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Review

Resource Cycling: Application of Anaerobic Utilization Methods

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Abstract: Human activity and modern production contribute to the formation of a certain amount of waste that can be recycled to obtain useful products and energy sources. Today, the higher the level of industrial development, the greater the amount of waste generated, and as a result, the more important the need for disposal. A similar pattern is typical for any human production activity; as a result of large-scale production, at least 70–80% of waste is generated in relation to the amount of raw materials used. The large-scale use of polymeric materials and the plastic waste generated after their use lead to environmental pollution. While a small part of the waste is utilized naturally due to the vital activity of soil microorganisms, and a part is purposefully processed by humans into products for various purposes, a fairly large amount of waste occupies large areas in the form of a variety of garbage. After the removal of garbage by incineration, the liberated territories cannot be transferred to agricultural land due to the high content of harmful contaminants. The harm to the environment is quite obvious. In practice, certain types of waste consist of more than 70% content of valuable substances that can find further practical application in a wide variety of industries.

Keywords: anaerobic digestion; biogas; resource; recycling; waste

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1. Introduction

Currently, the situation in the field of waste management is fundamentally changing. There are a variety of methods for processing a number of wastes to obtain new useful products from them for use in various economic areas. For these purposes, the principles of biotechnological orientation are implemented.

Anaerobic digestion is a biological process in which organic matter is decomposed under anaerobic conditions into simple compounds. One of the products is methane, an environmentally friendly renewable energy source [1–6]. The condition for effective anaerobic fermentation is that the moisture content of the substrate is more than 90%.

The process of anaerobic digestion of organic materials includes four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [7,8]. The speed and efficiency of each stage depends on the formed consortium of microorganisms, which to some extent are in syntrophic relationships and occupy different ecological niches [9].

Hydrolysis: At the first stage of anaerobic fermentation of organic substances, high molecular weight insoluble compounds (polysaccharides, lipids, proteins, nucleic acids) are decomposed into low molecular weight soluble substances [10]. Hydrolysis is usually the limiting step in the anaerobic utilization of organic matter [11–15]. The microorganisms involved in the hydrolysis secrete hydrolytic enzymes, such as amylase, lipase, cellulase, cellobiase, xylonase and protease. Most bacteria are strict anaerobes, such as Bacteriocides, Clostrodia, and Bifidobacteria. Facultative anaerobes include Streptococci and Enterobacteriaceae [8].

Acidogenesis: At the second stage, with the participation of acid-forming bacteria, further decomposition of molecules occurs, leading to the formation of organic acids and alcohols. Volatile fatty acids are produced by obligate acid-producing bacteria such as Bacteroides succinogenes, Clostridium lochhadii, Clostridium cellobioporus, Ruminococcus flavefaciens, Rumminococcus albus, Butyrivibrio fibrisolvens, Clostridium thermocellum, Clostridium stercorarium, and Micromonospora bispora [16].

Acetogenesis: At the third stage of anaerobic degradation from organic acids and alcohols, mainly acetic acid, CO_2 and H_2, are formed. Typical bacteria in this stage are Acetobacterium woodii and Clostrodium aceticum. The process is controlled to a large extent by the partial pressure of H_2 in the mixture, as the accumulation of hydrogen inhibits acetogenesis [7,8].

Methanogenesis is the final bacterial transformation of organic matter into CO_2 and CH_4. Methane fermentation is carried out by two groups of bacteria; the first group converts acetate into methane and carbon dioxide, while the second group carries out redox processes using hydrogen as an electron donor and carbon dioxide as an acceptor, resulting in the formation of methane. The reactions proceed in parallel.

Heterotrophic methanogens decompose acetate to CH_4 and CO_2. These are representatives of the order Methanosarcinales. They make much higher demands on the conditions of their existence than acid-forming bacteria [8,17,18], as they need a strictly anaerobic environment and require a longer time for development. In general, the rate and extent of anaerobic fermentation depend on the metabolic activity of methane-forming bacteria.

Autotrophic methanogens use CO_2/H_2, CO/H_2O, or $HCOO^-/H^+$. These include representatives of the orders Methanobacteriales, Methanococcales, Methanomicrobiales, and Methanopyrales [18]. The process of methanogenesis is carried out under mesophilic and thermophilic conditions. Bacteria synthesizing methane under mesophilic conditions include representatives of the genii Methanomicrobiales, Methanobacteriales, Methanosarcinales, and Methanococcales [19,20]. Thermophilic methanogens include Methanobacterium thermoautotrophicum, and Methanothermus fervidus [21].

The products of anaerobic digestion of organic matter are biogas and digestate [4,22]. Biogas is used as a renewable energy source, while digestate is an unconventional organic fertilizer. The composition of biogas includes methane (55–75%), carbon dioxide (30–45%), hydrogen sulfide (1–2%), nitrogen (up to 1%), hydrogen (up to 1%), and trace amounts of oxygen and carbon monoxide [23–27]. The net calorific value is 21–25 MJ/m^3, which is equivalent to burning 0.6 L of gasoline, 0.85 L of ethanol, 1.75 kg of firewood, or generating 2 kWh of electricity. The methane number is 110–120 [7].

A wide range of different raw materials are suitable for anaerobic digestion. This process of biological conversion is based on microbial decomposition of organic matter in the absence of oxygen. Summing up the data on anaerobic digestion of organic substrates, it can be concluded that biogas is one of the most promising sources of bioenergy, as it is the product of a cheap and environmentally safe method of recycling various waste. Anaerobic digestion reduces greenhouse gas emissions, reduces household use of coal, oil, natural gas and wood, increases the safety of sewage (anaerobic digestion kills pathogenic microorganisms due to high temperatures and anaerobic regime), increases soil fertility through the use of unconventional fertilizers based on digestate, and reduces discomfort from unpleasant odors and flies.

2. Influence of Factors on Anaerobic Digestion of Organic Substrate

For the efficiency of anaerobic processing of organic matter, it is necessary to comply with the main process parameters, the influence of which is crucial.

2.1. Substrate Pretreatment

Pretreatment of initial substrates is recommended to increase the yield of methane, which makes it possible to decompose complex organic compounds into simpler ones, which are more easily subjected to microbial degradation [5,15,28–32].

There are various methods of pretreatment of substrates: treatment of raw materials with alkali or acid, biological treatment of fresh substrate, thermochemical treatment, ultrasonic treatment, ensiling, ozonation, grinding of substrates, etc. [15,33–35]. According to the data from works involving ultrasonic treatment of sewage sludge, the yield of methane increases by 16–30% [33–35]. López et al. found that the thermochemical treatment of food waste with a solution of hydrochloric acid (1.12%) for 94 min at 100 °C increased the content of soluble sugars, which are an easily decomposable substrate, by 120% [36].

Estimation of biogas production from municipal solid waste showed that the yield of methane without pre-treatment with calcium hydroxide was 0.055 m^3 CH_4 per 1 kg of dry substances, while chemically treated waste showed methane emission at the level of 0.150 m^3 CH_4 per 1 kg of dry substances [37]. Bordeleau et al. have shown that the treatment of organic household waste with an alkali solution increases the gas yield by 47% [38].

Pre-treatment of raw materials requires additional financial or energy costs, and this is not always justified by an increase in biogas yield [39,40].

2.2. Temperature

Temperature is one of the most important factors influencing the rate of the fermentation process [10,41–43]. Depending on the temperature range, psychrophilic (<30 °C), mesophilic (30–40 °C), and thermophilic fermentation (50–60 °C) can be distinguished. Ellacuriaga et al. noted that methanogens are very sensitive to abrupt temperature changes during the anaerobic digestion process [42].

Anaerobes are known to be the most active in mesophilic and thermophilic temperature ranges [8,10,41–44]. The thermophilic process has several advantages; with an increase in temperature, the metabolic activity of microorganisms increases, which leads to a higher degree of waste stabilization and the almost complete death of viral and bacterial pathogens, as well as facilitating digestate decantation [4,45]. Disadvantages of thermophilic fermentation include high energy intensity and low stability. These factors hinder the commercialization of thermophilic fermentation [44]. For example, it has been shown that at temperatures below 55 °C and high NH_3 concentrations, the process stabilizes and the biogas yield increases [46]. Accordingly, the accumulation of ammonia at high temperatures increases the toxicity of the mass and leads to the extinction of methanogens [47]. The efficiency of co-digestion of the organic fraction of municipal waste with waste from grease separators was studied by Orangun et al. under the conditions of thermophilic digestion in [48]. Fermentation with cattle manure has been studied under similar conditions as well [49,50]. Mesophilic fermentation has been used to determine the methane potential of food waste, animal waste, and, plant biomass [50]. The effectiveness of co-digestion of the organic fraction of municipal waste and sewage sludge was evaluated in [6,51,52], while changes in the toxicity of oil components after anaerobic processing were studied by Kaya et al. in [53]. Other researchers have studied the efficiency of anaerobic processing of chicken manure under mesophilic conditions [53–56] and under thermophilic conditions [57–59].

The effect of inoculum and substrate pretreatment during thermophilic digestion of the organic fraction of municipal waste was evaluated in [49,60,61]. Silvestre et al. studied the effect of mixing during thermophilic digestion of the organic fraction of municipal waste [62].

2.3. Acidity

As methanogens are active at pH = 6.6–7.6, a stable pH value is the main condition for efficient substrate fermentation [63]. A review article on methanogenesis provides a narrower range of pH = 6.8–7.2 [64]. It was noted that methanogenesis stops at pH less than 6 and more than 8.5 [8]. The acidity of the medium is affected by the characteristics of the initial substrate and the composition of the products during fermentation. The release of ammonia during the processing of protein compounds increases the pH of the fermented mass. Thus, manure is an alkaline substrate, and the accumulation of volatile fatty acids makes it possible to stabilize the acidity [8].

It has been proven that anaerobic fermentation is possible when the concentration of volatile fatty acids is not more than 2000 mg/L. In this case, acetic acid can be present in higher concentrations than propionic and butyric acids, which are the most effective inhibitors of methanogenesis [8,11,65]. The sharp increase in acidity observed during processing may be due to the rapid oxidation of organic compounds [7]. It has been found that at pH > 5.0 the efficiency of methanogenesis increases by more than 75% [66]. Carbon dioxide, ammonia, and bicarbonates normalize the level of acidity [67]. To maintain the acidity of the mass, previous authors recommend mixing the substrates. Thus, mixing the organic fraction of MSW and cattle manure allows the buffering of the medium to be increased despite the accumulation of volatile fatty acids. [68].

2.4. C/N Ratio

For successful digestion of wastes, a ratio of C and N equal to 20:1–30:1 is preferable, because during the decomposition of organic matter microorganisms consume 25–30 times more carbon than nitrogen [8,69]. To achieve the required ratio of carbon and nitrogen, wastes with a high content of organic carbon can be mixed with wastes with a high nitrogen content [69,70].

In this regard, in certain cases it is advisable to co-ferment the substrates. Thus, co-digestion of sewage sludge and organic municipal waste leads to an increase in biogas yield by 65–138% [28,39,71–73]. Co-digestion of waste allows the optimal moisture content of the mixture to be achieved, while the concentration of macro- and microelements can reduce the influence of inhibitory factors or toxic components to optimize the yield of biogas and the stability of the digestate [1,26,74–77].

2.5. Substrate Moisture

The organic medium in the dry matter of the substrate undergoes anaerobic destruction. The gas output depends on the quantity. The optimal moisture content of the substrate is at least 90%, as more than 10% of the dry matter will overload the reactor and settle at the bottom [31,67,78].

2.6. Particle Size

Particle size influences the process of methanogenesis. Large particles lead to clogging of the reactor, while small particles provide a large surface area for adsorption, which leads to an increase in microbial activity and an increase in gas output. The effect of different particle sizes on the amount of biogas produced was studied for sizes of 0.088, 0.40, 1.0. 6.0, and 30.0 mm. It was found that the maximum amount of biogas was produced from raw materials with a particle size of 0.088 and 0.40 mm [79]. Previous studies suggest creating a homogeneous environment in the reactor, and it is recommended to use only crushed waste less than 2 mm in size [80]. Physical pre-treatment such as grinding can significantly reduce the volume of the reactor without compromising its biogas capacity [32,81]

2.7. Mixing

Mixing the contents of the reactor promotes closer contact between microorganisms and the substrate. There are different mixing devices: horizontal, vertical and at an angle. In addition, when stirring, additional grinding of the substrate and the release of gas dissolved in the substrate are carried out [71,72].

2.8. Inoculum Application

The introduction of inoculum into the fermentation mixture is a technique for increasing the efficiency of fermentation. The introduction of the microbial community of active methanogens shortens the period of adaptation and formation of a new microbial community. As a result, it is possible to shorten the retention period of the mixture in the reactor [28,73,74].

The temperature regimes of the process of obtaining an inoculum and anaerobic fermentation should be the same, as the species composition of the methanogen community depends on temperature. To do this, the inoculum is taken from operating biogas plants before adding to the batch reactors; in [75–79], the selected mixture was fermented for 14 days at thermophilic or mesophilic temperature conditions, depending on the operating temperature of the reactors.

The amount of inoculum applied affects the efficiency of anaerobic digestion. A number of studies have demonstrated the trend that with a decrease in the dose of inoculum in the fermented mass, the yield of biogas increases [80]. It has been shown that with equal amounts of inoculum and substrate, the maximum biogas yield per 1 kg of dry matter is 400 L, while the maximum amount of methane content is 59% [32]. However, from the point of view of biogas formation the use of the inoculum in a ratio with the substrate exceeding 3, 2, and 1.5 by weight is not effective. It has been noted that during thermophilic fermentation of food waste in a mixture with the addition of 25% inoculum the maximum biogas yield was 784 mL per 1 g of dry matter. The addition of inoculum in the amount of 32% and 63% leads to less stimulation of the process of gas formation. The introduction of the inoculum in an amount of less than 5% does not have a stimulating effect.

3. Biogas Output

Theoretically, the yield of biogas (l CH_4 per 1 kg of dry matter) during the fermentation of an organic substrate can be calculated based on the Bushwell formula [22,37,78]. The calculation is based on the elemental composition of organic matter.

For reaction (1):

$$C_nH_aO_bN_c + (n - a/4 - b/2 + 3c/4)H_2O = (n/2 - a/8 + b/4 - 3c/8)CO_2 + (n/2 - a/8 + b/4 + 3c/8)CH_4 + cNH_3 \quad (1)$$

The yield of biogas (l CH_4/1 kg of dry matter) will be (2)

$$YB = \left(n - \frac{a}{4} - \frac{b}{2} - \frac{3c}{8}\right) \cdot 22.4) / (12n + a + 16b + 14c) \quad (2)$$

In other works, the theoretical yield of biogas is estimated using Formula (3) based on the composition of organic matter (ml CH_4 per 1 g dry matter):

$$\begin{aligned} TYBorg = {} & (0.415\ \text{Carbohydrates} + 0.496\ \text{Squirrels} + 1.014\ \text{Lipids} + 0.373\ \text{Acetates} + 0.530\ \text{Propionates}) / \\ & (\text{Carbohydrates} + \text{Proteins} + \text{Lipids} + \text{Acetates} + \text{Propionates}) \end{aligned} \quad (3)$$

A modified version of Formula (4) is found in the works of other researchers (mL CH_4 per 1 g of dry matter) [76,79]:

$$TYBorg = (373\ \text{Volatile fatty acids} + 496\ \text{Proteins} + 1014\ \text{Fats} + 415\ \text{Hydrocarbons} + 727\ \text{Lignin})/100 \quad (4)$$

where volatile fatty acids have an average composition of $C_2H_4O_2$, fats—$C_{57}H_{104}O_6$, proteins—$C_5H_7O_2N$, carbohydrates—$C_6H_{10}O_5$, lignin—$C_{10}H_{13}O_3$.

The biochemical biogas yield potential (Vbg) is used as the most relevant indicator in assessing the degradation of organic matter [76]. Biodegradation of organic matter (BD) during anaerobic fermentation is estimated as the ratio of the actual biogas yield (Vbg) to the theoretical biogas yield ((5) and (6)):

$$BD = Vbg/TYB \quad (5)$$

$$BDorg = Vbg/TYBorg \quad (6)$$

The average yield of biogas per ton of feedstock type is shown in Figure 1.

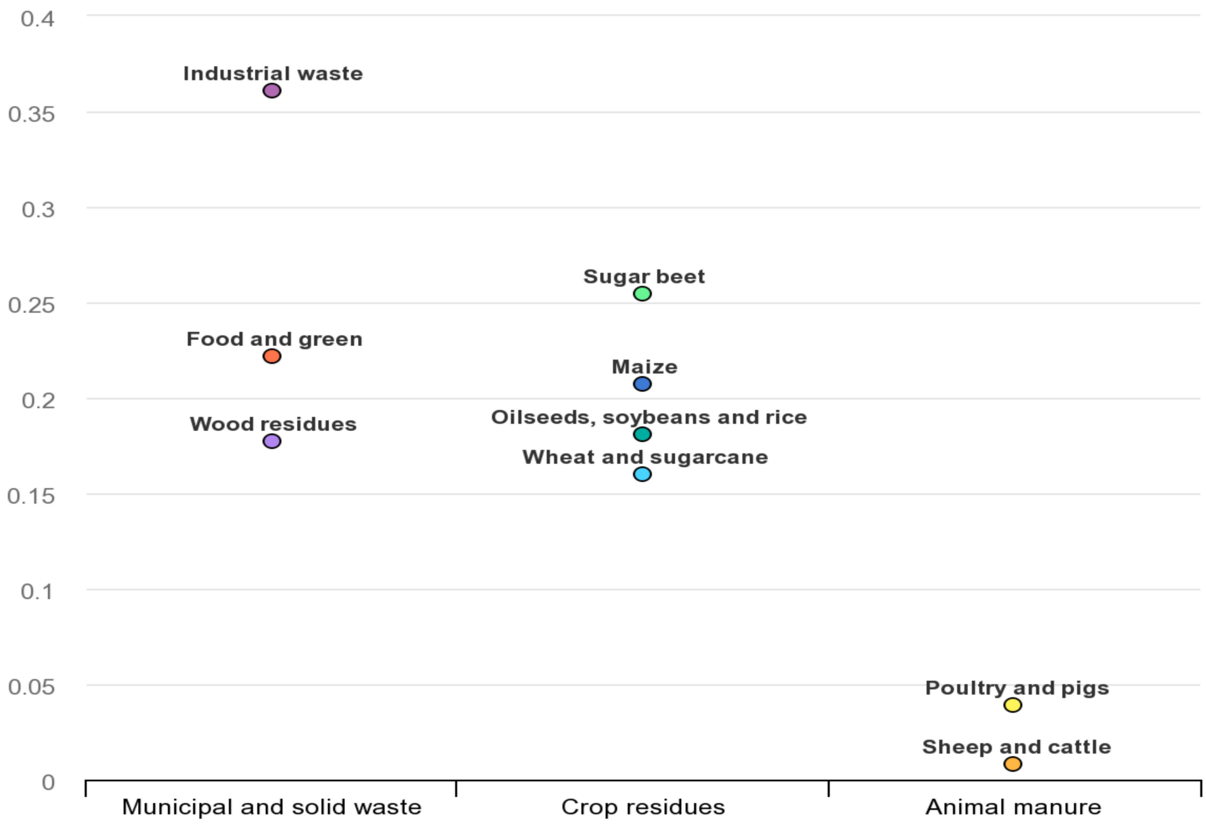

Figure 1. Average biogas yield per ton of feedstock type.

4. Process Performance Monitoring

The main indicators of the efficiency of the process of decomposition of organic matter as a result of anaerobic fermentation are a decrease in the content of dry matter [81], a decrease in the content of organic matter, the content of volatile fatty acids [8], the volume of biogas released with a percentage of methane, a change in pH values, and the content of ammonium [8,79,81].

To assess the effectiveness of preliminary aeration of the substrate before anaerobic processing, it is possible to use the following parameters: volumetric gas yield, percentage of CH_4, CO_2, H_2 in biogas, content of volatile fatty acids and hydrogen in the digestate, and acidity [52].

The maximum yield of biogas is observed on the second or third day, and is 16–18 L per day per 1 kg of dry matter. The release of biogas then decreases, and on the fifth day the volume of released gas is 8 L per day per 1 kg of dry matter.

The acidity during the first three days decreases to 7. Then, by the fourth day the fermented mass becomes alkaline to an indicator of—8, which is associated with the formation of the maximum amount of acetate on days 2–3 (80–90 mmol/L). To assess the efficiency of co-digestion of sewage sludge and the organic fraction of municipal solid waste, the following are used: the volume of released biogas and methane, changes in the content of volatile fatty acids, soluble carbon, and acidity in the digestate [40]. On days 1–3, a maximum biogas yield of 0.30–0.40 m^3/m^3 per hour with a maximum methane concentration of 60–64% was noted.

The content of volatile fatty acids and acidity are in the opposite pattern. The maximum concentration of volatile fatty acids was noted on days 2–4 at 4500–5500 mg/L; during this period, the minimum acidity of the mixture is pH = 7.15 . . . 7.4. On the 12th day, the content of volatile fatty acids decreases to 1000 mg/L, and pH values reach 7.6 . . . 7.7. The change in the amount of soluble carbon is a criterion for the efficiency of degradation of organic matter. For example, in the period from 2–6 days there is an abrupt increase in organic carbon from 2900–4100 mg/L to 8000–9000 mg/L. Then, there is a decrease in this indicator to 6000 mg/L, which is associated with the gradual decomposition of organic matter by microorganisms.

After 12 days of the anaerobic processing process before the end of the cycle, the content of soluble carbon stabilizes at the level of 4000 mg/L. Researchers have evaluated the effectiveness of anaerobic processing of the organic fraction of municipal solid waste using sewage sludge, food waste based on biogas yield, acidity changes, and a decrease in dry matter content. The maximum biogas yield of 4.25 m^3 per day was noted at a pH value of 7.5 and a decrease in the dry matter content by 64.9% [41].

5. Biogas Application

The main product of anaerobic digestion of organic substrates is biogas. Biogas usually consists of 50–87% methane and 13–50% carbon dioxide, and contains small amounts of ammonia and hydrogen sulfide. After cleaning biogas from CO_2, biomethane is obtained, which is a complete analogue of natural gas.

Biogas can be obtained from almost any organic waste. In addition to waste, biogas can be produced from specially grown energy crops, for example, silage corn or sylph, as well as algae [82,83]. Currently, hydrogen sulfide removal is most often carried out using biological installations [8].

The yield of biogas depends on the dry matter content and the type of feedstock used. From a ton of cattle manure, 50–65 m^3 of biogas with a methane content of 60% can be obtained. From various types of plants, 150–500 m^3 of biogas is obtained with a methane content of up to 70%. The maximum amount of biogas can be obtained from fat, at 1300 m^3 with a methane content of up to 87%. In practice, 300 L to 500 L of biogas are obtained from 1 kg of dry matter.

Biogas can be used as a fuel for the production of electricity, heat or steam, and as a vehicle fuel. Biogas plants can be installed as treatment facilities on farms, poultry farms, distilleries, sugar factories, and meat processing plants. A biogas plant can replace a veterinary and sanitary plant, i.e., carrion can be disposed of into biogas instead of meat and bone meal production.

The development of the biogas industry around the world is uneven, as it depends on the availability of raw materials and on policies that encourage their production and use. Europe, China, and the US account for 90% of global production (Figure 2) [84].

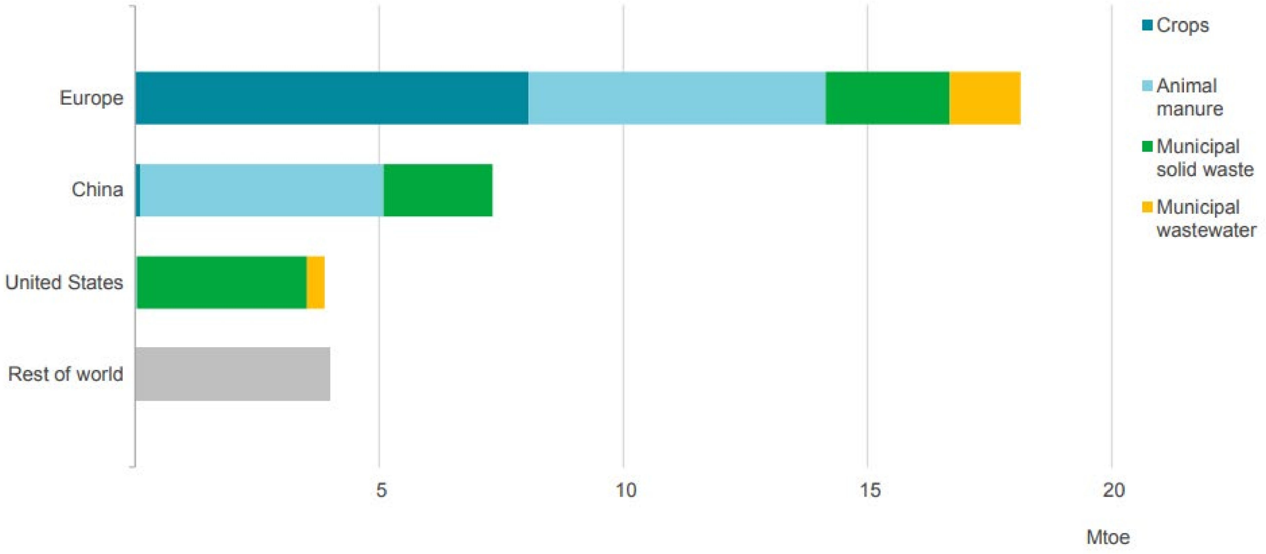

Figure 2. Biogas production by region and by feedstock type, 2018.

Currently, Europe is the largest producer of biogas. Germany is the largest market, accounting for two thirds of the European biogas plant capacity. Denmark, France, Italy, and the Netherlands are actively promoting biogas production.

In China, the installation of household digesters in rural areas is widely used to obtain clean fuel for cooking; these boilers account for about 70% of biogas produced. Various programs have been announced to support the installation of large-scale cogeneration plants, i.e., plants that produce both heat and electricity. In 2019, the National Development and Reform Commission of China approved the industrialization of biogas and the transition to biomethane as well as the use of biomethane in the transport sector.

In the United States, landfill gas collection is mainly used, accounting for almost 90% of biogas production. The production of biogas from agricultural waste from livestock is growing. The United States leads the way in the use of biomethane in the transportation sector.

About half of all biogas produced comes from developing countries in Asia, in particular from Thailand and India. Thailand produces biogas from starch waste from cassava and pig farms. India plans to develop about 5000 new compressed biogas plants by 2025. Argentina and Brazil also support the production of biogas, which is mainly produced in landfills.

Due to the lack of data, it is difficult to draw an accurate picture of current biogas consumption in Africa, however, its use is concentrated in countries with specific support programs. Governments such as Benin, Burkina Faso, and Ethiopia provide subsidies.

Almost two thirds of biogas production in 2018 was used to generate electricity and heat (Figure 3). About 30% was used in buildings, while the rest was processed into biomethane and fed into gas networks or used as transport fuel [84].

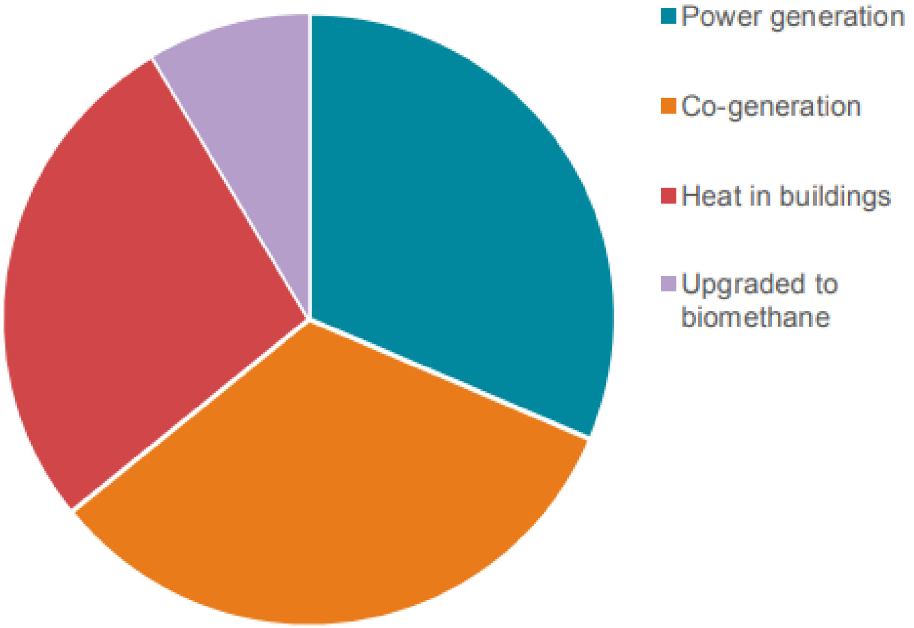

Figure 3. Biogas consumption by end use, 2018.

Currently, the global installed capacity for electricity generation from biogas is about 18 GW, most of which is located in Germany, the United States, and the United Kingdom (Figure 4) [84]. In the period 2010–2018, throughput increased by an average of 4% per year. In recent years, there has been an increase in China and Turkey.

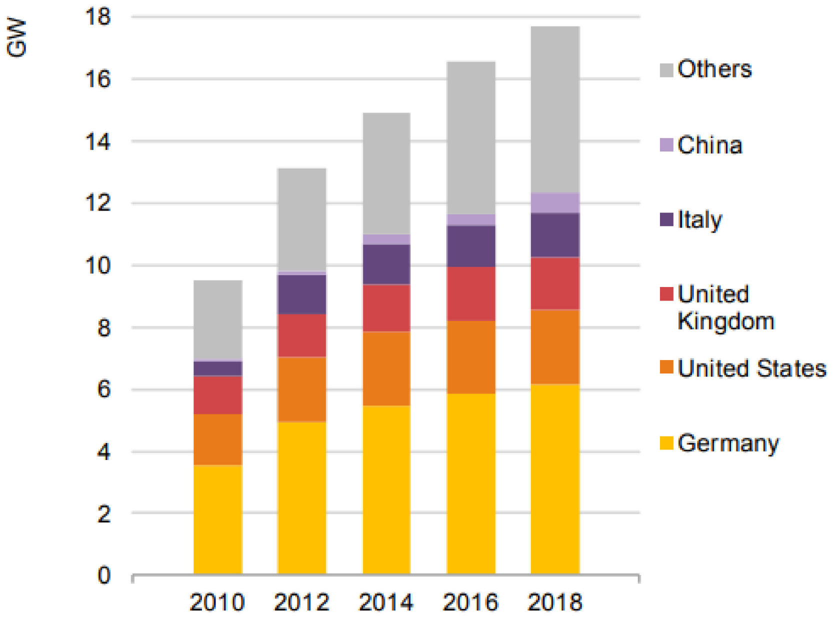

Figure 4. Biogas installed power generation capacity, 2010–2018.

The cost of producing electricity from biogas depends on the feedstock used and the complexity of the installation, and ranges from USD 50–190 per megawatt hour (MWh). Unlike wind and solar photovoltaics, biogas plants can operate flexibly and balance the power grid, which can stimulate future prospects for biogas installations. Industrial sectors such as food, beverages, and chemicals generate wet waste with high organic content, which is a suitable feedstock for anaerobic digestion. In this case, the production of biogas contributes to the reduction of waste and the provision of heat and electricity on site.

At the moment, a growing share of biogas produced in the world is converted into biomethane. This area has significant potential for further growth. More than 700 Mtoe can be sustainably produced at present, equivalent to more than 20% of global natural gas demand. It is planned that by 2040 this potential will grow to more than 1000 Mtoe. e., with an average global production cost of less than USD 15.

6. Use of Digestate Formed in the Process of Anaerobic Digestion

The second product of anaerobic digestion is the digestate, which is used as an unconventional fertilizer. This possibility is due to the presence of nitrogen in the digestate in the amount of 2.8–3.1 g/kg [85,86]. During the anaerobic decomposition of organic matter, organically bound nitrogen is mineralized to ammonium nitrogen, and the C/N ratio decreases [8]. Nitrogen in the ammonium form is most available to plants [8,87]. According to a number of authors, the optimal doses of digestate application are 150–170 kg/ha in terms of nitrogen, 270 kg/ha in terms of K_2O, 30 kg/ha in terms of MgO, and 80 kg/ha in terms of P_2O_5 [85,88]. The content of mineral nitrogen in the digestate is used as an index of fertilizers [89]. In addition, anaerobic digestion makes it possible to destroy weed seeds, bacteria (Salmonella, Escherihia coli, Listeria), viruses, fungi, and parasites of the original substrates [34]. From the point of view of sanitary indicators, long-term fermentation at temperatures above 50 °C is most effective.

A comparative analysis of the effectiveness of digestate and traditional fertilizers was carried out and it was shown that the use of digestate from four different biogas reactors had a comparable effect to the application of mineral fertilizers or pig manure [89]. Stimulation of the potential capacity of nitrogen mineralization and the potential rate of ammonium oxidation was observed.

The possibility of using digestate with wood ash as an unconventional fertilizer has been shown as well [90]. It was noted that the digestate from pig manure contains about

5–7% nitrogen, 30–50% phosphorus, and 70–100% potassium, the amount that plants are able to assimilate during one growing season. In addition, the availability of nitrogen for plants in the digestate is higher than in fresh manure, and the acidity is closer to neutral. It has been established that, as compared with fresh manure, anaerobically digested sludge increases yield.

According to a number of researchers, the nitrogen content in the digestate obtained from the fermentation of manure, corn, and organic waste is higher than in fresh manure [84]. Thus, it is advisable to replace mineral fertilizers with non-traditional ones based on digestate. In addition, the use of non-traditional fertilizers can stimulate the mobilization of nutrients from the soil, increasing the efficiency of the use of soil mineral compounds.

The authors of the aforementioned study concluded that it is technically possible to produce organic granular fertilizers based on digestate with an acceptable level of strength and availability [90].

7. Organic Waste: Challenges and Opportunities

The composition of waste is extremely diverse; the organic fraction is approximately 50% [91,92]. Most of recyclable waste is plastic. The prevalence of polymeric materials has led to the formation of a significant amount of waste [93]. At present, in terms of production volume, polymers are produced as much as cast iron, steel, and non-ferrous metals combined. The production of plastics at the present stage of development is increasing by an average of 5–6% annually.

Modern approaches to the management of plastic waste are based on the use of physical, thermal and chemical processing of polymeric materials. However, these methods have serious drawbacks, resulting in the loss of valuable materials and resources. As a result, the rapid accumulation of plastic in the environment creates one of the biggest environmental threats. Due to their complex nature, plastics are difficult to recycle and are often non-biodegradable.

Biodegradable polymers are one possible solution to the environmental problems associated with the accumulation of plastic waste, but they cannot replace the full range of applications of traditional polymers. These bio-based alternative materials are usually biodegradable or compostable under certain conditions. The bioplastics market is constantly growing, and its annual production capacity is about 2.11 million tons.

The degradation of conventional plastics and bioplastics is a combination of abiotic and biotic processes, including physical, chemical, biological synergy, hydrolytic degradation, and mechanical disintegration.

Indeed, polymeric waste is a quite suitable substrate for colonization, and can support the growth of the microbial community [94,95]. Biodegradation pathways include the mechanical action of organisms due to development and reproduction in breaks in the polymer surface, as well as enzymatic pathways due to polymer hydrolysis into oligomers and monomers [96,97]. In general, the biodegradation potential of a polymer depends on the hydrolysable or non-hydrolysable portion of the polymer. In addition, the molecular weight or morphology of the polymer affects the microbial degradation of polymeric materials [98].

In recent years, there has been a growing interest in the role of micro-organisms in the degradation of plastics to address the problem of pollution. There are many studies in the literature on the ability of certain microorganisms to degrade traditional polymers, such as PET [99–103], PE [104,105], PS [106,107], and PU [108]. In addition, environmental factors such as light, heat, moisture, and acidity increase bond breaking, resulting in increased microbial attack sites on polymer chains.

Works on the degradation of plastics by microbial consortia have been published [109]. Microbial consortia have been shown to degrade polyethylene, polypropylene, and other stubborn polymers [110,111]. It is likely that if plastic is used as the sole source of carbon for these communities then this could be a cost-effective approach.

Purified enzymes or mixtures thereof can be used to catalyze the depolymerization process. As there are no enzymes active for all types of polymers, the main problem is the processing of combinations of different polymers. Enzyme mixtures are already used in industry for the decomposition of natural complex compounds [112]. Work is underway on the selection of enzyme mixtures for the decomposition of plastic [113].

Co-digestion of municipal solid waste, sewage sludge, and food waste is often used to reduce the toxicity of digestates [114,115]. This can lead to the simultaneous presence of non-biodegradable waste (plastic, metals, glass, and other packaging materials) and biodegradable waste (eggshells, bio-bags, and bones). Moreover, plastic bags, packaging materials, and bulk garden waste are considered harmful materials for anaerobic digestion, delaying the biogas production process [116,117].

It is necessary to develop additional approaches to the handling of polymeric materials and to develop new ways of decomposition and recycling of plastic. Biorecycling of plastics represents a promising path towards the sustainable recycling of polymers and plastic building blocks. At the same time, valuable petrochemical raw materials and the quality of the final product are not lost.

8. Future Prospects

The large amount of waste generated in the world is an attractive sustainable source for industrially important chemicals. Known green recycling technologies are used to minimize waste disposal and protect the environment in general. In doing so, various types of waste can be converted into valuable chemicals and fuels.

Increasing recycling of food and plastic waste is curbing the growth of landfills in many parts of the world. Waste valorization is an attractive concept that is gaining popularity in many countries due to the rapid increase in waste generation. For this reason, researchers are not only developing valorization strategies, they are focusing on developing more environmentally friendly materials using a range of green technologies.

The development of methods for converting various raw materials into valuable products, including chemicals, biomaterials, and fuels, is being traced in research, highlighting the significant potential of advanced waste valorization strategies. Incorporating such processes into future value-added and fuel treatment plants is an important contribution to achieving the world's highest priority goal, namely, sustainable development. However, the most important issue now, which needs to be addressed for the sake of future generations, is that the understanding of waste as worthless must give way to a society-wide understanding of waste as a valuable resource. A resource that entails significant complexity due to its inherent diversity and volatility can simultaneously provide an infinite number of innovative solutions and end product alternatives through advanced valorization strategies. Developing innovative sustainable alternatives that will lead to a more sustainable society and economy will require a collaborative effort across a range of sciences, from engineering to biochemistry, biotechnology, environmental sciences, law, and economics.

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