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Review

Biogas Production Depending on the Substrate Used: A Review and Evaluation Study—European Examples

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Abstract: Biogas production is the most important and promising alternative for replacing fossil fuels in an environmentally friendly manner. Along with the many renewable energy sources available, biogas production occupies an irreplaceable position due to the undeniable availability of biomass and the need to manage agro-commercial waste. The article reviews the current state of technology used in the production of biogas for selected European examples in terms of methane fermentation efficiency and actual energy production. The novelty of the article is its description of innovative trends that have great potential to play an important role in this field in the near future. The development of the biogas industry in Europe is evident, although the dynamics vary from country to country. Different models are presented, which are based on the different types of feedstock used for biogas production and the proportion of substrates used in co-digesters. Of course, Germany is the undisputed pioneer in the use of this renewable energy source. Nevertheless, the efforts to improve energy self-reliance and environmental impacts are reflected in the growing number of operational biogas plants in other European countries, which provides hope for rapid progress toward the complete abolition of the conventional exploitation of fossil fuels.

Keywords: biogas plant; substrate; agricultural biogas plants; energy production

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1. Introduction

The world's constant environmental changes are caused by the burning of fossil fuels and overexploitation of natural resources. Global urbanization and economic and industrial development are creating solid waste that the Earth cannot cope with [1,2]. The continuous increase in the production of solid waste, including sewage sludge, is an alarming problem, and solving it has become a political and environmental priority. The human population is projected to reach 9.7 billion by 2050, indicating a continued increase in the demand for food, water and energy [3]. Renewable sources such as solar, wind and hydro power and biogas are potential candidates for meeting global energy requirements in a sustainable manner. In response to the problem of growing organic waste deposits and the need for new renewable energy sources, a number of scientific initiatives have been developed to explore the energy potential of biowaste for biogas production [3–5] The reuse of biosolids, such as sewage sludge and agricultural and industrial waste, is highly beneficial and reduces landfill and soil pollution.

Renewable energy sources are an important element in the country's energy balance, being a characteristic value of an innovative economy. Industrial-scale biogas plants have been built in Western Europe since the 1980s, but a sudden increase in the number of installations has occurred only in recent years. This is a result of commitments made by

EU countries to reduce greenhouse gas emissions and the spread of renewable energy sources [6–9]. The total electricity produced from biogas reached 0.088 GWh in 2017, 40% of which was generated in Germany [10]. In Poland, the first biogas plant was put into operation in 2005, while by mid-2020, there were 310 biogas plants with a total electrical capacity of 245.148 MW_e, including only 120 agricultural biogas plants (128 in 2021) with a total capacity of 101.3 MW_e. The potential for biogas is estimated at about 13–15 bcm per year, with 7–8 bcm of biomethane per year. In comparison, Poland consumes about 14 bcm of natural gas per year [6]. Given the global energy crisis, the construction of more biogas plants, both for agricultural and general utilization, is undoubtedly justified.

With methane fermentation technology, it is possible to produce biogas from various wastes [11–15]. These wastes can be of agricultural, municipal or industrial origin. The most common forms of waste that are used for energy production are agricultural waste, municipal sewage sludge, wood waste, energy crops, animal manure, algae feedstock, dairy waste, dairy wastewater treatment plant sludge and palm oil mill wastewater. In Europe, biogas is mainly produced by the anaerobic digestion of agricultural waste, manure and energy crops. In addition, another possible source of raw material is sludge from wastewater treatment plants, the organic fraction of municipal solid waste or solid waste disposed of in landfills [16–18]. With the use of appropriate technology and optimization of the process, efficient biogas production is possible. Different biogas plant start-up and operating conditions have a significant impact on their potential for biogas production. In order to achieve optimal biogas yield at the lowest cost, several parameters of independent variables must be controlled, in particular temperature, pH value, retention time and organic matter loading rate, which directly affect microbial activity. On the other hand, the physical properties of the feedstock can vary in terms of the content of toxic substances, which can also affect microbial activity [19,20]. Research into biogas production has found that the addition of mixed substrate co-digestion can yield significantly higher production yields than manure alone. Therefore, it is common practice among companies that use biogas for energy production to use manure and slurry or other components, such as energy crops, grass silage, corn silage, etc., in various combinations and different proportions.

In order to identify the state of the art in terms of research results related to the most popular substrates used for biogas production, an analysis of the literature (the methodology is based on 79 publications cited in major scientific journals in the industry, and databases contained in these journals were used) was carried out, focusing on experiments carried out on a large, pilot-scale plant. The article reviews the current state of the art used in biogas production worldwide in terms of methane fermentation efficiency and actual energy production. The novelty of this article is its description of innovative trends that have great potential to play an important role in this field in the near future.

2. Aspects of Biogas Production in Relation to the Type of Substrate Used

Over the 15 years of operation of agricultural biogas plants in Poland, one can see clear changes in the structure of substrate use. The first biogas plants, modeled on technologies used in Germany, were based on corn silage and liquid cosubstrates from agriculture (manure) and processing (decoctions, whey) [21–23]. Gradually, silage from targeted crops was replaced by by-products from the agri-food industry. Agriculture and industry based on agricultural components produce many feedstocks that can be used for biogas production. Suitable substrates for biogas plants are both plant and animal products that contain organic compounds and can be fermented [6,9]. Raw materials for biogas production are divided into monosubstrates and cosubstrates. Monosubstrates have the ability to ferment due to the presence of methane bacteria, such as slurry, manure, the stomach contents of animals, especially ruminants, and have a broad composition of macro- and micronutrients necessary for the growth of microorganisms. Cosubstrates are added to the digester to increase the efficiency of the process, achieve adequate hydration or prevent inhibition [6] These include agricultural by-products and wastes, targeted biomass from energy crops, greenhouse waste, etc. The raw materials used affect both investment and operating costs. A special group of substrates is re-food (in 2021 it accounted for 2.97%), i.e., food from stores, warehouses, and transportation, which cannot be marketed and has been withdrawn from the market for various reasons. The large share of this substrate can create problems for those biogas plants that have been designed to meet standards typical of the so-called NaWaRo technology common in Germany, which mainly uses vegetable silage and liquid cosubstrates from agriculture and processing [22]

Distillery stock at 18.98%, manure at 16.41%, waste from the agro-food industry at 16.61% and residues from fruit and vegetable processing at 16.20% (fruit and vegetable residues, post-production waste) accounted for the largest share of substrate use for agricultural biogas production in 2021 (Figure 1) [22,23]. The popularity of these raw materials is mainly due to their high availability, ability to be easily transported and low acquisition costs. Straw, grasses from uncultivated permanent grasslands or biomass obtainable from marginal land unsuitable for food production, remains a significant and underutilized resource. These feedstocks are difficult to ferment without the use of appropriate pretreatment processes. Agroenergy is increasingly being blamed for rising global food prices, and this aspect is forcing the introduction of second- and third-generation biofuels, i.e., those made from waste, lignocellulosic feedstocks and algae. The increase in the use of by-products and wastes from agriculture and processing in Polish biogas plants will increase biogas production without reducing the land resources necessary to maintain the country's food security. At the same time, the development of second-generation biofuel production, rational management of by-products and waste and harmonization of the biogas industry with the idea of a closed-loop economy will be seen. However, this requires the support of modern methane fermentation technologies and methods of preconditioning a new range of substrates.

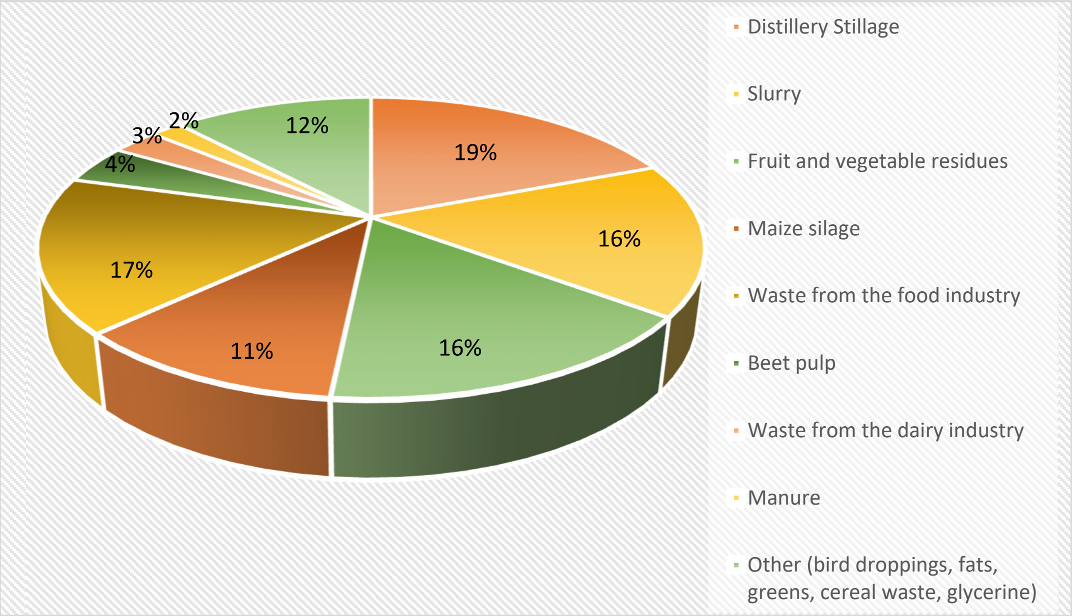


Figure 1. Raw materials used for agricultural biogas production in 2021 in Poland. Own elaboration according to data [22,23].

For an efficient methane digestion (AD) process, in addition to considering of the type of substrate used, optimization of several process conditions is crucial. Critical parameters include temperature, pH, organic loading rate (OLR), hydraulic retention time (HRT) and the carbon-to-nitrogen ratio. It has been found that the anaerobic digestion process can run efficiently in the temperature range of 55–60 °C, when we call it thermophilic fermentation. This process requires significant heating energy, but results in a high rate of biogas production. Mesophilic fermentation occurs between 35 and 40 °C, which provides more economical operating conditions, but results in lower biogas production [24–27]. The

OLR is a parameter that refers to the input rate of organic feedstock per unit volume of the digester. It varies depending on the type of substrate used for biogas production and is determined experimentally. The HRT refers to the average time the feedstock remains in the digester. According to Nsair [28], optimum biogas production can be obtained at different HRTs, depending on the substrate used. Various HRTs were evaluated in the literature to find the optimum values for the different substrates. The adopted HRT varied from 0.75 to 60 days. The optimum HRT was suggested to be in the range of 16 to 60 days [28–30]. According to Schmidt, in order to prevent washouts of microorganisms required for the process, the HRT should not be less than 10 to 25 days. Another parameter that strongly influences the AD process is the ratio of carbon to nitrogen in the medium. Microorganisms use carbon as an energy source, while nitrogen is essential for their growth and metabolism. A low C/N ratio can lead to an overproduction of ammonia, which inhibits the process and thus lowers the efficiency of biogas production. On the other hand, too high a C/N ratio can result in insufficient nitrogen concentration for bacterial metabolism and growth. A very difficult parameter to define is pH, as the different types of bacteria present in the brewer require or prefer different pHs for optimal performance. Maintaining an optimal pH for all microorganisms present in the same reactor is a difficult task, and even more complicated if the substrate has different nutrient compositions [31].

2.1. Manure and Animal Slurry

Polish agriculture is unique in its own way compared to Europe. According to the latest data, 99 million tons of cattle and pig manure alone are produced in Poland annually, with as much as 78 million tons being manure. In addition to this is the (not included in the calculations) production of poultry manure, of which we are Europe's largest producer, and other animals—totaling well over 20 million tons. In Western Europe, due to the small amount of manure produced, scientific research conducted on greenhouse gas emissions has focused primarily on the manure that is prevalent in these countries, during its storage and during and after its application in the field. Meanwhile, methane emissions from slurry are not nearly as significant as those occurring from manure stored in heaps. Therefore, research should be conducted on fermentation and co-digestion processes based on slurry and manure substrates.

Morken et al. [32] used liquid cow dairy manure and a municipal food waste mixture to study the kinetic constants of CSTR reactors during a process running with increasing organic loading rates. The supply of liquid cow dairy slurry was kept constant, the amount of municipal food waste increased, and the efficiency of biogas production was evaluated, reaching the maximum amount obtained from 1 m^3 of the active volume of the fermenter equal to 818.18 m^3 CH_4/year. The amount of energy obtained from 1 m^3 of biogas (with an average methane content) was 0.02166 MWh.

Rusanowska et al. [33] studied the use of cow manure along with a plant commonly used as livestock feed, *Sida hermaphrodita*, which has recently been investigated as a potential high-energy crop. The purpose of this study was to investigate the effect of lignocellulosic biomass pretreatment on methane production efficiency. With a relatively good-quality product (about 54% methane content), the amount of biogas produced reached 9345.80 m^3 CH_4/month, resulting in the production of 0.00006495 MWh of energy.

Tišma et al. [34] studied the anaerobic co-digestion process of cow manure with the addition of whole-plant corn silage pretreated biologically with *T. versicolor* species. This fungal process, where the substrate consists of cow manure, industrial digestate, corn grit and corn silage, resulted in a biogas yield of 0.381 $kgVS^{-1}$ with relatively good biogas quality, reaching 62% methane content.

Comino et al. [35] designed a mobile pilot-scale anaerobic digester and conducted trials of treating a cow manure and whey mixture. The advantage of being able to transport this type of mobile equipment is that it can produce biogas and manage agricultural waste. The authors of [35] proved that by transferring the results of the pilot plant to a real-scale application, an electricity production of 0.00886 MWh per 1 t/d could be achieved.

Winaya et al. [36] investigated the quality of biogas produced at a pilot scale using NaOH and $Ca(OH)_2$ adsorbers and implemented a filtration system to enrich the produced gas with methane. Using cow dairy as feedstock, biogas production reached 0.00072750 m^3/h using NaOH as a CO_2 adsorber, and CH_4 content increased by 14% compared to production without filtration.

Cavinato et al. [37] compared the biogas production efficiency of a real-scale plant and a pilot plant during thermophilic anaerobic digestion of cow dung with other substrates. They proved the importance of using appropriate experimental conditions and increasing biogas production from 0.45 to 0.62 m^3/kg vs. and CH_4 content from 52% to 61%. Daily biogas production averaged 10,200 m^3/day. The economic analysis showed that electricity production from the medium-sized plant was 8789 MWh/year.

Kaparaju et al. [38] studied the impact of adding black candy and confectionery raw material (CRM) to energy crops (ECs) and digested cow dung (DCM) compared to farm-scale biogas production. They found that when industrial candy waste was co-fermented with cow dung, an approximately 60% increase in methane yield was observed.

Ormaechea et al. [39] evaluated the improvement in biogas production from cattle manure (CM) at the pilot plant scale under the following conditions:

(a) Ultrasonic pretreatment (0.14456 kW_hh/kg total solids (TSs), 0.11386 kW_hh);
(b) Co-fermentation with crude glycerin (Gly) from the biodiesel industry (6%);
(c) Pretreatment in (0.14456 kW_hh/kg TS; 0.09452 kW_hh), applied to both substrates prior to anaerobic co-fermentation. The reactor used for this purpose was an induction bed reactor (IBR) with an available volume of 1.25 m^3. CH_4 production from CM was enhanced by low-energy ultrasound pretreatment (0.14456 kW_hh/kg TS) (0.29 to 0.46 m^3 CH_4/kg volatile solids (VSs added)) and by co-fermentation with Gly (0.29 to 0.44 m^3 CH_4/kg vs. added). The best results were achieved when the CM + Gly mixture was pretreated with US (up to 0.59 m^3 CH_4/kg vs. added) [39].

Ferrer et al. [40] turned their attention to the problem of water scarcity in the suburban Lima region of Peru. They designed a low-cost anaerobic digester to study the efficiency of biogas production from pig manure and urine, focusing on the effects of a high solids content. They obtained higher biogas production from a substrate composed of pig manure diluted with urine compared to that diluted with water. In the former case, the CH_4 content of the extracted gas was also higher. The use of urine instead of water resulted in biogas production (0.0077 m^3 of biogas per day) and a yield of 0.0766 m^3 of biogas kg VS^{-1} at an ambient temperature. The dry matter content of the manure was 8% TS/6% VS.

Asam et al. [41] found that the addition of cosubstrates, such as corn or grass silage, significantly increases the efficiency of biogas production by up to 124%. An even more spectacular result was obtained by De Vries et al. [42], who also showed that the addition of other additives (corn silage, corn silage and glycerin) increased biogas production efficiency by 568% compared to the process with pig manure alone. In contrast, co-digestion of pig manure with grass silage increased the total energy efficiency by 226% in a study by Zhang [43].

Xie et al. [44] found that anaerobic co-fermentation of grass silage and pig manure on a 1:1 basis was successful in this pilot study. The study showed that co-digestion of swine manure with grass silage had several advantages over PM monofermentation, including a higher CH_4 content in biogas, higher unit CH_4 yields from swine manure and higher vs. and soluble COD removal.

Kapłan et al. [45] developed a new strategy based on an adsorption–absorption technique based on combining a mixture of carbon (activated carbon) and turf ore (iron compounds) to remove hydrogen sulfide from biogas obtained from swine manure.

Walowski [46] conducted pilot-scale experiments to study the qualitative composition of agricultural biogas produced from swine slurry. He found a strong relationship between the hydrodynamic mixing system of the substrate and the volumetric flow rate of biogas for average daily production. The basis for assessing biogas production is the so-called course of changes in the average daily gas flow; it should be indicated that after the 10th day, biogas production stabilized and continued 4 days. Polydisperse substrate was used as an innovative solution for hydrodynamic feeding. This led to stable biogas production from day 39 onwards. The polydisperse substrate from which agricultural biogas is produced depends on the fattener feed, which translates into the quality of agricultural biogas, where CH_4 can reach up to 80% with very low H_2S release. Within 24 h, with a minimum exchange of 1.5 m^3 of polydisperse substrate for 15 m^3 of fermenter volume to maintain the biogas production process, acidity increases; i.e., H_2S begins to be released. It was observed that for the optimal production of biogas (1.5–2.0), m^3 of polydisperse substrate should be applied.

Liberti et al. [47] fed samples of corn silage, olive pomace and swine slurry to an anaerobic digestion plant operating under mesophilic conditions. The digester consisted of three components: two primary digesters and one secondary digester with working volumes of 2000 m^3 and 5000 m^3, characterized by a net electrical output of 0.999 MW_e. The results show that the maximum methane yield is 67.84% when the reactor feed is enriched with a nutrient mix.

Nsair et al. [48] evaluated different mixing scenarios over a period of 6 years, using agricultural waste consisting of manure and other components, such as manure, corn silage, corn, rye and sugar beets. The highest electricity production obtained averaged 0.550 ± 0.00446 GWh per month. The result obtained by this researcher indicates the great importance of the mixing process in biogas production, as the internal energy consumption was calculated as (5.8–7.2)%, which is a good result in comparison to that of others, such as Mönch-Tegeder et al. [49], whose plants were operated with horse manure.

Piekutin et al. [50] reviewed the efficiency of biogas production at real-scale biogas plants in Poland. In this study, in addition to plants operated with a mixture of agricultural waste, a wastewater treatment plant was evaluated. Higher energy production was recorded at the co-digestion plant, which was operated with a substrate composed of corn silage, manure, slurry, fruit pomace, mulch, stomach contents and potato pulp, and amounted to 117 m^3 of biogas per 1 ton of substrate. In this work, another substrate that yielded relatively good biogas production was chicken manure, which resulted in an average production of ~83 m^3 of biogas per ton of substrate.

Stan et al. [51] studied the co-digestion of the organic fraction of municipal solid waste and fruit and vegetable waste under mesophilic conditions to determine the performance of a 2 m^3 pilot plant in terms of biogas and methane yields and process stability. The results show that the presence of inoculum and temperature and pH control were necessary to improve biogas production and composition. With the use of liquid inoculum, the CH_4 content of biogas oscillated in the range of (44–51)% and biogas production was in the range of (0.504–0.6) m^3/day. Compared to domestic wastewater, pig and cow manure increased the CH_4 concentration in biogas (up to 63%), while daily biogas production increased by 26% and fluctuated in the range of (0.693–0.786) m^3 [51].

2.2. Agricultural Crops

All types of agricultural feedstocks and residual materials can be used for biogas production; even intercrops, whole-crop silage and energy beets are capable of providing good yields with the right technology.

Podkówka [52] in his work discussed the efficiency of biogas production using various energy crops, focusing on corn silage. He reported that 15.906 MWh/ha of energy can be obtained from this crop. He also noted that good results in biogas production and quality are obtained when corn silage is mixed with pig manure.

Another comparison of the energy efficiency of different organic sources was described by Gissen, who compiled data collected for hemp, sugar beets, corn, triticale, grass and winter wheat. Thorina et al. [53] investigated the impact of treating feedstock to increase the rate of fermentation and reduce the ballast of organic matter in the recycled water stream during the process, utilizing on-farm biogas residues such as biowaste and oilseed silage. They discovered the possibility of increasing biogas yield by more than 30% by pretreating the feedstock and incorporating membrane filtration into the process. In addition, they demonstrated the potential of biogas residues as fertilizers. The same group confirmed increases in biogas production of 59% and 43% after mechanical pretreatment of the substrate.

Biogas production reached 350 NmL/g vs. for the first technology, and an energy analysis by Lindmark [54] showed that an energy yield of 40% would be achieved, resulting in a positive energy balance, as the energy production would be 8–11 times higher for the applied substrate treatment.

Nges et al. [55] presented the results of a pilot-scale operation for anaerobic digestion of corn and sugar beet silage with continuous mixing. They also investigated the effect of adding a nutrient to test the properties of the digestate as a biofertilizer. This resulted in a good methane yield and biogas production of 318 m^3/ton. The experiment lasted 13 months, and the results were comparable to the highest yield of CH_4 production on a laboratory scale.

Another crop being tested for biogas production is wheat straw. Straw consists mainly of lignin, which is considered a major impediment to the biodegradation of lignocellulosic substrates. The general strategy for increasing the biodegradability of such compounds is to degrade lignin, reducing the crystalline nature of cellulose and thereby increasing the porosity of lignocellulosic substrates. With this change in structure, the availability of enzymes and microorganisms during biogas production is higher and degradation can occur. Novacovic et al. [56] used enzymatic saccharification and detoxification of wheat straw and improved the efficiency of biogas production in anaerobic digestion. They achieved a biogas production of 1.06044 m^3 per day.

Ciccoli et al. [57] investigated biogas production and microbial population composition in a pilot biogas plant fueled solely by above-ground biomass (AGB) of Jerusalem artichoke (JA). Biochemical methane potential (BMP) tests conducted on fresh, air-dried, and ensiled above-ground JA biomass showed that air-dried JA biomass yielded the highest biogas production, while ensiled biomass showed the lowest. The anaerobic process was carried out in a Plug-Flow digester (ET-Ecoinnovative Technologies S.r.l., Via del Borgo di San Pietro 26, Bologna (BO), 40126 Italia) with a working volume of 1.5 m^3 under mesophilic (36–38) °C conditions. As can be seen, air-dried JA gave the highest biogas production, with 0.000676 $m^3\ g^{-1}$ TS added, while ensiled JA showed the lowest production, with 0.000567 m^3 and 0.000476 $m^3\ g^{-1}$ TS added for four-month-old and six-month-old ensiled JA, respectively [57].

2.3. Municipal Waste and Sewage Sludge

In line with environmental principles, waste should also be considered as a potential source of renewable energy. One form of this energy is biogas. It can be obtained from landfills, which by law must an installation to capture it, as well as be produced from municipal waste. Fermentation facilities for municipal waste can produce biogas in an organized and controlled manner. The product of this process, in addition to electricity, heat and possibly biomethane, is digestate, which can be used as a fertilizer. In 2018, there were 286 municipal waste landfills in operation. Of these, 258 were equipped with degassing facilities, and of these, 23 were equipped with degassing facilities with thermal energy recovery and 68 with degassing facilities with electrical energy recovery [22]. In 2018, landfill gas disposal produced 23.57 GW_hh of thermal energy and 105.356970 GWh of electrical energy in degassing facilities. Municipal waste management can be even more difficult than processing agricultural residues. Recently, many researchers have focused on finding a way to reuse them, giving them the opportunity to fully exploit their energy potential [22].

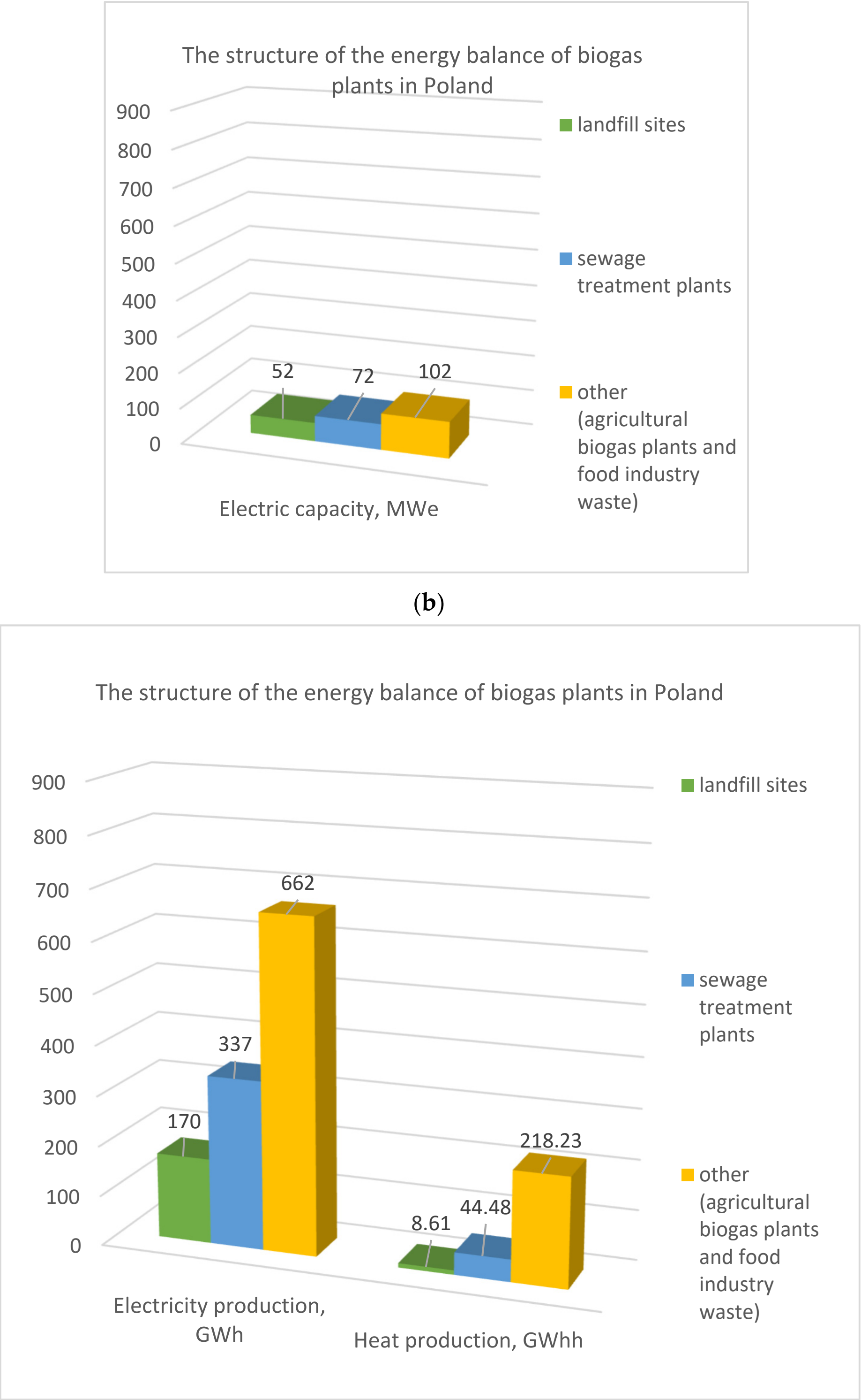
Palm oil mill effluent (POME) is the wastewater generated by palm oil milling activities. This waste requires excessive treatment before being discharged into watercourses, as it is highly polluted and hazardous to the environment. The use of POME in biogas production has been evaluated by Abdurahman et al. [58] on a small pilot scale. In order to achieve a higher CH_4 content in the produced gas, they established a methane content of 79% using an ultrasonic membrane cleaning system, and the biogas production recorded in this study was 26,790 (mLCH_4/L POME).

A biogas production rate of 0.0038 m^3/day was achieved by Nazmus and Mamunur [59], who carried out a careful optimization of the process to obtain biogas from POME, adjusting the pH, organic loading rate and carbon/nitrogen ratio.

More recently, Park [60] also proved the potential of this waste for biogas production using POME and EFB (empty fruit bundle, another by-product of the palm oil industry) as substrates for an anaerobic digestion plant, using alkaline pretreatment with an EDTA iron solution. The resulting gas quality was relatively good, having a CH_4 content of 54%, and production reached up to 0.24 kg of CH_4 per kg of COD processed. Going one step further, he proposed a method for enriching the gas for CNG fuel, combining it with a membrane separation unit to achieve a yield of 98% CH_4 with 90% CH_4 recovery.

Biogas generated by sewage sludge digestion has a relatively stable methane content, which translates into a relatively high calorific value compared to agricultural or landfill biogas. Biogas management at wastewater treatment plants can be seen as an element that fits into the EU's concept of a closed-loop economy, as it allows waste (sewage sludge) to be managed while recovering energy, thus reducing the need for less desirable waste handling through landfilling [6,61]. In 2018, a 72 MW_e electrical capacity was achieved using biogas from wastewater treatment plants, which accounted for 31.86% of the total capacity (values refer to Poland-Figure 2a), compared to about 102 MW_e using biogas from other sources (mainly agricultural and food industry biogas) and about 52 MW_e using landfill biogas, accounting for 23%. The above generation capacity generated about 337 GWh (Figure 2b) of electricity from treatment plant biogas, accounting for 28.83% of the total capacity, compared to about 622 GWh from biogas from other sources (mainly agricultural and food industry biogas) and about 170 GWh from landfill biogas, accounting for 14.5%. The heat production from treated biogas in Poland was about 44.48 GW_hh, accounting for 16.4% of the total share, compared to about 218.23 GW_hh from biogas from other sources (mainly agricultural and food industry biogas) and about 8.61 GW_hh from landfill biogas, accounting for 3.2% [6,22,23].

Nowadays, municipal wastewater treatment and sludge treatment should be carried out under more economical and less energy-intensive conditions, suggesting operation under natural ambient conditions up to 30 °C. Recently, in order to overcome this obstacle, anaerobic membrane bioreactor (AnMBR) technology has been used to treat low-COD municipal wastewater at low temperatures, as reported by Kong et al. [62] Using this technology on a large pilot scale, they achieved a biogas production of (0.000025–0.000027) m^3 g^{-1} COD removed, operating at 25 °C. Comparable results were achieved in the work by Chen et al. [63], who obtained a CH_4 yield of 0.000024 m^3 CH_4 (STP)/g COD removed at mesophilic temperatures and 0.000021 m^3 CH_4 (STP)/g COD removed at low temperatures, in a range of (5–15) °C. A different approach to solving the problem of low biogas productivity from municipal waste was presented by Zahedi et al. [64], in their work using forward osmosis as a sub-treatment to concentrate wastewater. Baba et al. [65] used raw glycerin and excess sludge as a source of N_2 in substrates for CH_4 production. The pilot plant was a continuous reactor with an operating volume of 30 m^3, which operated for 1.5 years with an optimal raw glycerol load of 0.0030 m^3 per day and an organic sludge load (m^3/30 m^3 of sludge per week of digestion. It was found that the maximum CH_4 (or biogas) yield was (141.3 m^3 CH_4/30 m^3 week) COD. In addition, at this load factor, an energy yield of 106% of the energy input was achieved in one year. Furthermore, the digested sludge contained fertilizer components that, when applied to grass fields, increased grass yields by 1.2 times; hence, raw glycerol is an attractive biosource that can be used both as a raw material for CH_4 production and as a liquid fertilizer.


(**a**)

(**b**)

Figure 2. The structure of the energy balance of biogas plants in Poland in 2018: (**a**) electric capacity of biogas-burning facilities (MW_e); (**b**) electricity production (GWh) and heat production from biogas-burning ($GW_h h$).

Ebunilo et al. [66] examined two different samples of household waste after cutting them into pieces to increase their surface area and then mixing them with water in a 1:2 ratio, which were loaded into a biogas pilot reactor. They found that when the reactor operates under mesophilic conditions, this leads to faster substrate digestion in the digester, producing biogas with a maximum CH_4 yield of about 67% [66].

An important aspect of biogas production from sewage sludge is the start-up process of the plant. Studies under real conditions were conducted by Ignatowicz, Piekarski and Kogut [6], who determined the effect of the dosage of selected substrates on the start-up process of a biogas plant under real conditions. Based on the results of the analysis performed during the start-up of the industrial-scale biogas plant using water, liquid manure, corn silage and inoculated sludge, it can be concluded that the use of substrates in the form of corn silage as a source of protein and carbohydrates to provide a nutrient for methano-genic bacteria located in the inoculated sludge results in the acceleration of the fermentation process and faster achievement of proper biogas parameters. As the weight of the dosed corn silage increased, the rate of biogas production increased. The methane concentration stabilized at 54–62%. The value of the fermentation mass index, expressed as a quotient of volatile fatty acids LKT (mg $HAceq/dm^3$) and total inorganic carbon OWN (mg $CaCO_3/dm^3$), increased from 0.18 to 0.34 (on day 70) and began to stabilize to a constant level in the range of 0.3–0.5.

3. Status of Biogas Plants in Europe

Without a doubt, the outstanding leader in terms of biogas production and the number of biogas plants in Europe is Germany, which by 2020 already had more than 10,000 operating biogas plants. Germany produces 52,158 GWh of energy per year, and in 2018 almost 13% of all renewable electricity was generated from biogas and was used mainly for electricity and heat. The German model is based on corn silage as the main substrate for biogas production. There is considerable potential for the use of small AD plants, fed mainly on manure, but nevertheless, higher electrical potential is shown by plants using energy crops as a substrate [67].

More than 600 biogas agricultural plants are in operation in the UK, Switzerland and France, with 381, 111 and 108 plants, respectively [68–70]. Most of the biogas plants are in the agricultural sector, but when compared with those in other sectors, they are significantly smaller in terms of capacity. This sector has been most successful in the development of the industry. In the UK, the most used substrate in biogas plants is wastewater, sewage sludge and municipal biowaste, due to regulations stipulating that no more than 50% of the feedstock used can be energy crops. There are also significant restrictions on the type of plant that can be used to produce biogas and where it can be generated [68]. In Switzerland, the substrates are similar, and although the number of plants in operation is similar, the reported energy production is almost 3 times lower [70] than that in France. In France, a strong development of on-farm and centralized biogas plants, with the aim of recovering biogas to produce electricity for their self-service operations, has been evident for several years. For example, in 2017, 113 of 240 landfills used biogas. About 47% of the recovered energy was found to be converted to electricity, 43% to heat and almost 10% to biomethane. The raw materials used for biogas production in France include residues from wastewater treatment plants, biowaste, agricultural and industrial waste and landfills [68].

In Austria and Sweden, 287 and 44 biogas agricultural plants, respectively, were in operation in 2020 [71,72]. While in Austria, most of the feedstock used consists of manure and organic waste, in Sweden the focus is on the utilization of sewage sludge, which accounts for almost 50% of substrates used. In addition, biowaste, agricultural and industrial waste and landfills are used [72]. Comparing the amount of energy produced annually, Sweden's production efficiency is 3.4 times higher than Austria's. Austrian regulations require a minimum of 30% of the substrate used for biogas production to be manure in order to receive a feed-in tariff. If organic waste is used, the tariff can be reduced by 20% [71].

The Netherlands had 250 reported biogas plants in 2018. Although this number remained almost the same until 2019 (252), the energy efficiency of these installations was truly impressive. Of the 95 cosubstrate installations alone, registered in the report of dn. 2018, the annual energy production was 3720.83 GWh/year [73], a figure close to the result achieved by France's more than 600 biogas plants. Most of the Dutch digesters use local agricultural and animal waste as feedstock for biogas production. Many facilities are technologically adapted to convert biogas to biomethane, which can be used as a substitute for natural gas and can be directly injected into the natural gas grid.

Although Denmark (which in 2020 had 166 biogas plants) has 100 fewer biogas plants than Sweden and Austria, the amount of energy produced is very similar to the value achieved by its Scandinavian neighbor and much higher than in Austria. There is a strong initiative to fully utilize the digestate from agricultural crops, which is further used as fertilizer for crops. Denmark is also limited to using no more than 12% of energy crops for biogas production as AD feedstock by 2020. The new regulation was put in place to lower this limit even further [74].

In Poland, 128 agricultural biogas plants were in operation in 2021 [22,23,75], a significant increase from 2014, when there were 45 plants in operation. In 2021, 342.9 m^3 cubic meters of agricultural biogas were produced, resulting in 732.6 GWh of energy [23]. The raw materials used for production mainly include agricultural waste, manure and energy crops. In recent years, there has been a steady increase in the consumption of waste feedstocks used for agricultural biogas production. The percentage of substrates such as corn silage, cereals or fruits and vegetables used in Polish biogas plants in 2019 was only 10.6%, the lowest it has been since the beginning of the development of biogas plants in this country. On the other hand, in 2021, the most frequently used substrates for agricultural biogas production were distillery stock, accounting for 18.98% of the total share, manure at 16.41%, waste from the agro-food industry at 16.61% and residues from fruit and vegetable processing at 16.20% (fruit and vegetable residues, post-production waste)

Norway has the fewest biogas plants. In this Scandinavian county, there were 46 biogas plants in operation in 2020, of which 6 were farm-scale, 13 were upgraded to produce transportation gas and 2 were connected to the local gas grid. About 40% of the extracted gas is used for transportation purposes, and the total production in 2019 was 922 GWh. The predominant substrates used to operate biogas plants in Norway are sewage sludge and food waste [76].

The development of the biogas industry in Europe is evident, although the dynamics vary from country to country. Different models are presented, which are based on the different types of feedstock used for biogas production and the proportion of substrates used in co-digesters. Of course, Germany is the use of this undisputed pioneer in this renewable energy source, with 8400 biogas agricultural plants. Nevertheless, the efforts to improve energy self-reliance and environmental impact are reflected in the growing number of operational biogas plants in other European countries, which provides hope for rapid progress toward the complete abolition of the conventional exploitation of fossil fuels.

The number of biogas plants in Italy is 1391, thanks to which the biogas market was developed, creating a favorable system of financial support in the form of subsidies for sales of energy from biogas [77].

Development of the agricultural biogas plant sector, which in a key way determines investors' decisions to enter this market, established a permanent guaranteed price system (e.g., in Germany or Austria), which was the basis for the effective entry of financial institutions into biogas projects. In turn, where a significant increase in the share of biogas in the structure of transport fuels is observed, i.e., in Italy or Sweden, it was decided a special aid path would be established in the form of production subsidies. Thanks to this, such activity has a stable economic basis, which reduces the risk of price fluctuations, for example, in the biocomponent sector [78].

Although in recent years biogas technology has increased the number of operating agricultural and municipal biogas plants in Europe, it is worth pointing out that the data are not readily available. Table 1 presents a comparison with reference to the analysis conducted on the basis of the available literature on the state of technology in individual European countries.

Table 1. Biogas plant status in Europe—selected examples. Own elaboration according to data: [22,23,67–78].

Country	Feedstock	Year	Use of Biogas	Quantity of Energy GWh·Year^{-1}
Austria	Manure and organic wastes	2019	Electricity, vehicle fuel and flare	564.52
Denmark	Sewage sludge, biowaste, agriculture, industrial and landfills	2019	Heat, transport, process, grid injection and electricity	1763
France	Wastewater treatment plant, biowaste, agricultural, industrial and landfill	2017	Electricity and vehicle fuel	3933
Germany	Agriculture, biowaste, sewage sludge and landfill	2020	Electricity, heat, vehicle fuel and flare	52,158
The Netherlands	Landfill, sewage sludge, codigestion and others (mainly municipal waste)	2019	Electricity and heat	3720.83 (only co-digestive ones, 95)
Norway	Mostly sewage sludge and food waste	2020	Heat, electricity, flare and vehicle fuel	922
Poland	Agriculture, manure and others	2019	Electricity and heat	477 306,396 mln m^3 in 2019
Sweden	Sewage sludge, biowaste, agriculture, industrial and landfills	2018	Electricity, heat, automotive fuel, industrial use, other uses and flare	2044
Switzerland	Agriculture, biowaste, industrial and wastewater treatment plants (WWTPs)	2018	Electricity, heat and biomethane	1409
United Kingdom	Agriculture, biowaste, industry, WTPP and landfills	2018	Electricity, heat and biomethane	1511 MWe-equivalent

Energy security, economic development and protection of the Earth are the priorities of the national energy policy of every country in modern Europe. Biogas could be a solution to the requirements and expectations for renewable energy sources. This clean and accessible source of energy can help reduce the carbon footprint, manage organic waste and produce electricity, heat and even transport. It has been estimated that the use of upgraded biogas for transport (90% methane content in biogas) allows for a significant reduction in greenhouse gas emissions. In addition, the digestate obtained during the production of biogas is an additional benefit and can be used as fertilizer and returned to the soil. Turning waste into energy through biogas production is not only a viable option with huge potential to reduce or even eliminate dependence on fossil fuels, but also a sustainable and efficient way to produce decentralized energy with a smaller carbon footprint.

Europe has always been and is still one of the biggest promoters of renewable energy practices and development. The governments of European countries have so far questioned many technical, economic and political issues related to their commitment to the UN Sustainable Development Goals (UN SDGs), which must be achieved by 2030 [79]. One of these goals, "Cheap and clean energy", requires a rapid and unprecedented scale of restructuring of energy systems, not only in terms of technology, but also in terms of economy. This task may prove difficult to accomplish, especially in developing countries. Nevertheless, the current position of the European Union in the field of RES has resulted in a significant increase in the development of the biogas sector, which is visible in the number of biogas plants and successive improvements in the production of renewable energy over the years, with many countries consequently switching to the production of biohydrogen.

4. Conclusions

Biogas production is one of the most important and promising alternatives for replacing fossil fuels in an environmentally friendly manner. Along with the many renewable energy sources available, biogas production occupies an irreplaceable position due to the undeniable availability of biomass and the need to manage agro-commercial waste. Therefore, scientists around the world are conducting extensive research to develop low-cost and sustainable biogas that can be used for transportation, electricity and heat generation. The success of this endeavor would benefit the environment, economy and sustainable development of countries around the world. Studies have identified various resources as biogas feedstocks that show high energy potential, such as manure and slurry, energy crops, municipal waste and others. The number of biogas plants in operation is increasing every year, providing hope that the target set by governments will be reached. At the same time, new approaches to finding the ideal technology for the economic and sustainable production of biogas production, its refinement and finally its operation are constantly emerging. There is still a long way to go on the path to perfection, but certainly the steps that have already been taken have been significant.

According to the methodology adopted in this article, the following should be pointed out:

(1) The share of consumption of substrates for the production of agricultural biogas in 2021 is as follows: stillage 18.98%, manure 16.41%, agricultural and food industry waste 16.61% and fruit and vegetable processing residues 16.20%;
(2) The production of electricity using biogas from sewage treatment plants accounted for 31.86% of total electricity generated (values for Poland in 2018), compared to biogas from other sources (mainly biogas from the agri-food industry) and landfill biogas, accounting for 23%;
(3) The generation capacity of biogas from treatment plants was 337 GWh of electricity, accounting for 28.83% of the total capacity, compared to about 622 GWh from biogas from other sources (mainly agri-food biogas) and about 170 GWh from landfill biogas, accounting for 14.5%;
(4) Production of heat from purified biogas in Poland amounted to approx. 44.48 GW_hh, accounting for 16.4%, compared to approx. 218.23 GW_hh from biogas from other sources (mainly agricultural and food biogas) and approx. 8.61 GW_hh from landfill biogas, accounting for 3.2%.

Energy security, economic development and protection of the Earth are the priorities of the national energy policy of every country in the modern world. Biogas could be a solution to the requirements and expectations for renewable energy sources. This clean and accessible source of energy can help reduce the carbon footprint, manage organic waste and produce electricity, heat and even transport. It has been estimated that the use of upgraded biogas for transport (90% methane content in biogas) allows for a significant reduction in greenhouse gas emissions. In addition, the digestate obtained during the production of biogas is an additional benefit and can be used as fertilizer and returned to the soil. Turning waste into energy through biogas production is not only a viable option with huge potential to reduce or even eliminate dependence on fossil fuels, but also a sustainable and efficient way to produce decentralized energy with a smaller carbon footprint.

Europe continues to be one of the biggest promoters of renewable energy practices and development. The goal is “Affordable and clean energy”, which requires a rapid and unprecedented scale of restructuring of energy systems, not only technologically, but also economically. This task may prove difficult to accomplish, especially in developing countries. Nevertheless, the currently progressing position of the European Union in the field of RES has resulted in a significant increase in the development of the biogas sector, which is visible in the number of biogas plants and successive improvements in the production of renewable energy over the years.

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