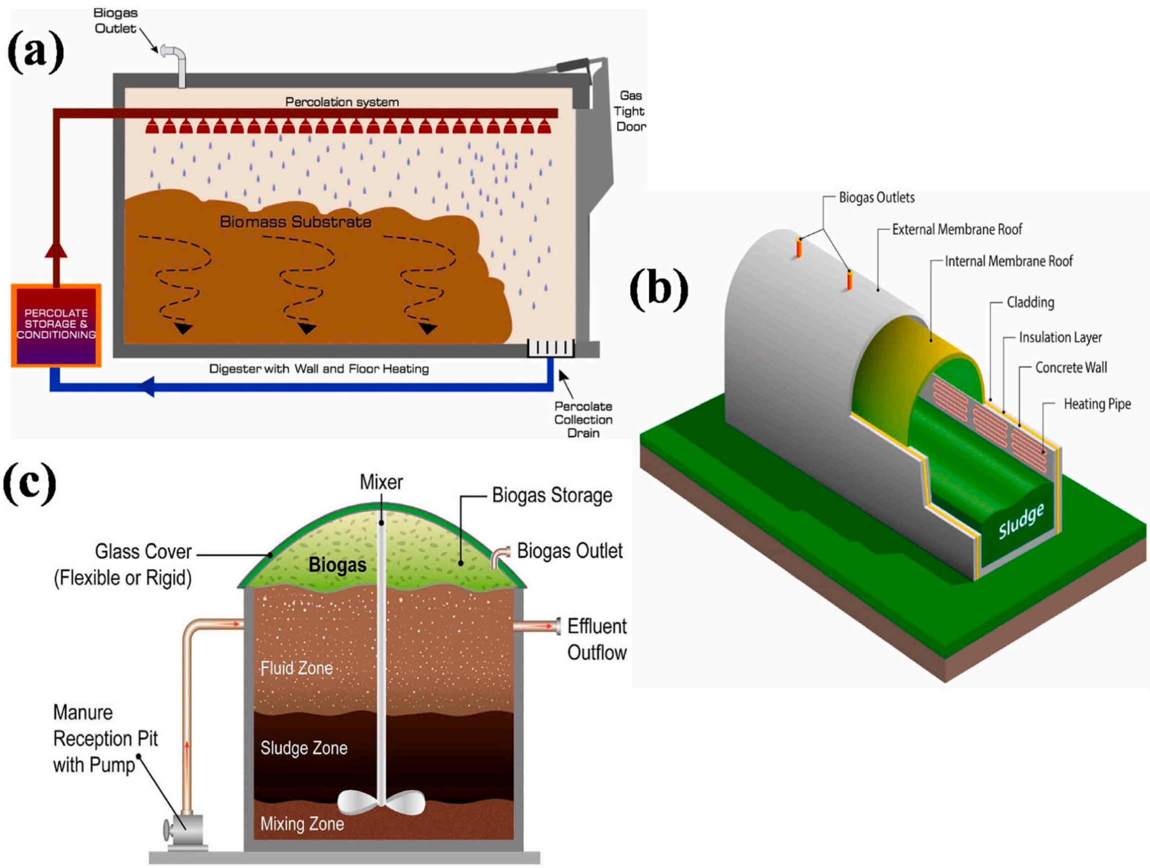

Fig. 13. Different low rate systems for biogas reactors; (a) Garage-type, (b) Plug-flow and (c) Complete mix reactors (O'Connor et al., 2021).

transforming organic acids (OA) to biogas (Calise et al., 2023). Yadav et al. (Yadav and Vivekanand, 2021) used CSTR system for biogas and the influence of combined fungal and bacterial pretreatment of wheat and pearl millet straw for biogas production is studied. It was determined that without bacteria biogas yield increased by 31 % and 46 % for pretreated wheat straw and pearl millet straw. On the other side with the bacteria presence obtained biogas yield was 41 and 57 % for wheat and pearl millet straw.

High rate systems are systems in which solids are kept longer time in digesters and in which low energy fraction of the liquid of biowaste is kept in the reactor for a shorter time. Hence, concentrations of microorganisms are higher and there is a reduced time of retention (less than 10 days) (O'Connor et al., 2021). The types of high-rate systems are fixed-film digesters (Ahmed et al., 2021) and induced bedded reactors.

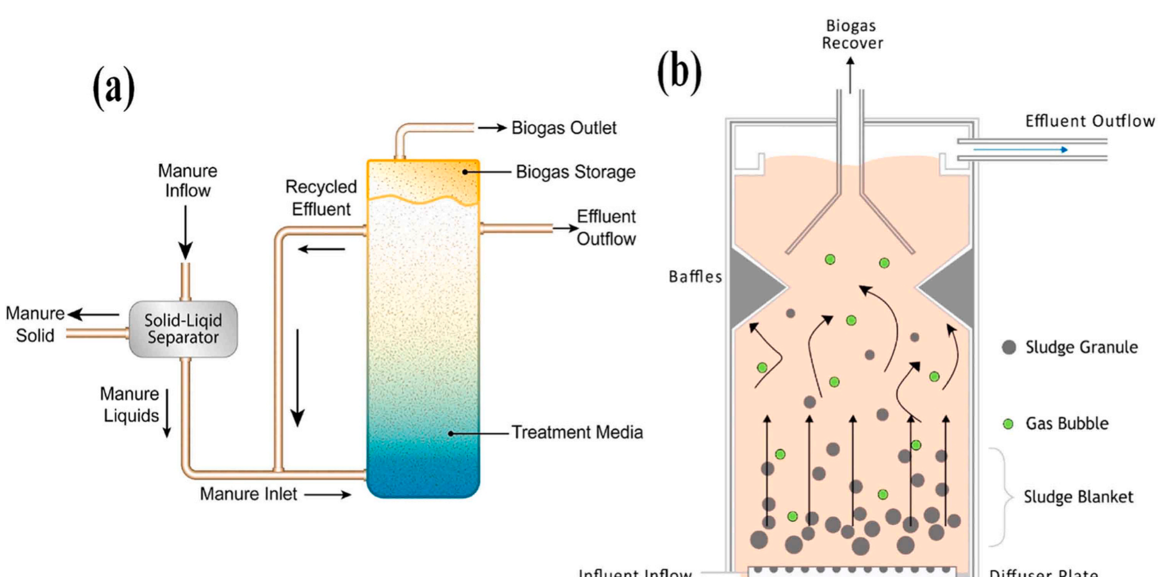

Fig. 14. Different high rate systems for biogas reactors; (a) Fixed-film digester and (b) Induced bedded reactor (O'Connor et al., 2021).

The fixed film digester has in its structure a bioreactive medium reactor. Thus increasing the surface area for the growth and propagation of microbes (Fig. 14(a)). Since there is a great biomass of microbes in the reactor unit hydraulic retention time is decreased and ranges from 2 to 6 days. Induced bedded reactor Fig. 14(b) utilizes constant liquid upward flow with the aim to suspend utilized microbes which results in smaller particles. These particles are then washed out while larger particles remain retained in the digester. The increased volume of used methanogens in the reactor is a result of microbes which have formed biofilms around the greater particles. The two most used induced bedded reactors are up-flow anaerobic sludge blanket and digester with induced media. The up-flow anaerobic sludge blanket is suitable for the diluted streams of waste with a total solid content of less than 3 % and digesters with induced media are more effective with a higher content of total solids (ranging from 6 to 12 %) (Wikandari and Taherzadeh, 2019).

5. Biogas applications, perspectives and opportunities

Biogas and methane as major components occur naturally and have a significant harmful part in scenarios of global warming. Methane was utilised as a source of fossil fuel and was transferred into energy production, for transportation and heating (Liang et al., 2022). Most of the consumption and use of methane comes from natural gas sources. Biomethane production approaches from waste recovery have grown significantly and therefore developed countries are using advanced biogas production facilities. In addition, several industrial applications are being advanced for biomethane use in plants for biogas as a substitute for natural gas, since biogas is regularly used to produce electricity and heat. The generation of energy required for social or industrial sectors offers different ways of using biogas technology as shown in Fig. 15 (Abanades et al., 2021). The most promising renewable energy resource is biogas produced from organic waste. CO_2 and CH_4 are the main biogas components, which when released from landfills or farms contribute to the greenhouse effect.

Therefore, it is of great importance that the production of biogas is under conditions which can be controlled and that it could be used for the generation of electricity and as well for thermal energy (Koniuszewska et al., 2020). Substances that are used for the production of biogas are sugar cane, forest residues, grass, wheat straw, corn stalks, energy cane, residues from livestock etc. In the EU about 70 % of biogas plants are utilising the substrates from agriculture sectors (Kasinath et al., 2021). Biogas plant capacity on a global level at the end of 2019 was approximately 19.5 GW. The capacity growth is being fuelled by among others, low-cost and easy availability of feedstock originating from biomass, high costs of fossil fuel and concerns over global warming. Biogas production by anaerobic digestion significantly enables the conservation of natural sources and the protection of the environment and improves the energy status of countries (Abanades et al., 2021).

Fig. 16(a) gives feedstock shares for biomethane production in Europe countries. In Europe, bioCH_4 is mainly produced from organic residues and biowaste and this type of biogas complies with EU RED II quotas for renewable fuel. On the other side, biogas production in Germany is mainly led by energy crops as feedstocks in the last ten years. As a result, of these policies, corn and grains from cereals are only used with 40 % in the production of biogas. Furthermore, France is not using any more energy crops for the production of biogas and they are more oriented on using feedstocks such as livestock manure (IAE, 2023). In Germany, France and Italy biogas is used mostly for combined heat and power (CHP) purposes as given in Fig. 16(b). In Denmark, the majority of produced biogas (80 %) is used for residential needs. In Spain, biogas has more usage in various sections and in Sweden biogas is mostly used in the industry sector and for transport (around 30 %) ((IAE, 2023).

5.1. Renewable natural gas for domestic and industrial heating

Biogas is a highly desirable substitute for natural gas as a source for the production of power. Raw biogas could be directly and indirectly used for different purposes as given in Fig. 17. Biogas's direct application is for lighting and cooking, but when biogas is treated chemically, physically or biologically for the improvement of its quality/future then it is used indirectly for various systems (Kapoor et al., 2020b). Combustion of biogas by direct approach is cheap, well established and generally the most utilized method that requires technology which is in general simple for maintenance. This type of biogas use doesn't demand H_2S removal and a high percentage of moisture. Additionally, it has been utilized for a very long period across the whole world, with emphasis on areas which are rural evolving countries. The flame of biogas while burning is blue and clean and emits fewer pollutants (Kapoor et al., 2020a). Physical methods for biogas treatment like upgrading and cleaning are common to improve its future. The conversion of gas components into other forms by chemical treatment is another approach for the enhancement of biogas quality. The third approach is biological

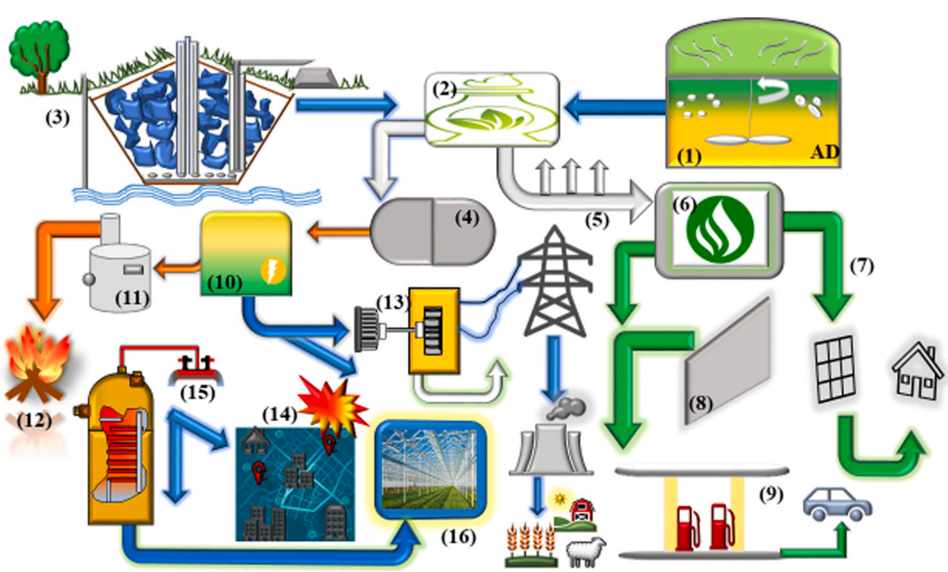

Fig. 15. Various implementations and utilizations of green biogas technology; (1) AD - Anaerobic digester, (2) Crude biogas, (3) Sanitary landfills, (4) Scrubber, (5) Improvements, (6) Natural gas, (7) Implementation to grid, (8) Compressor, (9) Gas station, (10) Biogas, (11) Burner, (12) Heat, (13) Turbine and generator (14) District heating, (15) Hot water and (16) Cogeneration.

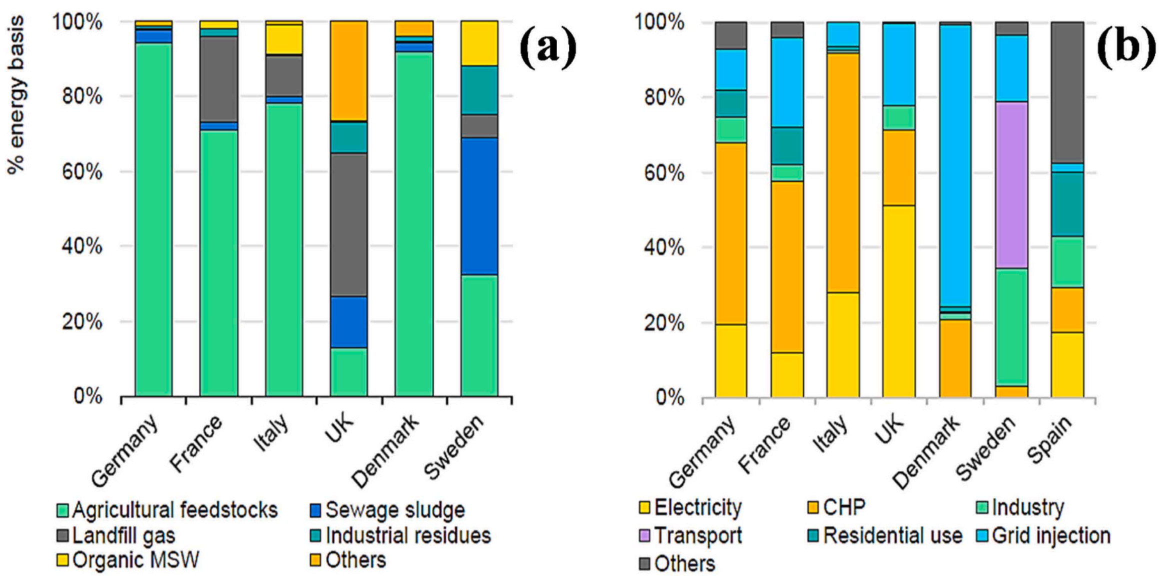

Fig. 16. (a) Shares of feedstock for biogas and biomethane production in EU. (b) Final shares of end users for produced biogas in selected EU countries IAE) (IAE, 2023).

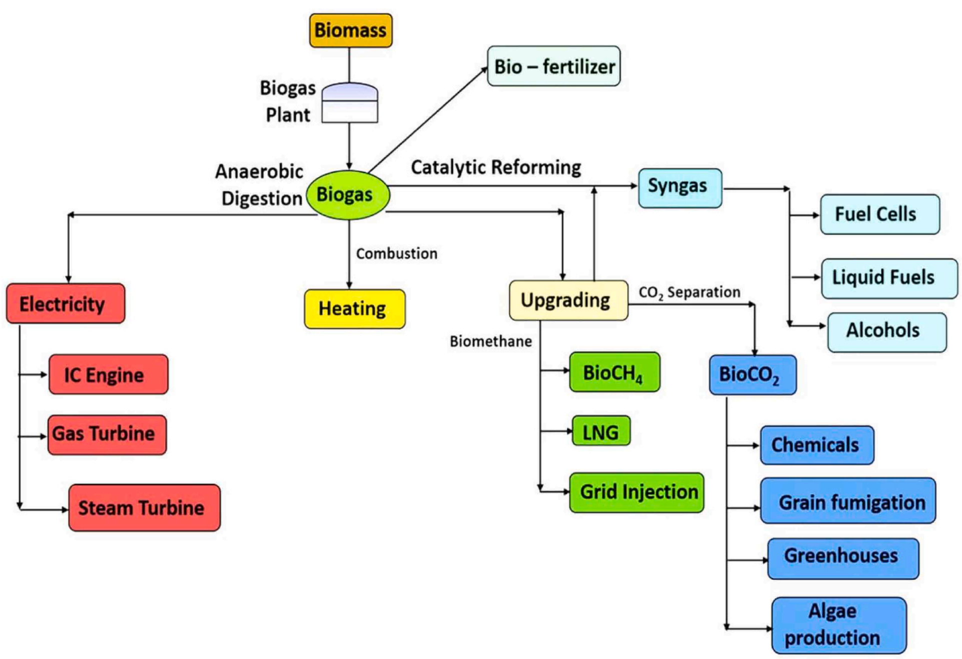

Fig. 17. Direct and indirect utilization pathways of biogas, bioCO_2 and bioCH_4 (Kapoor et al., 2020a).

which includes the conversion of biogas components by methanotrophic bacteria (Wang et al., 2022). Production of biogas is under the influence of many parameters such as time of retention, amount of nutrients, pH value of substrate, temperature and rate of loading which all could slow or delay the production of biogas (Sawyerr et al., 2019).

5.2. Biogas electricity generation

For decades, energy demand has been on the rise, resulting in the depletion of coal and gas reserves. Therefore, there is a need to find a cleaner and economically viable energy source. Biogas, a renewable and clean energy source, could be a possible solution to this issue. The production of biogas through anaerobic digestion could enable an efficient means of energy generation. Biogas is a mixture of CH_4 and CO_2 that could be used as a transportation fuel, or to generate electricity and heat (Osman et al., 2023). This energy could be utilized as fuel in households, systems of vehicle fuels and as a source of electricity. India's renewable electricity production by source has increased significantly since the early 1980s. Biogas has emerged as a popular alternative energy source to fossil fuels, alongside solar, wind, and hydropower. In 2019, biogas production accounted for approximately 45 TWh/year of electricity (Karne et al., 2023).

Some scientists investigated the possibility of generating green electricity from biogas produced by anaerobic digestion of agricultural livestock waste and residues in Iran. The study analysed various crops, such as wheat, rice, barley, corn, potatoes, apples, grapes, alfalfa, sugarcane, and sugar beet. The amount of agricultural waste produced is 24.3 million tons. This waste has the potential to produce 6542 million cubic meters of biogas, 2 million and 443 million litres of biobutanol and 2082 million cubic meters of biohydrogen. Livestock waste alone has a biogas potential of 11,523.84 million cubic meters per year (Heidari-Maleni et al., 2023). Rouhollahi et al. (Rouhollahi et al., 2020) conducted a study on farm biogas plants in Iran. The study aimed to determine the economic feasibility of establishing a biogas plant in a country where natural gas and cheap electricity are widely available. The results indicated that biogas production is generally economically feasible in Iran.

5.3. Biogas transportation fuels

Biogas produced from AD has a wide range of usages. It could be burned directly to enable thermal or electrical energy. To make it usable for other applications, such as transportation fuel and injection into the natural gas system, biogas could be enhanced. The grade of natural gas contains CH_4 and CO_2 in equal or greater parts (Manikandan et al., 2023). The global energy demand is increasing due to population growth. Fossil fuels are finite and have the potential to harm the environment in numerous ways. Biogas is a clean and economically viable solution to the current fuel problems (Archana et al., 2024). The use of biomethane in transportation is a crucial component of decarbonization efforts. Its environmental and economic performance should be compared to that of conventional solutions in various transport sectors, such as public transportation, trucks and shipping. Research studies indicate that by 2030, road transport is expected to consume a significant portion of the projected EU bioCH_4 production. In the long term, maritime applications are expected to gain momentum (Noussan et al., 2024).

5.4. Biogas for fuel cells

Fossil fuels are the primary global energy source, accounting for around 85 % of the world's energy supply. However, due to the rapid growth of emissions and depletion of existing fossil fuel resources, a rapid transition to alternative fuels is required. For this reason, the development of more efficient and cleaner energy systems is essential to satisfy demand while preserving the environment (Abouemara et al., 2024; Nouri et al., 2024). In addition to renewable sources like wind, solar, geothermal, and hydropower, researchers are also exploring the use of biogas fuel produced from biomass through anaerobic fermentation or conversion as an alternative power source. The continuous biomaterial availability from various sources such as landfills, water waste treatments, and agricultural biowaste could ensure reliable substrates of biogas for power generation (Aznam et al., 2023).

Among the different energy systems, biogas production is a beneficial process for generating eco-friendly hydrogen gas and reducing the use of natural gas (Awad et al., 2024). Fuel cells (FCs) highlighted in Fig. 18 are devices that enable the direct chemical conversion of fuels into electricity. Fuel cells represent an electrochemical apparatus with an electrical efficiency of 30–70 % and decreased emissions. The electricity and heat are generated without the process of combustion or environmental pollution by using the H_2 which is from fuel and O_2 which is from air. They are comprised of an electrolyte, cathode and anode. H_2 gas is being oxidized on the electrode (anode) by catalysis thus ensuring the electrons flow from cathode to anode through the solution of electrolyte and thus electricity producing. The ions of H_2 are then reacting with the oxygen at the other electrode (cathode) and produce water (Fig. 18). The operation of fuel cells (FCs) coupled with biogas produced by the process of gasification or anaerobic digestion is a topic of great significance due to the good compatibility between the two systems. Among the different fuels that could be used to power these devices, this combination is particularly noteworthy. Integrated biogas fuel cell systems could maximize the production of clean energy from low calorific value gas generated from biomass and/or waste (Tamburrano et al., 2024).

5.5. Biogas for sustainable chemical manufacturing

After several decades of research and industrial action, there is now a general consensus that converting waste to energy is a promising waste management option (Rafiee et al., 2021). Biogas is an economical and renewable biofuel. The composition of the mixture is mainly made up of primary and secondary gases. The primary gases consist of methane (CH_4) (50–60 %) and carbon dioxide (CO_2) (40–50 %). The secondary gases consist of trace gases, such as hydrogen (H_2), hydrogen sulphide (H_2S), water vapour (H_2O) and siloxane, which make up only 2–3 % of the total gases (Singh et al., 2023). The emissions from biogas (CH_4 and CO_2) were previously considered waste but now they are recognized as renewable sources. The biogas industry has two main business strategies: direct transformation into calorific energy and renewable fuel generation. The transformation of biogas into valuable chemicals such as acetic acid, methanol, olefins and ammonia is a promising method for reducing greenhouse gas emissions.

The upgrading of biogas through chemical transformation is an area that has not been fully explored. This field offers numerous possibilities

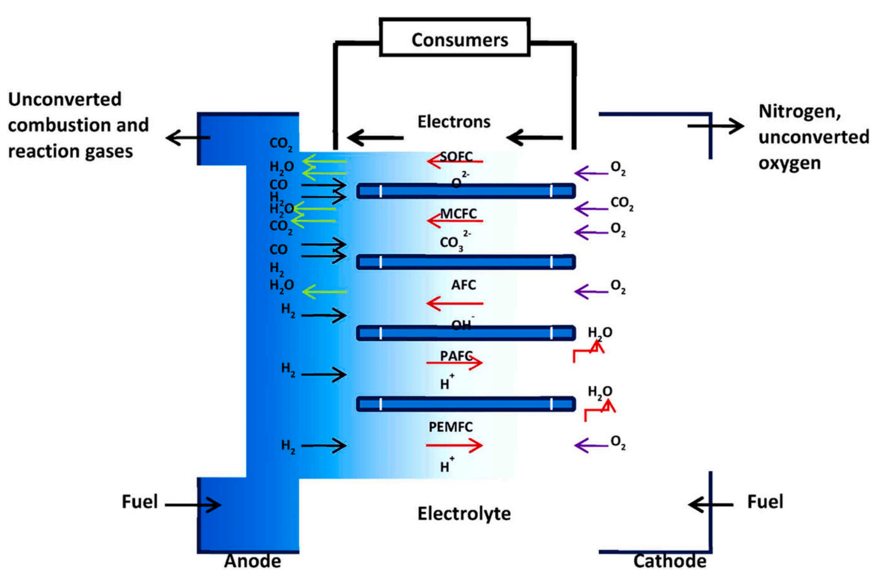

Fig. 18. Fuel cell's working mechanism (Kapoor et al., 2020b).

for the chemical industry to address greenhouse gas emissions. Acetic acid (AA) is a valuable intermediate product that can be generated from biogas and later transformed into other valuable products (Martín-Espejo et al., 2022). Additionally, hydrogen (H_2) could be produced from biogas through the BSR (biogas steam reforming) process (Abanades et al., 2021). With that, biogas could be used as either the pyrolysis medium to modify pyrolysis products or as a renewable source of value-added chemicals. When used as a pyrolysis medium, the quality and quantity of pyrolysis products can be modified by the synergistic effects of CH_4, which has a reductive nature, and CO_2, which has an oxidative nature, on the pyrolysis process. Different chemicals, such as acetic acid, ethylene, and methanol could also be produced from a mixture containing CH_4 and CO_2 via processes of catalysis or plasma-catalysis (Lee et al., 2022).

6. Current scenario and future perspectives

The global combined production of biogas and biomethane has reached more than 1.6 EJ in 2022 which represents an increase of 17 % from 2017. Almost 50 % of the biogas production is settled in Europe, with Germany producing about 20 % of all global consumers, then China with 21 %, USA with 12 % and India with 9 %. Fig. 19 represents biomethane historical, forecast and targeted production for EU countries (Fig. 19(a)) and for China, US and India (Fig. 19(b)). According to REPowerEU, the EU has set a target which is nonbinding for 34 billion cubic meters (bcm) production of bioCH_4 by 2030. The same target for China is 20 bcm until 2030 for biomethane production (Fig. 19(b)). In 2023 Denmark has achieved 37.9 % progress in bioCH_4 production compared to other countries such as Spain and Belgium which are still at the stage of development.

The technology of biogas has various environmental advantages and could help exceed environmental issues and enable the treatment and reuse of different biowaste varieties such as food waste, municipal solid waste and industrial and livestock waste. For example, anaerobic digestion enables very low costs of used feedstocks and the highest GHG preservation (Archana et al., 2024). Additional research is greatly needed to increase the electrical efficiency and minimum limits of methane concentration in biogas utilized as a fuel in piston engines. The lifetime of fuel cells and the cost of produced energy require improvements in competence with engines having internal combustion using biogas as fuel (Kapoor et al., 2020b). Using waste from food and other organics biowaste for AD ensures the preferences for nitrogen and phosphorus, which could be specifically useful in agriculture for organics and could restrict the utilization of fertilizers (inorganic). Production of biogas is performed mainly in medium or large-scale plants for wastewater and biogas plants on farms or waste. On the other side, in more developed countries small digesters are rather utilized on a domestic scale (Scarlat et al., 2018).

AD gives advantages to all parts of society and is especially utilized in rural areas by farmers. Farmers have a stable and open approach to waste from animals and residues from crops, which ensures substrates for the digesters for biogas production. In this process, digestate is utilized as a fertilizer (Kasinath et al., 2021). As a by-product of upgrading biogas plants, rich gas is produced. An area that needs more attention is the use of bioCO_2 in the process of grain fumigation and atmospherically modified packaging. For that reason, power to-gas concept is a prominent technology where the requirement of low-cost sources of power, for example, wind, solar etc. is a major challenge (Götz et al., 2016). In recent years, many researchers have focused their studies on methanol generation, as well as higher alcohols from biogas.

Furthermore, studies are focussing on the methods which could be applied for the utilization of biogas/biomethane in the process of syngas generation. This product is of great importance for the generation of H_2-rich resources for fuel cells or DME, urea, or some alcohol production (Yentekakis and Goula, 2017). Furthermore, there are great research opportunities that should be directed toward the catalytic treatment of

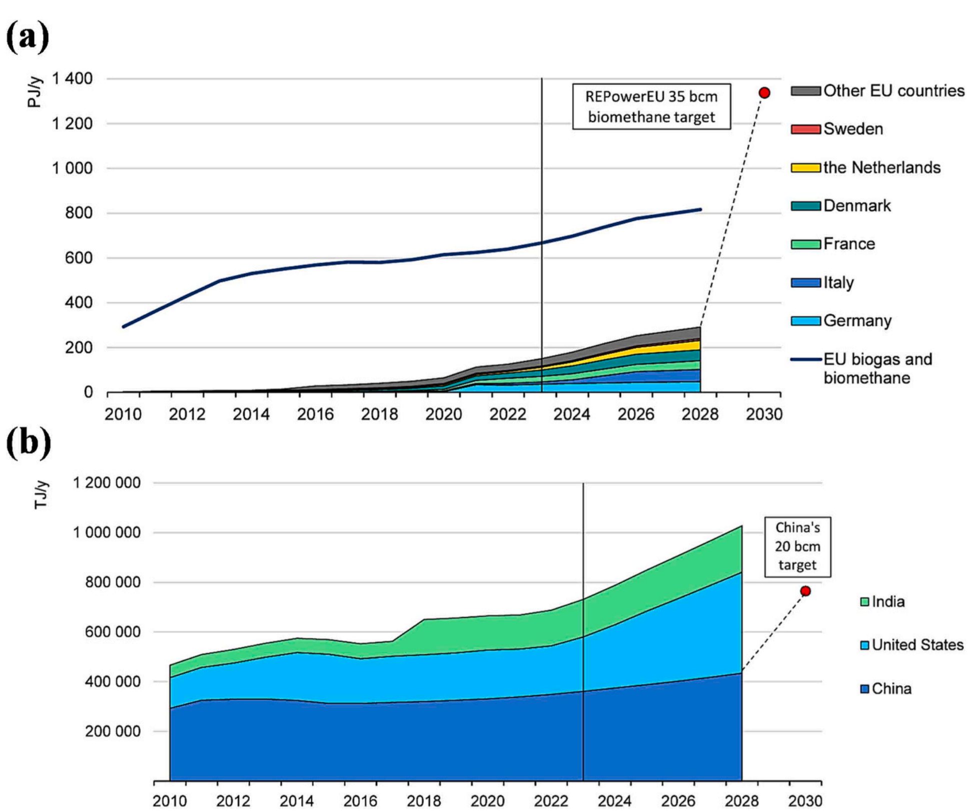

Fig. 19. (a) EU historical, forecast and targeted biomethane production and (b) China, US and India's historical and forecast production of biogases, and China's target ((IAE, 2023).

biogas to syngas and nanofibers from carbon. They are promising materials with various applications, such as solar cells, supercapacitors, transistors etc. (Ghosh et al., 2020). Methanotrophs and acetogens can produce liquid fuels from methane, but on the other side, there is very limited research about their industrial use, which is required for their widespread utilization (Kapoor et al., 2020a). Furthermore, industrial sectors for the production of biogas and biomethane could also provide wider advantages regarding the development of the countries.

The Biogas production sector in coordination with social and ecological point of view within the countries could provide many jobs for people in rural areas (Kasinath et al., 2021). There is great potential for the degradation of biomass in which H_2S, volatile organic compounds with sulphur, aromatics, ketones, amines and aldehydes could be obtained (Byliński et al., 2019). In addition, the formation of a significant amount of ammonia, with the decomposition of the proteins to amino acids causes the emission that could range from 18 to 150 g per ton of sludge (Kasinath et al., 2021). Overall, biodegradability, characterisation of FW, bacterial activities development, upgrading of CH_4 production, accessibility and balance of nutrients are expressed as the main challenges for effective biogas production (Wu et al., 2021).

7. Conclusion

Due to the crisis in global energy, there is a great effort made by many scientists worldwide to enhance technologies for biogas production, pretreatment and upgrading. It is of great importance on a global level to harness the potential of biogas production since it could help in greenhouse gas emissions mitigations and carbon storage. Hence, the current review has discussed selected emerging technologies for biogas production. The overview of its current usage and future perspectives on the global level has been presented as well. It was found that from all biogas production on the global level in 2022, 50 % is produced in Europe with Germany producing around 20 %, which is followed by China (21 %), USA (12 %) and India (9 %). In Germany around 90 % of produced biogas is from agricultural feedstock, as well as in France (≈ 70 %), Denmark (≈ 85 %) and Italy (≈ 80 %). In UK the main feedstock for biogas production is landfill gas with around 40 %. It was found that pretreatment technologies are enhancing methane yield in the range from 25 to 190 %. For example, pretreatment of swine manure by membrane-based extraction with ammonia has improved methane yield by 49 % and resulting yield was 566.1 ± 7.8 mL/gVS by using a continuous stirred tank reactor. Furthermore, there is an extensive number of novel green upgrading technologies which are sustainable and effective with low requirements of energy such as biofixation of CO_2 by microalgae, the introduction of microbial electrolysis cells and bioconversion of carbon dioxide into methane which is done by utilization of hydrogenotrophic methanogens. Hence, CH_4 yield by ex-situ H_2 technology upgrading was found with the value >97 % for a sludge used as a feedstock for biogas production. Future studies should focus more on the development of low-cost and sustainable technologies for effective biogas production since the majority of used techniques are still high-cost and non-eco-friendly.

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.

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