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Review

The Review of Biomass Potential for Agricultural Biogas Production in Poland

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Abstract: Adequate management of biomass residues generated by agricultural and food industry can reduce their negative impacts on the environment. The alternative use for agricultural waste is production of biogas. Biomass feedstock intended as a substrate for the agricultural biogas plants may include energy crops, bio-waste, products of animal and plant origin and organic residues from food production. This study reviews the potential of selected biomass residues from the agri-food industry in terms of use for agricultural biogas production in Poland. The most common agri-food residues used as substrates for biogas plants in Poland are maize silage, slurry, and distillery waste. It is important that the input for the agricultural biogas installations can be based on local wastes and co-products that require appropriate disposal or storage conditions and might be burdensome for the environment. The study also discusses several limitations that might have an unfavourable impact regarding biogas plants development in Poland. Given the estimated biomass potential, the assumptions defining the scope of use of agricultural biogas and the undeniable benefits provided by biogas production, agricultural biogas plants should be considered as a promising branch of sustainable electricity and thermal energy production in Poland, especially in rural areas.

Keywords: biomass; agricultural biogas plants; agricultural waste; sustainable and renewable energy; organic residue management; Poland

1. Introduction

Global environmental change caused by excessive exploitation of natural resources and combustion of fossil fuels causes a range of negative impacts on human health and functioning of ecosystems humans ultimately depend on. Generation of solid waste is increasing rapidly as a result of industrialization, global urbanization and economic development [1,2]. Projections indicate that by the 2050 the word population will reach 9.7 billion [3]. There is therefore an increasing pressure on land and water resources to supply food and industrial products. Inability to effectively manage wastes as recently highlighted by scientists and decision-makers lead to serious environmental and socio-economic problems that need urgent and reliable solutions [4,5]. In response to this problem, a number of scientific initiatives were founded with the goal of creating new usages for organic residues [6]. One of the solutions of organic waste management can be their use for production of biogas, during anaerobic digestion (AD) [7].

Biomass [8] represents an important source of alternative energy and provides an opportunity to decrease environmental problems such as pollution and depletion of natural resources [6]. It is widely available and regenerates in a relatively short time [9]. There are many possibilities of biomass processing. For example, agricultural residues and municipal solid residues for biogas and biofuel production [10,11], the use of organic waste for vermicomposting [12], as a supplement during combustion with hard or brown coal or use of agricultural, urban, woody and industrial pyrolyzed residues to improve soil quality [13,14]. This paper discusses the potential of using residual biomass in Poland for the energy sector. It focuses on the assessment of the suitability of biomass from agricultural production and by-products or residues from the agri-food industry as a substrate for biogas production.

2. Methods

The first stage of the study was the literature review, which was performed in English and in Polish languages. The search was conducted on the online databases such as Google Scholar, Scopus, Web of Science, and Science Direct (without restriction to year). For this purpose, we provide an extensive combination of keywords in English and Polish (Table S1). The second stage was the selection of the scientific papers (articles, conference papers and PhD theses), based on title and abstract content. The selected documents were archived in the literature database Mendeley. Additionally, we reviewed the bibliography in the key documents with the aim of finding other relevant titles on the specific subject ("snowball" search method).

3. The Role of Biomass in Energy Production in Poland

The rational use of renewable energy sources is essential for sustainable development. Nowadays, Poland is the second largest coal consumer in the EU (after Germany), and the 10th largest coal (here referred to both: hard coal and lignite) consumer in the world, with consumption of 77 million tonnes of coal per year. In addition, the country is a leader in hard coal extraction and import. For example, in 2016 Poland produced 70.7 million tonnes of hard coal and imported 8.3 million tonnes [15]. Current data provided by the World Energy Council from 2017 showed that 92% of electricity and 89% of heat in Poland is generated from coal [16]. Biomass co-firing with fossil fuels might be a promising solution, allowing an increase in the share of renewable energy sources (RES) in the total energy in Poland [17]. Supporting energy production from renewable energy sources has become an essential objective of the European Union's policy as a strategy to pursue sustainable development [18,19]. In the case of Poland, the need for RES development results from the commitments of the "3 × 20" climate package imposed by the EU. By year 2020 Poland is obliged to obtain 15% of RES in gross final energy use and reduce emissions of air pollution. The use of biomass as the renewable energy source might be an essential aspect to achieve these obligations [20].

Biomass is one of the oldest as well as the most promising development of RES in Poland, with a great potential to be used for energy purposes [21]. It is mostly related to favourable geographical and climatic conditions for biomass production, wide range of its application, and its large resources [21–23]. In case of other RES, the limiting factors may result from unfavourable topography or insufficient resources (hydropower, wind energy), as well as the costs of production: for example, the high price of the solar cells for solar energy [21]. The energy obtained from biomass in Poland comprise approximately 80% of the entire energy pool, which is obtained from RES [20]. The technical potential of biomass in Poland is around 900 PJ/year [24]. The structure of primary energy production from renewable energy sources in Poland from 2016 is shown in Figure S1 [25]. Additionally, Poland is one of the largest exporters of biomass in Europe [21]. The annual biomass energy potential that can be managed is estimated as follows: over 20 million tons of waste straw, 4 million tons of wood waste (sawdust, tree cortex, sawdust, pellets), 6 million tons of sewage sludge from the paper industry and pulp, food and municipal waste [26].

From an environmental point of view, biomass can be considered better than coal. Previous studies demonstrated that combustion of biomass emits less SO_2 compared to coal and has zero-balance carbon dioxide emission [27,28]. Furthermore, the ash gained from the combustion of biomass is returned to the soil, where the plants used for thermal process were cultivated and collected, is consistent with the principles of sustainable development [21]. Despite the fact that electric energy in Poland is obtained mainly from coal [17], it has been demonstrated that using biomass from agriculture co-products for energy purposes is fully justified [23].

4. The Potential of Use of Agricultural Residues for Biogas Production in Poland

In Poland, the production of agricultural biogas has a great potential to grow given increasing demand for heat and electricity from renewables. Moreover, availability of feedstock (substrates) presents interesting opportunities for potential investors, farmers in particular [29]. Because the production of agricultural biogas requires a daily input of substrates [30], location of agricultural biogas installation and its capacity to process the biomass is determined by the constant supply of raw material [31]. This ensures high biogas yield, stability of the fermentation process and possibility of formed digestate utilization [32]. The composition and capacity of biogas obtained from biomass depends on many indicators, including moisture and physical state of the feedstock, technology used, temperature and pressure. As the input for agricultural power plant, both animal and plant origin substrates can be applied as well as waste from the agri-food industry [30,33].

4.1. Utilization of Biomass from Animal and Plant Production

Large breeding farms and agri-food processing generate a significant amount of organic waste [34]. In accordance with the requirements of environmental protection and waste management, if the breeding farm presents more than 40,000 places of poultry, or pig stock more than 2000, farmers are obliged to dispose at least 70% of animals manure on their own farmlands [35]. Semi-liquid and liquid slurry from animal farming are valuable fertilizer, however, their improper storage, application and spillage can lead to environmental pollution and cause odour problems [36]. Their utilization as the substrate for agricultural biogas plants could be one of the options. This solution might be practically attractive for farmers that produce large amounts of organic waste characterized by high energy value. In Poland, approximately 80,750 tons of manure and 35 million m^3 of slurry is provided as the organic waste of agricultural production. About one third of this amount could be processed into biogas for local use [34]. Banaszkiewicz and Wysmyk [37] estimated that the total technical potential to produce agricultural biogas from livestock excreta in Poland is 674 million m^3, i.e., 26.2 PJ. Furthermore, the anaerobic digestion conducted in agricultural biogas plants provides stabilization and deodorization of raw manure, also changing the category of fertilizer from "natural" to "organic" as the final product, so it can be disposed-of easier [36]. Nevertheless, digesting of raw manure as the only substrate under thermophilic conditions might be unprofitable due to some exploitation issues and inhibition of biogas production due to higher N amounts in animal excreta than in other organic waste [38,39]. A mixture of slurry with plant-biomass enhances C/N (carbon to nitrogen) ratio and nutrient balance, contributing to the improvement of biogas quality and lowering production costs [40,41].

In the case of farming, not only animal excrements can be used as a substrate for an agricultural biogas plant. Straw is commonly used in agriculture as feed for farm animals, however, its surplus is not suitable for agricultural purposes and may be burdensome for the environment. Currently, the surplus of straw is estimated to be 10–11 million tonnes per year. [42]. Nevertheless, straw has been recognized as a valuable biomass for the energy sector. This raw material can provide 934 TJ of energy. Assuming that the average calorific value of coal is 24 MJ kg^{-1}, the evaluated biomass could replace over 9.16 million tonnes of coal. However, it should be considered that straw combusting arouses controversy due to CO_2 emissions [43].

In Poland, approximately 25% of arable lands can be used for the growing of annual energy crops with the aim of agricultural biogas production [44]. Among them, maize, more precisely maize silage combined with slurry is used often for the co-fermentation process [33]. In comparison with other grain plants, maize shows higher biogas efficiency (Table S2), high yielding potential, harvesting and silage [45–47]. It is worth mentioning that silages of various plants, especially corn silage, are used for large-scale energy purposes. In Poland, maize growing is concentrated mainly in the western and northern part of the country [48]. The spatial analysis conducted by Jędrejek and Jarosz [31] demonstrated that the most suitable voivodeships for the construction of 50–100 kW micro-biogas plant using 100% maize silage are: Lower Silesian, Pomerania, Lubusz, Greater Poland, Warmian-Masurian and West Pomeranian. In the communities located in the voivodeships mentioned above, there is also a prospect of building micro-biogas plants obtaining biogas from a blend of maize silage (70%) and slurry (30%). Nonetheless, cultivation of monoculture—as in the case of maize intended for silage—might have an unfavourable impact for the environment, especially for soil [31]. Thus, due to the growing interest of advantages resulting from agricultural biogas production, the number of installations built in recent years and high costs of the feedstock, more attention is paid for alternative substrates for biogas plants.

4.2. Biomass from the Agri-Food Industry

The Polish agri-food industry generates large amounts of organic waste [49]. Replacing or co-firing of biomass obtained from agricultural crops with the raw material from agri-food production can be a promising solution for biogas production in Poland [50]. The usage applies to processed and unprocessed waste from the agri-food production, e.g., fruit processing [51], residues from diary industry, [52,53], distillery waste [54], meat processing [55] or fresh vegetables and fruits [56,57]. Theoretically, any biodegradable biomass that contains carbohydrates, proteins and fats can be used as the substrate for the agricultural biogas plant, however the prerequisite for the profitability of using raw material is the content of the organic dry matter amount above 30% [58,59]. It should be emphasized that regarding the methane fermentation process, it is important to use technologies based on the use of by-products from agriculture that do not compete with the production of food or forage [44].

4.2.1. Fruits Residues

During extraction of juice from fruits, a by-product called fruit pomace is separated. A certain amount of leftover goes to landfill, contributing to environmental pollution, while a significant part can be applicable as an energy source [50]. The use of fruit pomace as an input for a biogas facility has been well-described in literature. For example, Pilarska et al. [60] showed that the quantity of biogas and methane obtained from apple pomace was as follow: 203.64 m^3/ton of fresh substance and 101.36 m^3/ton of fresh substance. As a comparison, the results for activated sludge in the current study is: 4.38 m^3/ton of fresh substance for biogas and 2.21 m^3/ton of fresh substance for methane. Moreover, Prask et al. [61] demonstrated that grape pomace obtained during wine production might be successfully used in agricultural biogas plants, both as a substrate or co-substrate. It is important to highlight that fruit residues contain low concentrations of heavy metals [62]. Thus, as the result of processing the fruit residues during the methane fermentation, valuable organic fertilizer which is nutrient-rich and free from heavy-metals can be obtained [63].

4.2.2. Dairy Industry

The main by-product of the dairy industry is whey, whose annual production in Poland is 2–3 million m^3 [64]. Utilization of whey may be problematic, because it contains chemical substances, resistant for biodegradation in the conventional wastewater treatment [64]. Due to the content of lactose, which is the source of energy for many microbial groups like lactic acid bacteria, whey can be used in numbers of biotechnological processes, including methane fermentation, instead. Wesołowska-Trojanowska and Targoński [52] demonstrated that from one ton of substrate, up to 55 m^3 of biogas, containing about 78% of methane, can be obtained. In addition, the product does not contain sulphur compounds and can be directly used for combustion in steam boilers without prior desulphurisation. Nevertheless, it should be noticed that depending on the milk processing technology used in the dairy plant, acid, sweet and casein whey may be formed, differing mainly in pH. Whey is characterized by extremely high chemical oxygen demand (COD)—approximately 50,000 mg O_2/dm^3, and nitrogen (Kjeldahl nitrogen (Nog) 600 mg N/dm^3; nitrate nitrogen ($N\text{-}NO_3$) 2.5 mg/dm^3; $N\text{-}NH_4$ + 60 mg/dm^3). Therefore, despite the high biogas potential estimated, it is not recommended to use whey as the only substrate in the methane fermentation process, mainly due to the low C/N ratio required for the correct course of the process [53].

4.2.3. Meat Industry and Post-Slaughter Waste: Inconveniences Continuation

Meat industry, pork particularly, is one of the most important products of Polish agriculture [55]. However, the meat processing generates annually about 18 million tons of waste [65]. It poses a serious environmental and epidemiological threat and should be disposed of properly [44,65,66]. Due to the restrictive regulation regarding disposal of slaughterhouse waste, meat producers are struggling with the high costs of animal waste management [67]. Methane fermentation in purpose of their utilization seems to be an optimal solution [55]. The research conducted in the Institute of Biosystems Engineering (University of Life Sciences in Poznań) showed that the waste from the meat industry might be promising for biogas efficiency, due to the high content of protein and fats [68]. For example, the amount of biogas obtained from 1 ton of the content of the digestive tract was 275.77 m^3, including methane: 194.38 m^3/t fresh matter, which is 70.48% of gas. Also, it has been demonstrated that the mixture of slurry and digestive tract content of pigs is an energetically effective input in the methane fermentation process, producing high-energy biogas with a methane content exceeding 60% [55].

Nevertheless, the use of waste from slaughterhouse and meat processing in Poland as a substrate for biogas plants is associated with certain problems. First, this type of waste requires the prior sanitary treatment (thermal), in accordance with the Regulation of the European Parliament and Council Regulation (EC) No 1069/2009 of 21 October 2009. The exception applies to the content of the digestive tract [65]. Second, the technological issues related with processing of selected organs. For instance, brains and spinal cords that cannot be used as a substrate for a biogas plant, as they might be the potential source of pathogenic prions [69]. Third: regarding the UE legislation, post-slaughterhouse wastes are divided into three categories (Animal by-product, ABPs), based on the risk they pose: category I ABPs classed as "particular risk" (SRM—from polish language: "material szczególnego ryzyka"), category II ABPs—"high-risk", category III—"low-risk". Only waste classified to category II and III can be used to produce agricultural biogas, after earlier treatment [70].

An appropriate and efficient fermentation process depends on the quality and proper balance of the supplied substrate. In the case of meat waste, the other, considerable issue is the high amount of nitrogen which makes a lot of difficulties in running the anaerobic fermentation process properly. Balance of the C/N components ratio is an important element because in the fermentation process the organic nitrogen from the substrate is converted into ammonium nitrogen, which is partly used for the synthesis of protein of newly emerging bacterial cells. In addition, ammonia is formed with excess nitrogen, which inhibits bacterial growth at low concentrations, while higher carbon to nitrogen ratio causes a decrease in the amount of methane due to disruption of the carbon metabolism [63].

Despite of mentioned inconveniences, a number of studies showed that waste of meat processing has a higher biomethane yield, i.e., compared to maize silage, the basic biogas input used in Europe. Furthermore, the biomass fermentation can be an effective tool to reduce the unfavourable effects of improper waste management from the meat industry, and the electricity and heat obtained can be an additional source of income for meat processing plants or used for their technological purposes [55,69].

4.2.4. Distillery Waste

Distillery stillage is a main by-product obtained during ethanol production [71,72]. Poland is one of the largest spirits producers worldwide and the amount of distillery stillage exceeds up to 12 times of alcohol, resulting in an estimated several million tons per year [73]. It creates a great problem with disposal of its surplus. Distillers contain, in addition to organic carbon (Ct) compounds, mineral nutrients necessary for plants and can be used to fertilize or improve the soil quality. A common feature of decoctions is too low phosphorus content in relation to nitrogen and potassium and relatively high Ct content [74]. Grain stillage is characterized by high content of B vitamins, minerals, exogenous amino acids, dietary and lactogenic value and favourable protein–oat ratio; therefore, it is used in the forage industry [75]. In turn, molasses stillage is not suitable for the forage purpose, however, for the economic reasons, is often used by biofuel producers as a substrate to produce ethanol [76]. Though molasses stillage may be used as fertilizer, the application on the field might be problematic due to its polluting potential and would generate further costs related with the constructions of the appropriate tanks for its storage [71,76]. At this point, attention should be paid to the hazard associated with excess potassium accumulation in the case of fertilization with this waste of crops grown for feed purposes [75]. Moreover, the period of usefulness of stillage is relatively short because of the risk of microbiological development [73].

Nevertheless, a number of studies were conducted with the aim of finding an optimal solution, regarding the difficulties associated with the large loads of distillery waste. The anaerobic digestion with biogas production is one of the alternative methods proposed for the utilization of stillage [49,54,77,78]. Biogas efficiency from stillage has been estimated in the range between 430–725 m^3 Mg^1 of dry organic matter, with methane content of 55% and is comparable to other substrates from the agri-food industry [79]. From the other hand, the use of stillage as the input for biogas plants can be justified in the case of a stable situation of the domestic ethanol industry and when the installation is located in vicinity of a distillery that generates great quantities of this waste. This would minimize the costs related with transport which might contribute to unfavourable economic stability [80,81]. Additionally, the high amount of potassium in molasses and accordingly in distillery waste, not only contaminates fields when it is used as fertilizer but may also inhibit bacteria involved in the anaerobic digestion. Therefore, when supplying the fermentation chamber, special attention should be paid to quality as well as chemical and elemental composition of the substrate [74,82].

4.2.5. Fresh Fruits and Vegetables: The Controversial Case

Utilization of fresh agricultural products for energy purposes seems to be unjustified and controversial. On other hand, in certain cases might be necessarily. Fresh fruits and vegetables require appropriate storage conditions, which most of the farms are deprived of. The amount of unused fresh biomass might be problematic for many food producers, as the product that stays with the farmers, become a waste and need to be disposed. For instance, the embargo imposed by the Russian Federation in 2014, had significant influence on Poland´s economic situation, causing the saturation of local markets with fresh agricultural products [56,57]. Thus, the farmers were recommended to use the waste as the substrate for biogas plant, because it would be profitable from the economic point of view [83]. The study conducted by Smurzyńska et al. [57], with the aim to determine the biogas yield and dynamic of the fermentation process of surplus of fresh vegetables and fruits (biogas and methane productivity tests were carried out for the following vegetables and fruits: eggplants, pumpkins, cauliflower, cabbage, peppers, tomatoes, cucumbers) demonstrated that the process of methane production has not been impaired by any inhibitory factors and biogas yield obtained from individual vegetables and fruits tested was comparable. Furthermore, a large number of polysaccharides in substrates tested contributed to a short but intense process of biogas production. A comparable study (also with the fruits covered by embargo, such as: apples, pears, nectarines, peaches and plums) showed that the biogas yield obtained from the tested fruits were also similar (653 m^3/Mg peaches, 829.66 m^3/Mg apples on organic matter) [56]. Based on these studies it can be concluded that biomass obtained from fresh non-traded agricultural products are a suitable substrate for biogas production, however, should be used only in case of exceptional situations.

5. Limitation for Development of Agricultural Biogas Plants in Poland

Agricultural biogas plants have huge potential that can positively influence both the environmental aspect and socio-economic development of a given area [34,84]. Currently there are 96 agricultural biogas plants in Poland under operation [85]. In Germany, for example, the number of installations is over 9400 and the country has similar potential for biogas production, when comparing arable land [85]. This difference can be explained by limiting factors such as the location. Construction of the installation may cause social resistance of the local communities. For instance, the surveys conducted with the residents of rural commune Kamionka in Lublin province, Poland, demonstrated that most of the residents were concerned about the unpleasant odour (60% of respondents) [86]. Other fears of the respondents were related to pollution, noise and risk of explosion. On the other hand, over 80% of the respondents indicated the benefits from an agricultural biogas facility, such additional income for the farmers, provision of the cheap energy for the community and positive impact on local environment. Moreover, some local producers were willing to cooperate with the owners of biogas facilities, by buying the energy, providing the biomass and using the post-fermentation pulp (digestate) for fertilizing purposes. The inconvenience related with cost of transport or seasonality of agri-food waste availability, characteristic for the areas with small farms that may cause input instability can be clarified by cooperation between farmers, producing different biomass [87]. Therefore, the decision regarding the selection of the place for the biogas installation should not only consider technological, environmental and legal issues, but also the social aspect should be taken into account [86].

The utilization of digestate might be another limiting factor for the development of agricultural biogas plants in Poland. The operating of agricultural biogas installations is associated with the generation of a large amount of post-fermentation pulp. This product, resulted from the digestion process contains more inorganic nitrogen than non-digested organic fertilizers, and, in consequence, more nitrogen in a form available for plants [88]. Previous studies conducted in EU countries demonstrated the possibility of using the digestate as a replacement for the traditional fertilizer or soil amendment, with the benefits both for the farmers (impact on the crop yields) and soil properties [89–93]. Nevertheless, in some cases the digestate management can be problematic for the biogas producers. When using digestate as the organic fertilizer, it is necessary to comply with several legal requirements regarding both storage methods of biomass intended for methane fermentation as the input and for fermentation pulp on the premises [93,94]. The other important issue of utilizing digestate for fertilizing purposes concerns is its classification. According to the law, digestate may be considered waste or by-product. However, numerous legal regulations for the digestate to be classified as a by-product and therefore qualify it for use as an organic fertilizer (or soil amendment), may be inconvenient for the producers (e.g., farmers, owners of the installation, etc.). Furthermore, the bio-fertilizers based on digestate require accurate physicochemical and microbiological tests in specialized research institutions and need to meet the procedures set by decision-makers [95]. These procedures apply to the use of digestate in agriculture as well as in gardening and forestry. The most important legal acts regarding the utilization and the requirements for the classification of digestate as a by-product, as well as legal requirements regarding methods of storage of substrates and digestate on biogas plant areas were discussed by Czekała et al. [94] and Łagocka et al. [96]. Nonetheless, due to the growing interest in energy obtained from the agricultural biogas installations in Poland, and consequently, an increased amount of post-digestate pulp attention should be given to the alternative methods of its management. In Italy for instance, the usage of digestate became a key factor to maintain profitability of biogas plants and to promote bioeconomy [88,97].

For the further development of agricultural biogas plants in Poland it is crucial to show farmers and residents the benefits of this type of investment. Promotion of bioeconomy as an important element of environmental sustainability and usage of renewable biological resources [98] as well as creating favourable conditions for research on cost-effective and implementing practical solutions [99].

6. Final Considerations

Agriculture plays an important role in the Polish economy and Poland is considered a producer and exporter of good quality products. The country has also considerable potential for biomass processing using agricultural, forest and municipal waste. Biomass from the residues of agri-food production and agricultural, especially bovine slurry, maize silage and distilleries has a great energy potential and is a valuable substrate for agricultural biogas production. Simultaneously it would be essential to implement and develop available and cost-effective technologies that convert biomass of agricultural origin into energy, while not competing with the food and forage market. The use of controversial products, for example fresh fruits and vegetables as a substrate should be considered with caution. Regarding the use of biomass for energy purposes, factors such an economic aspect, substrate availability and substrate storage should be taken into account. Utilization of digestate as a bio-fertilizer or soil amendment and its effect on crop yields is a priority for farmers. Nevertheless, here we propose further research on the impact of digestate on soil carbon sequestration, greenhouse gas emissions and on the use of digestate in degraded areas in order to restore soil ecosystem services. Agricultural biogas installations have the potential to contribute to the greening of the Polish energy sector but unless certain restrictions are overcome, the share of biomass for energy production might be limited.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/11/22/6515/s1, Table S1: List of keywords used for literature search, Table S2: Comparison of biomass from agriculture plants in terms of biogas yield, Figure S1: Structure of primary energy production from RES in Poland, 2016.

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