fermentation

Review

Characteristics of Substrates Used for Biogas Production in Terms of Water Content

Wojciech Czekała *, Mateusz Nowak and Wiktor Bojarski

Department of Biosystems Engineering, Poznań University of Life Sciences, Wojska Polskiego 50, 60-637 Poznań, Poland; mateusz.nowak@up.poznan.pl (M.N.); wiktor.bojarski@up.poznan.pl (W.B.)
* Correspondence: wojciech.czekala@up.poznan.pl; Tel.: +48-749-265-938

Abstract: New technologies based on the anaerobic digestion process make it possible to manage problematic waste. Methane efficiency depends largely on the level of the hydration of the substrates used for biogas production and their ability to decompose easily. The aim of this study was to present the current state of knowledge and practices in substrate hydration characteristics, focusing on pretreatment methods as the preferred method for improving efficiency. The paper discusses issues related to the degree of hydration of substrates in the context of their use in biogas plants. Reference was also made to topics related to the transportation and logistics of raw material supply regarding environmental impact. Biogas plant projects should be expanded to include an element related to assessing the impact of raw material deliveries on the immediate environment. Previous papers have not sufficiently analyzed the aspect related to the hydration of substrates used in anaerobic digestion processes. The presented and discussed research results can be implemented to optimize biogas plant water management processes. By replacing standard feedstock transportation methods with a pipeline, the environmental impact can be reduced by nearly ten times.

Keywords: anaerobic digestion; fermentation; water content; pretreatment; biomass; biogas

Citation: Czekała, W.; Nowak, M.; Bojarski, W. Characteristics of Substrates Used for Biogas Production in Terms of Water Content. *Fermentation* **2023**, *9*, 449. https://doi.org/10.3390/fermentation9050449

Academic Editor: Alessia Tropea

Received: 11 April 2023
Revised: 25 April 2023
Accepted: 4 May 2023
Published: 9 May 2023

1. Introduction

1.1. Climate Problems

Climate change resulting from relentless economic development poses a significant threat to future generations. It is necessary to make reasonable and practical changes, primarily in economic sectors related to food production and energy [1]. One of the most noticeable climate changes around the world is the phenomenon of global warming. Emissions of greenhouse gases such as methane, carbon dioxide, and nitrous oxide, for example, contribute to this situation [2]. Replacing fossil fuels with biomass-derived fuels is one way to reduce greenhouse gas emissions into the environment. Biogas produced by anaerobic digestion is a solution for the environmental and energy crisis [3]. The use and production of this type of biofuel are possible both in developing countries whose economy is based on agriculture and in developed ones that produce significant amounts of waste with high energy potential. Despite the possibilities, the development level of biogas technologies in many countries currently varies [4]. This sector's problems on the road to expansion are often due to inadequate legal conditions in this area and a lack of capital. However, it should be noted that countries in Europe and Asia building biogas plants are solving an important aspect: the possibility of processing various types of waste [5].

1.2. Biomass Characteristics and Utilization

The quantity and quality of research on processing and ways to use hard-to-find biomass have recently increased significantly [6]. Biomass is a valuable energy material. Biomass includes products and wastes of plant and animal origins. Sawdust is also an example of biomass, the waste generated after felling trees [7]. Some other agricultural wastes, e.g., olive pruning and tea leaf residues and wetland vegetations, are also biomass-rich lignocellulosic materials that can be subsequently reused for biogas production [8,9]. Ongoing research indicates that it is possible to use available biomass sources, such as composting or anaerobic digestion [10,11]. By processing and removing excess moisture from such renewable substrates, the possibilities for their use can be expanded. Biomass, briquettes or pellets are an alternative that reduces fossil fuel extraction [12]. In addition, biomass is also used to produce biochemical compounds or biocatalysts that enable chemical transformations [13]. In a breakdown of the world's total energy demand, biomass, and waste provide 55.7 EJ, ranking fourth. For years, the top three have consistently been coal, oil, and natural gas [14]. Biomass is the primary energy resource in developing countries with limited access to fossil fuels [15].

The use of waste biomass is currently becoming a popular solution worldwide [16]. One can distinguish between sources of traditional biomass that have been used since the beginning of time on earth, such as wood, and biomass, which has been divided into three distinct generations [17]. The first generation of biofuels are products derived from crops that compete with human food production. This includes liquid biofuels produced from feedstocks with high starch and sucrose content. There are concerns about the competition between food and energy production from such sources, hence, second-generation biofuels have been introduced [18,19]. A good example is biofuels from inedible plants or agricultural and forestry residues. The second generation is thus a solution to produce green energy while processing waste [20]. The last type is third generation biofuels, which use algae for energy. These are microorganisms characterized by their easy culture and simple cellular structure. Major advantages of algae are: no competition with food crops for arable land, high growth rates, and low fractions of lignin, which reduces the need for energy-intensive pretreatment. However, some disadvantages, such as the presence of high water content, seasonal chemical composition, and the occurrence of inhibitory phenomena during anaerobic digestion, make algal biofuels not yet economically feasible, even though they are more environmentally friendly than fossil fuels. They also thrive in polluted water, which they filter during growth [21].

There are various ways and technologies to convert biomass to energy. The current climate policy of EU countries seeks to reduce greenhouse gas emissions by 40% by 2030 from 1990 levels [22]. Biomethane facilities play an essential role in the energy transition, enabling the production of biomethane to replace the need for natural gas. As is well known, using and replacing hard coal with natural gas or biomethane reduces smog and high particulate matter emissions in many countries, including Poland [23,24]. The increase in demand for gaseous fuel contributes to developing and constructing new biogas plants. This potential is significant in countries producing significant amounts of waste with appropriate energy parameters [25]. The versatility of modern biogas plants makes it possible to use a variety of feedstock substrates. The waste processing through anaerobic digestion and the generation of environmentally friendly renewable energy fits perfectly with the goal of climate neutrality [26]. The resulting by-product of the process, the digestate, is a valuable organic fertilizer used in the agricultural sector [27,28]. Research conducted by Kumar et al. [27] suggest the sustainable up-cycling of spent mushroom substrates inspired by a circular economy approach through a synergistic production of bioenergy and secondary fruit crops, which could potentially contribute to minimize the carbon footprints of the mushroom production sector.

1.3. Water Requirements for Biomass Production

In addition to the fertilizer aspect, energy crops require certain amounts of water for growth and development. Despite the availability of good fertilizer in the form of digestate, the current problem for agriculture is drought. Research conducted by Mathioudakis et al. [29] presents results on substrate conversion technology in terms of water use. According to the paper's authors, biogas is the energy source with the smallest water footprint, among other biomass conversion technologies, such as pyrolysis and gasification [28,29]. A closed-loop operation of the plant has a beneficial effect on water management. It is possible to use digestate pulp for fertilizer or, after careful separation, also for crop irrigation [30,31]. Comparing total freshwater demand globally, the agricultural sector uses about 92% of the resource [32]. Authors Mekonnen and Gerbens-Leenes [33] point to a high water footprint for certain biofuels, particularly the first hydropower generation. For biomass from crops directed for use as biogas feedstock, the total water footprint for this type of agricultural production always remains the same. However, some directed crops have a relatively high water footprint due to limited opportunities to harvest residues [16,33].

Research on the carbon footprint is increasingly being analyzed, but recent years have also directed another essential aspect—water footprint analysis. The study aim was to discuss the topic of water content in substrates used for biogas production. The main chapters analyze our own and the literature research considering the importance of the proper water management of modern biogas plants. The paper also presents the latest methods used during substrate pretreatment that increase the efficiency of anaerobic digestion processes. Activities and topics related to the work are necessary to increase the efficiency of water use and conservation, which can contribute to achieving climate neutrality.

2. Characteristics of Substrates Used for Anaerobic Digestion

2.1. Types and Potential of Raw Materials Used for Biogas Production

By analyzing the literature on the use of raw materials and waste for biogas production, it is predicted that it is possible to reach 108 EJ by 2030. Using the potential of biomass, it is possible to replace 20% of primary energy in this way [34]. Regardless of the projections, reaching this level is challenging for the biofuel sector due to the limited availability of raw materials and the difficulty of their conversion. The residues used present significant differences in chemical composition and dry matter content. In addition, some chemical compounds in the feedstock can severely limit the biogas production potential, negatively affecting the anaerobic digestion [35]. Using biogas facilities is, therefore, a rational alternative to reduce the consumption of fossil fuels. In the anaerobic digestion process, it is possible to use a variety of substrates, including highly hydrated waste from the agro-food industry. After anaerobic digestion, the waste is transformed into an environmentally safe substance as digestate [36,37]. In addition, biogas facilities are part of conducting a closed-loop economy. In the case of biogas combustion in cogeneration engines, the emitted carbon dioxide is reabsorbed in the photosynthesis process of plants that are substrates in the anaerobic digestion process, such as corn. The seasonality of the production of some of the substrates is also an important aspect. In most installations, it is necessary to build a storage area to ensure continuous production [38,39].

Dividing the substrates used in anaerobic digestion into appropriate categories is possible. According to Yuan and Gerbens-Leenes [32], the first category is biomass from agriculture. Substrates can come from crops directly directed to produce high-energy crops, e.g., corn, and from crop residues and residues such as manure. Forestry-related residues are included in the following category. This sector is characterized by logging waste or waste from the paper industry. All other municipal and industrial organic wastes were included in the third category of anaerobic digestion substrates [32]. The primary criterion for selecting a suitable feedstock mix is biogas efficiency, feedstock availability, and economic and environmental aspects. The introduction of an additional substrate can have a beneficial effect on increasing the energy efficiency of the process. Carbohydrates and proteins are characterized by a faster rate of decomposition compared to a substance made up of fats. However, according to Table 1, it is fats that have the highest methane efficiency [40]. An essential parameter for the substrates used in the anaerobic digestion process is also the C/N ratio, which should be at an equilibrated level to ensure the stability of biogas production [41].

The potential for using selected feedstocks for biogas production is determined by methane efficiency. In addition to the differences in methane efficiency, an important aspect is the availability of substrates near the biogas plant [42]. Table 1 shows the theoretical potential for the methane efficiency of selected compounds contained in substrates used by biogas plants.

Table 1. Maximum theoretical biogas efficiency (own elaboration based on [43–45]).

Component	Methane Efficiency ($m^3\ kg^{-1}$ VS)	Reference
Carbohydrates	0.42	[43]
Proteins	0.50	[43]
Fats	1.01	[4]

Table 1 shows that the most significant potential in the amount of methane produced is in the substrates containing significant amounts of fat. Types of fat-rich substrates include oil leachates. A side effect of using fat-rich substrates is the formation of long-chain fatty acids in the decomposition process, which become toxic to bacteria at excessive concentrations [46]. Another group of substrates exhibiting high methane efficiency are products containing significant amounts of proteins. During the decomposition of proteins, NH^{4+} compounds are formed, which are converted into ammonia compounds at a later stage of the process. Too high a concentration of ammonia can lead to the inhibition of anaerobic digestion. However, it is possible for microorganisms to adapt to an environment with higher concentrations of ammonia [47,48]. In addition to protein, lipid, and carbohydrate compounds, it is also possible to use biomass with high levels of lignocellulose. Lignocellulosic biomass makes it more difficult to decompose the substance, which translates into lower methane yields compared to the other groups [49].

The key findings and the preferred direction of biogas plants is to process and use problematic substrates to manage and treat waste, which is also costly to dispose of [50]. An essential aspect of the efficient operation of biogas plants is to ensure the correct proportions of the feedstock, which allows for the optimal anaerobic digestion process and the growth of new structures of methane bacteria. Meeting the difficulty of achieving a high level of biogas efficiency is not possible if the anaerobic digestion process is carried out using only one substrate. New trends indicate using two or more substrates, most often in the co-digestion process, thus increasing plant profitability [51,52].

2.2. Water Content of Substrates vs. the Environmental Effect of Their Transport

Using various feedstocks for biogas production often necessitates transporting and delivering them to facilitie several or tens of kilometers away. Ongoing research indicates that the logistics of supplying feedstock substrates and the export and management of digestate are components of biogas plant operations that adversely affect the environment. The distance involved in transportation has the most significant impact on environmental pollution and affects global warming in particular [53,54]. Another critical issue is how raw materials are stored on the biogas plant site before they are used for anaerobic digestion. Adequate storage has a positive effect on preserving the freshness of the products and keeping their methane efficiency constant. Water in the form of moisture bound in many substrates creates problems during improper storage, as it can lead to the appearance of bacteria and mold [55].

Based on the problems associated with the operation of a biogas plant, Tucki et al. [56] analyzed factors affecting operational efficiency. The main aspect impacting the efficiency of biogas plants is the transportation distance of substrates. In addition, it is also necessary to prepare appropriate technological infrastructure to facilitate the process of feeding digesters. The authors also point out an essential and often overlooked aspect: the need to manage the digestate. The use of the by-product in question on one's fields or the provision of guarantees in receiving the digestate determines the efficiency of the plant's operation. However, the analyzed article does not specify a vital aspect: the minimum distances that guarantee the economic justification of the transportation of pulp and substrates. It is proposed to research transportation's economic and environmental aspects [56].

The carbon footprint associated with substrate supply is also significantly affected by the parameter of dry matter and dry organic matter. Running the anaerobic digestion process with a highly hydrated substrate decreases methane efficiency per ton of fresh matter. Therefore, it is a good practice to use and collect the raw material from a fixed location to ensure commensurate parameters for a specific type of substrate. In addition, if the owner of a biogas plant contracts a significant amount of substrate, it is necessary to establish acceptable deviations from the assumed parameters indicative of its quality. An important aspect is also the possibility of transporting acceptable and, at the same time, maximum quantities of transported substrates by vehicles with a large capacity [57,58].

Research conducted by Muradin and Foltynowicz [59] describes the environmental impact aspect of feedstock transports for an example of biogas plants. The authors conducted their experiments with four different biogas plants. This impact was expressed in [Pt] points based on ISO 14040-44 and LCIA Impact 2002+ [58,59]. The results on the logistics of transporting raw materials to biogas plants are presented in the analyzed article. The standard transportation of slurry using a farm tractor with a barrel to a modern pipeline was compared. The results also show that transportation has a negative impact on the environmental effect. Using a pipeline, it is possible to reduce the negative environmental impact by up to 10 times compared to the standard transportation method [59].

As mentioned earlier, the key findings is the dry matter level for liquid and solid substrates. The feedstock dry matter parameter mainly determines the methane efficiency. In general, the higher the feedstock dry matter value, the higher the methane efficiency per ton of fresh substrate mass [60].

3. Feedstock Hydration and Anaerobic Digestion Technology

Processing biomass to produce biogas can be carried out in many different ways. Classification of the anaerobic digestion process requires the determination of an appropriate criterion. The most popular division of anaerobic digestion technologies is based on the temperature range at which the process occurs. Determining the optimal temperature level is related to the type of bacteria involved in the anaerobic decomposition process. The optimum temperature value allows for the proper decomposition of organic matter and provides a suitable environment for a particular group of bacteria. Using this variable, the different types of anaerobic digestion technology have been characterized as psychrophilic, mesophilic, and thermophilic [61]. Another possibility is the division resulting from the number of process steps, the method of substrate dosing, or the degrees of separation of the different phases of anaerobic digestion. Depending on the type of substrate processed, the critical factor determining the anaerobic digestion technology is the degree of hydration. The dry matter content of the chamber determines the type of technology used, distinguishing between wet and dry anaerobic digestions [62].

In biogas plants, the average daily feedstock requirement ranges from a few to tens of Mg of feedstock. A biogas plant with a capacity of 0.5 MW_e requires a daily supply of 30 Mg of feedstock to the digester [63]. A biogas facility's size and electrical capacity also depend on factors related to the amount and type of substrates used, which are found in the immediate vicinity. Regardless of the biogas plant size, each consists of the same essential components, including those related to feedstock storage. In the case of solid feedstock such as corn silage, for example, it is essential to ensure proper conditions during preparation and storage [55]. A portion of waste is characterized by odor nuisance and requires storage in storage halls with biological or activated carbon filters. In the case of liquid substrates, problems are encountered with the need to install mixers or heating systems at the storage site. Therefore, the choice of the appropriate anaerobic digestion technology can be determined, in addition to the availability of raw material and the convenience of its storage [55,64]. In addition, it should be noted that the selected anaerobic digestion method is not determined by the dry weight compactness of the individual feedstock but by the hydration of the feedstock mixture entering the digester [64].

3.1. Wet Anaerobic Digestion

For years, the wet anaerobic digestion process has continued to be the most common and dominant way of treating various types of substrates processed in biogas plants [62]. This type of anaerobic digestion is popular due to the nature of the process, in which the bacteria for each of the different phases require an aqueous environment in their surroundings. If the reactor mixture is not hydrated enough, the bacteria will have difficult access to the substrate, which can cause only partial decomposition and a decreased biogas production. Moisture is also a factor that provides a substrate for bacteria to grow and multiply, ensuring the high efficiency of the ongoing process. In addition, for wet technology, natural process inhibitors are distributed throughout the mixture, ensuring their low concentration and not interfering with the process. Low hydraulic retention time (HRT) for highly hydrated substrates such as slurry can result in the leaching of microorganisms. When selecting substrates for biogas plants, it is necessary to take into account the dry matter input and dry organic matter input load of the digester [65,66].

Dry matter values in the reactor chamber are conventional and are defined differently depending on the available literature sources. The most commonly accepted values for the wet process are <10–15% dry matter [67–69]. The low solids content and liquid consistency create the possibility of pumping the mixture between chambers and the subsequent management of digestion residues [30]. In wet technology, operating biogas plants are characterized by a full flow of substances through the entire volume of the reactor. Before refilling the reactor with a new portion of the substrate, a conditioning process is used, i.e., adding process water or the liquid fraction of the digestate to maintain the assumed level of the dry mass of the feedstock. Ensuring a suitable mixing ratio is possible through vertical and horizontal mechanical mixers or a hydraulic mixing process (liquid recycling). The advantages of building this type of plant are the ease of construction of the tank and the possibility of carrying out maintenance work without emptying the reactor [69]. Based on research conducted by Luning et al. [70], a mass flow model was developed for the wet anaerobic digestion process for a full-scale plant, as shown in Figure 1.

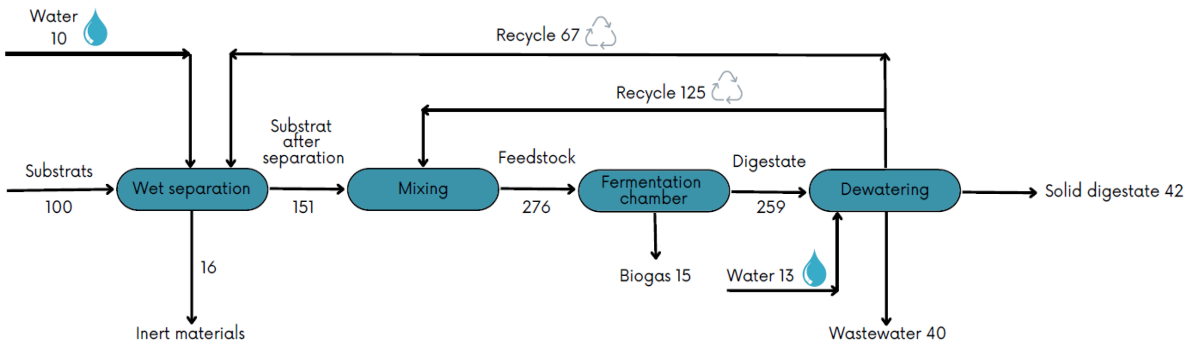

Figure 1. Mass balance in the wet anaerobic digestion process (own elaborated based on [70]).

One biogas plant analyzed by Luning et al. [70] used a wet substrate separation process to eliminate sand and other materials that adversely affect the process. The process uses the phenomenon of sedimentation. The substrate is then mixed and directed to the digester. The final stage is dewatering the digestion residue using belt presses. It should be noted that dewatering the digestate from the wet anaerobic digestion process results in about 40% wastewater and 42% solid fraction. This waste should be managed appropriately. The costs associated with the disposal of solid fraction waste are significantly higher than the disposal of process wastewater. This aspect has a significant impact on the profitability of the biogas plant and the resulting water footprint. In the case of dry anaerobic digestion, the final mass balance is in the ratio of 10% wastewater and 77% solid fraction digestate.

This ratio facilitates the introduction of technology for drying the solid fraction and using it as an energy fuel [69].

3.2. Dry Anaerobic Digestion

The dry anaerobic digestion method allows for the processing of various types of the feedstock of varying compositions, such as manure or food waste [11]. Using such substrates without prior dilution and preparation is impossible in wet technology, as they exceed standard equipment's 'pumpability' limit. The finished batch substrate mixture in the reactor contains a high amount of dry matter at levels ranging between 20 and 40% [69]. Large-scale biogas production using dry anaerobic digestion technology is currently considered a fledgling method. This may be due to the lack of prevalence among most industrial biogas plants [11,70]. However, differences in process parameters and the feedstock used and the bacteria for dry and wet conditions are similar [71].

A system based on dry anaerobic digestion is devoid of the drawbacks of a wet digestion process. It is possible to conduct anaerobic digestion in a discontinuous process, and no additional energy inputs are required for mixing and grinding the feedstock [72]. The dry process prevents the formation of foam and crusts on the surface of the digester and also counteracts the phenomenon of sedimentation [73]. The benefit of dry technology is the processing of waste in its original form. In addition, a process of this type does not require additional diluent liquid and, according to Jha et al. [74], is capable of producing a higher volume of methane per m^3 of bioreactor volume [74]. A 540–750 NL kg VS biogas efficiency was obtained for the substrate studied using the wet anaerobic digestion process [75]. Comparing methane efficiency for the dry process with the wet process in the literature has been analyzed at the laboratory scale [74] and at the large scale of industrial biogas plants [70]. The authors of the paper [75] established, based on their research, the higher methane efficiency of the dry-fermentation process of grass compared to the dry-wet method. A 420–540 NL kg VS biogas efficiency was obtained for the substrate studied using the dry anaerobic digestion process [75]. A study by Angelonidi and Smith [66] compared nine plants using dry and wet technologies for anaerobic digestion processes. For the dry method, a greater flexibility related to the type of feedstock used, reduced water consumption, shorter retention times, and an easier management of the end products of the process were evaluated. In contrast, the wet technology was characterized by a more favorable final energy balance [69].

In recent years, Europe has seen progress related to dry anaerobic digestion efficiency by up to 50%, although methane anaerobic digestion is responsible for managing only 35% of all waste [76]. Additionally, on other continents, e.g., in China, interest in dry anaerobic digestion has increased, which is an ideal solution for managing the 0.9 billion tons of straw generated annually in China. Straw is a problematic feedstock for anaerobic digestion, as there are difficulties with its breakdown by bacteria, so pretreatment may be necessary [77]. The use of dry anaerobic digestion technology allows for treating wastes containing high values of organic matter in their composition, such as municipal solid waste and agricultural waste [76]. By analyzing the water footprint and substrate hydration for dry digestion technology, it was estimated that it requires four to ten times less water than wet processes [78]. This fact also has the benefit of reducing the volume of the digester and the savings associated with substrate pretreatment processes, as it only requires the removal of very large particles—larger than 5 cm [79]. Challenges posed by the dry anaerobic digestion process relate to generating a homogeneous mixture and transportation. The use of equipment for transporting solid substrates is more expensive than for liquid substrates. It is possible to design and build pumps, belts, or screw conveyors transporting substances with a high dry matter value [80]. The authors of the paper [81] show the problem associated with the inhibition of the dry fermentation process when the concentration of total solids is above 40%. At such a high level of total solids, methane bacteria have difficulty decomposing substrates. An excessively high amount of total solids can also cause plant heating problems [78,81].

4. Substrate Pretreatment as Key to Increasing Anaerobic Digestion Process Efficiency

Biogas production technology is constantly optimized for biological processes and chemical reactions to increase productivity and reduce operating costs [82]. It is theoretically possible to carry out the methane anaerobic digestion process for the organic fraction of any substrate. Depending on availability, it is possible to process wood, crop residue, lignocellulosic waste, food waste, or cotton stalks [19]. Some feedstocks are not naturally adapted to anaerobic digestion, as they are characterized by complicated or very long decomposition by bacteria. In addition, some of the raw materials may also contain natural inhibitors of the process. Therefore, it is becoming necessary to develop technology related to the pretreatment of substrates allowing the management of difficult-to-degrade wastes, which can contribute to increasing the potential of biogas facilities worldwide [83,84].

Most raw materials inherently characterized by susceptibility to fermentation, such as slurry and sewage sludge, are used. This type of waste, too, often requires pretreatment processes due to excessively high levels of hydration, which reduces methane efficiency. Using appropriate pretreatment technology, it is possible to increase the availability of valuable biogas substrates while helping to reduce environmental pollution [83,85]. Substrates containing large amounts of cellulose (40–60%) and hemicellulose (20–40%) after pretreatment have high biogas potential [86]. Waste containing lignocellulosic compounds is one of the most considerable organic resources in the world, providing an average of about 200 billion tons per year [87]. Organic wastes, such as bird feathers, contain more than 90% creatine in their content [88]. The use of pretreatment allows creatine to be broken down into oligomers, which are easily submitted to anaerobic fermentation [89]. Waste from fruit and food processing are also substrates with high methane potential after pretreatment [83]. In recent years, research has been conducted to manage waste polyethylene terephthalate (PET). Yoshida et al. [89] found that a new type of bacteria *Ideonella sakaiensis* 201-F6 can degrade PET compounds, but further research is needed to expand the scale and possibilities of this type of technology [89]. An innovative option for converting problematic waste is gasification technology before anaerobic digestion. Gasification converts the substrate into synthesis gas, which is directed into the environment with anaerobic bacteria, thus producing biogas [90]. Combining the two types of technology brings some benefits [83].

Substrate pretreatment processes are designed to improve availability and facilitate anaerobic microorganisms' utilization of organic matter. Several pretreatment types are classified as chemical, biological, mechanical, and thermal, respectively [91]. In addition, substrates are often prepared by removing solid contaminants such as sand and metals, which can be found in municipal waste. In addition, pretreatment allows for grinding the feedstock or even removing process inhibitors such as oils. An important aspect also concerns the compaction of substrates before they are delivered to the biogas plant site. This procedure is an opportunity that allows for reductions related to greenhouse gas emissions. The reason for the unfavorable water and carbon footprint of biogas plants is the necessity to transport substrate characterized by low biogas efficiency and then manage the highly hydrated digestate pulp [83,92,93]. Similarly, in the case of chemical methods, various types of chemical compounds, such as strong acids and alkalis, are used. The acidic chemical treatment process allows lignocellulosic compounds.

Analyzing the aspect of the application of storage solution leads to significant cost reduction at the storage and handling stage of the biomass supply chain, which results in considerable cost savings for the whole biomass logistics function. This reduction exceeds by far the extra cost imposed by biomass material losses. However, side-effects of applying cheaper storage solutions without biomass drying, such as a heating value reduction in the biomass, health and fire risks, etc., should be further investigated [94,95].

4.1. Chemical and Biological Pretreatment

The use of the pretreatment of substrates by biological and chemical methods is relatively the same. In the case of chemical methods, various types of chemical compounds, such as strong acids and alkalis, are used. The acidic chemical treatment process allows lignocellulosic compounds to be broken down into simpler monosaccharides [96]. In addition, the acidic reaction of this type of treatment can be controlled by the presence of hydrolytic bacteria [97]. High costs resulting from the pretreatment of substrates by acidic methods limit the development of this technology on the industrial scale of anaerobic digestion processes [98]. Another type of chemical method is alkaline compounds such as hydroxides, which allow them to be used at ambient temperatures [99]. The anaerobic digestion process may require the addition of alkaline reagents to balance the pH, and alkaline pretreatment is a preferred method over acidic pretreatment [100]. Research by Liew et al. [101] showed that the pretreatment of leaves using a 3.5% NaOH solution allows for a 20% increase in methane efficiency within three days. This type of treatment contributes to an increased anaerobic digestion efficiency for substrates containing lignocellulose compounds. Continuous anaerobic digestion with substrates after alkaline pretreatment can lead to salt accumulation and pH increase, thus contributing to the inhibition of the methanation process [101,102]. Chemical treatment processes are also not widely used on an industrial scale due to the lack of economic viability currently resulting from the high cost of alkali. However, this type of treatment may be the only option for highly acidic or lignin-rich substrates to ensure a stable anaerobic digestion process [103].

Biological pretreatment of substrates can be carried out at a low temperature and without additional chemicals. It includes processes under aerobic and anaerobic conditions, but this type of substrate preparation is not used for municipal waste [96]. The treatment conditions of anaerobic technology are often used as a pre-acidification or dark anaerobic digestion. This technology makes it possible to separate the methane generation process from hydrolysis and acid production. The pH value for the pre-acidification stage is between 4 and 6, which inhibits the methane generation process and causes volatile fatty acids to accumulate. In a study by Liu et al. [104], a 21% higher methane efficiency was achieved by introducing a pre-acidification stage for household waste. In addition, it resulted in the benefit of a higher methane concentration in biogas [103,104]. Compared to other pretreatment methods, biological methods require a more extended period of substrate preparation while having low efficiency [105]. Research conducted by Mshandete et al. [106] also presents pretreatment methods involving aeration. Their tests showed an increased methane production efficiency of 26% for a 9 h treatment stage. Prolongation of the assumed aeration stage leads to the aerobic breakdown of the substrate and reduces the amount of methane produced [106].

4.2. Mechanical and Thermal Pretreatment

Pretreatment of substrates using mechanical and thermal methods is categorized as a physical process. The rationale for using mechanical pretreatment is to reduce the particle size of substrates while increasing the surface area of bacterial activity [18]. In addition, grinding the substrates facilitates the mixing process in the digesters and reduces the problem associated with dross formation. Most industrial biogas plants use mechanical processing of substrates, allowing for uniformity of the feedstock mixture [101]. Nah et al. [107] conducted research related to substrate pretreatment using high-pressure particle breaking. This process reduced the hydraulic retention time of sludge from 13 days to 6 days while maintaining the same process efficiency. This research was conducted only on a laboratory scale, and the final stage did not test the methane content of the biogas [107]. Fine grinding of waste containing lignocellulosic compounds increases the anaerobic digestion process's efficiency, but too fine particles can cause acidification because they dissolve quickly [96]. In addition, the disadvantages of mechanical treatment processes include the possibility of damage from inert materials such as stones [96]. A number of researchers have studied the effect of knife milling on biogas production. Menind and Normak [108] found that about a 10% higher gas yield was obtained when hay was ground to 0.5 mm compared to 20–30 mm. A different investigation found that grinding sisal fibers from 100 mm to 2 mm produced about 20–25% higher gas yields [109].

The thermal pretreatment process is based on processing substrates under high temperatures (typically 125 to 190 °C) and pressure while maintaining the set conditions for about an hour [96]. Biogas plants using substrates after thermal pretreatment can use an increased reactor load factor and conduct a more stable anaerobic digestion process [108]. A crucial factor during thermal treatment is selecting an appropriate temperature value. If the value is too high, feedstock substrates can be degraded. In addition, conducting the thermal process allows the destruction of pathogenic pathogens contained in some wastes [96,110]. An example of the thermal pretreatment of feedstock on an industrial scale is the thermo-druck-hydrolyse (TDH) process. The technology has been used for diluting to about 10–15% dry weight of kitchen waste and plastics. The TDH reactor is pressurized for about 20 min at 20 to 30 bar and 170–200 °C. It was found that this type of technology increased biogas production by 20 to 30% for the substrates analyzed. Thermal pretreatment plays a unique role in locations with a free supply of waste heat from plants such as factories or power plants [96]. Table 2 shows the advantages effect of pretreatment on the fermentation process from selected methods.

Table 2. Effect of pretreatment on the fermentation process (own elaboration based on [94–107]).

Pretreatment Process	Advantages	Reference
Chemical	decomposition of lignocellulose only solution for highly acidic substrate	[98,101,102]
Biological	used as pre-acidification low temperature	[96,104]
Mechanical	increasing the surface area for bacterial activity	[94,97,105]
Thermal	more stable anaerobic digestion process	[94,95,107]

5. Conclusions and Directions for Further Research

In addition to managing waste, biogas plants also process significant amounts of ballast water in anaerobic digestion. The agricultural sector and related agricultural production are the largest consumers of water resources. The development and exploitation of biogas plants that use agricultural residues optimize aspects of the water footprint. In addition, waste biomass is generally characterized by high hydration, so pretreatment methods are required. Removing excess moisture even before transporting the substrates to the biogas plant site is good practice.

Recently, the situation related to protecting the world's water resources is also not insignificant. Creating assumptions in the context of water limits in the future can help avoid the problem of unsustainable water consumption. Numerous studies are being conducted to determine the water footprint for products and industrial plants, including biogas plants and their substrates. It is becoming necessary to look for solutions related to the low efficiency of the anaerobic digestion process when over-hydrated substrates are used. Due to the multitude of available technologies related to the pretreatment of substrates and for the direct execution of the anaerobic digestion process, further research needs to optimize the discussed solutions. It should also be emphasized that pretreatment processes are often an expensive and energy-intensive technology. The most common method used to pretreat substrates is a mechanical one. Reducing the particle size of substrates results in a greater surface accessibility for microorganisms.

Transportation distance is essential in the production and delivery of substrate for a biogas plant. Depending on the conditions of the selected location for a newly built biogas plant, the impact of harmful greenhouse gas emissions associated with transportation should be considered. It is proposed to initiate new research on transportation elements and biogas substrate management. The use of modern technologies related to the continuous analysis of selected substrate parameters and control of delivery processes can allow for a breakthrough optimization of the biogas sector in Poland and the world.

Author Contributions: Conceptualization, M.N. and W.C.; methodology, M.N. and W.C.; software, M.N.; validation, M.N. and W.C.; formal analysis, M.N. and W.C.; investigation, M.N. and W.C.; resources, M.N. and W.C.; data curation, M.N. and W.C.; writing—original draft preparation, M.N., W.B. and W.C.; writing—review and editing, M.N. and W.C.; visualization, M.N.; supervision, W.C.; funding acquisition, M.N. and W.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Sanson, A.V.; Van Hoorn, J.; Burke, S.E.L. Responding to the Impacts of the Climate Crisis on Children and Youth. *Child Dev. Perspect.* **2019**, *13*, 201–207. [CrossRef]
2. Lamb, W.F.; Wiedmann, T.; Pongratz, J.; Andrew, R.; Crippa, M.; Olivier, J.G.J.; Wiedenhofer, D.; Mattioli, G.; Khourdajie, A.A.; House, J.; et al. A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environ. Res. Lett.* **2021**, *16*, 073005. [CrossRef]
3. Ahmad, S.; Razzaq, S.; Rehan, M.A.; Hashmi, M.A.; Ali, S.; Amjad, M.S.; Mehmood, U. Experimental Investigation of Novel Fixed Dome Type Biogas Plant using Gas Recovery Chamber in Rural Areas of Pakistan. *Int. J. Renew. Energy Res. IJRER* **2019**, *9*, 1537–1547.
4. Patinvoh, R.J.; Taherzadeh, M.J. Challenges of biogas implementation in developing countries. *Curr. Opin. Environ. Sci. Health* **2019**, *12*, 30–37. [CrossRef]
5. Jarrar, L.; Ayadi, O.; Al Asfar, J. Techno-economic Aspects of Electricity Generation from a Farm Based Biogas Plant. *J. Sustain. Dev. Energy Water Environ. Syst.* **2020**, *8*, 476–492. [CrossRef]
6. Adeleke, A.; Odusote, J.; Lasode, O.; Ikubanni, P.; Madhurai, M.; Paswan, D. Evaluation of thermal decomposition characteristics and kinetic parameters of melina wood. *Biofuels* **2022**, *13*, 117–123. [CrossRef]
7. Ibikunle, R.A.; Titiladunayo, I.F.; Lukman, A.F.; Dahunsi, S.O.; Akeju, E.A. Municipal solid waste sampling, quantification and seasonal characterization for power evaluation: Energy potential and statistical modelling. *Fuel* **2020**, *277*, 118122. [CrossRef]
8. Werghemmi, W.; Fayssal, S.A.; Mazouz, H.; Hajjaj, H.; Hajji, L. Olive and green tea leaves extract in *Pleurotus ostreatus* var. florida culture media: Effect on mycelial linear growth rate, diameter and growth induction index. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1090*, 012020. [CrossRef]
9. Elbagory, M.; El-Nahrawy, S.; Omara, A.E.-D.; Eid, E.M.; Bachheti, A.; Kumar, P.; Abou Fayssal, S.; Adelodun, B.; Bachheti, R.K.; Kumar, P.; et al. Sustainable Bioconversion of Wetland Plant Biomass for *Pleurotus ostreatus* var. florida Cultivation: Studies on Proximate and Biochemical Characterization. *Agriculture* **2022**, *12*, 2095. [CrossRef]
10. Czekała, W.; Janczak, D.; Pochwatka, P.; Nowak, M.; Dach, J. Gases Emissions during Composting Process of Agri-Food Industry Waste. *Appl. Sci.* **2022**, *12*, 9245. [CrossRef]
11. Jansson, A.T.; Patinvoh, R.J.; Sárvári Horváth, I.; Taherzadeh, M.J. Dry Anaerobic Digestion of Food and Paper Industry Wastes at Different Solid Contents. *Fermentation* **2019**, *5*, 40. [CrossRef]
12. Adeleke, A.A.; Odusote, J.K.; Ikubanni, P.P.; Orhadahwe, T.A.; Lasode, O.A.; Ammasi, A.; Kumar, K. Ash analyses of bio-coal briquettes produced using blended binder. *Sci. Rep.* **2021**, *11*, 547. [CrossRef] [PubMed]
13. Liu, H.; Kumar, V.; Jia, L.; Sarsaiya, S.; Kumar, D.; Juneja, A.; Zhang, Z.; Sindhu, R.; Binod, P.; Bhatia, S.K.; et al. Biopolymer poly-hydroxyalkanoates (PHA) production from apple industrial waste residues: A review. *Chemosphere* **2021**, *284*, 131427. [CrossRef] [PubMed]
14. World Energy Outlook 2020—Analysis. Available online: https://www.iea.org/reports/world-energy-outlook-2020 (accessed on 1 February 2023).
15. Aberilla, J.M.; Gallego-Schmid, A.; Azapagic, A. Environmental sustainability of small-scale biomass power technologies for agricultural communities in developing countries. *Renew. Energy* **2019**, *141*, 493–506. [CrossRef]
16. Anal, A.K. Quality Ingredients and Safety Concerns for Traditional Fermented Foods and Beverages from Asia: A Review. *Fermentation* **2019**, *5*, 8. [CrossRef]
17. Gerbens-Leenes, W.; Vaca-Jiménez, S.; Mekonnen, M. Burning Water, Overview of the Contribution of Arjen Hoekstra to the Water Energy Nexus. *Water* **2020**, *12*, 2844. [CrossRef]
18. Irfan, M.; Zhao, Z.-Y.; Panjwani, M.K.; Mangi, F.H.; Li, H.; Jan, A.; Ahmad, M.; Rehman, A. Assessing the energy dynamics of Pakistan: Prospects of biomass energy. *Energy Rep.* **2020**, *6*, 80–93. [CrossRef]

19. Branco, R.H.R.; Serafim, L.S.; Xavier, A.M.R.B. Second Generation Bioethanol Production: On the Use of Pulp and Paper Industry Wastes as Feedstock. *Fermentation* **2019**, *5*, 4. [CrossRef]
20. Robak, K.; Balcerek, M. Review of Second Generation Bioethanol Production from Residual Biomass. *Food Technol. Biotechnol.* **2018**, *56*, 174–187. [CrossRef]
21. Chowdhury, H.; Loganathan, B. Third-generation biofuels from microalgae: A review. *Curr. Opin. Green Sustain. Chem.* **2019**, *20*, 39–44. [CrossRef]
22. Nugent, N.; Rhinard, M. The 'political' roles of the European Commission. *J. Eur. Integr.* **2019**, *41*, 203–220. [CrossRef]
23. Khan, M.U.; Lee, J.T.E.; Bashir, M.A.; Dissanayake, P.D.; Ok, Y.S.; Tong, Y.W.; Shariati, M.A.; Wu, S.; Ahring, B.K. Current status of biogas upgrading for direct biomethane use: A review. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111343. [CrossRef]
24. Wielgosinski, G.; Czerwińska, J. Smog Episodes in Poland. *Atmosphere* **2020**, *11*, 277. [CrossRef]
25. Kozłowski, K.; Pietrzykowski, M.; Czekała, W.; Dach, J.; Kowalczyk-Juśko, A.; Jóźwiakowski, K.; Brzoski, M. Energetic and economic analysis of biogas plant with using the dairy industry waste. *Energy* **2019**, *183*, 1023–1031. [CrossRef]
26. Theuerl, S.; Herrmann, C.; Heiermann, M.; Grundmann, P.; Landwehr, N.; Kreidenweis, U.; Prochnow, A. The Future Agricultural Biogas Plant in Germany: A Vision. *Energies* **2019**, *12*, 396. [CrossRef]
27. Kumar, P.; Eid, E.M.; Taher, M.A.; El-Morsy, M.H.E.; Osman, H.E.M.; Al-Bakre, D.A.; Adelodun, B.; Abou Fayssal, S.; Goala, M.; Mioč, B.; et al. Biotransforming the Spent Substrate of Shiitake Mushroom (*Lentinula edodes* Berk.): A Synergistic Approach to Biogas Production and Tomato (*Solanum lycopersicum* L.) Fertilization. *Horticulturae* **2022**, *8*, 479. [CrossRef]
28. Czekała, W. Digestate as a Source of Nutrients: Nitrogen and Its Fractions. *Water* **2022**, *14*, 4067. [CrossRef]
29. Mathioudakis, V.; Gerbens-Leenes, P.W.; Van der Meer, T.H.; Hoekstra, A.Y. The water footprint of second-generation bioenergy: A comparison of biomass feedstocks and conversion techniques. *J. Clean. Prod.* **2017**, *148*, 571–582. [CrossRef]
30. Czekała, W.; Lewicki, A.; Pochwatka, P.; Czekała, A.; Wojcieszak, D.; Jóźwiakowski, K.; Waliszewska, H. Digestate management in Polish farms as an element of the nutrient cycle. *J. Clean. Prod.* **2020**, *242*, 118454. [CrossRef]
31. Mudryk, K.; Frączek, J.; Jewiarz, M.; Wróbel, M.; Dziedzic, K. Analysis of Mechanical Dewatering of Digestate. *Agric. Eng.* **2016**, *20*, 157–166. [CrossRef]
32. Yuan, Z.L.; Gerbens-Leenes, P.W. Biogas feedstock potentials and related water footprints from residues in China and the European Union. *Sci. Total Environ.* **2021**, *793*, 148340. [CrossRef] [PubMed]
33. Mekonnen, M.M.; Gerbens-Leenes, W. The Water Footprint of Global Food Production. *Water* **2020**, *12*, 2696. [CrossRef]
34. IRENA. *Renewable Energy Prospects: China, REmap 2030 Analysis*; IRENA: Abu Dhabi, UAE, 2014; Available online: http://www.irena.org/remap/IRENA_REmap_China_report_2014.pdf (accessed on 10 March 2023).
35. Langeveld, H.; Kalf, R.; Elbersen, H.W. Bioenergy production chain development in the Netherlands: Key factors for success. *Biofuels Bioprod. Biorefining* **2010**, *4*, 484–493. [CrossRef]
36. Li, Y.; Chen, Y.; Wu, J. Enhancement of methane production in anaerobic digestion process: A review. *Appl. Energy* **2019**, *240*, 120–137. [CrossRef]
37. Mikhaylov, A.; Moiseev, N.; Aleshin, K.; Burkhardt, T. Global climate change and greenhouse effect. *Entrep. Sustain. Issues* **2020**, *7*, 2897–2913. [CrossRef]
38. Abbas, I.; Liu, J.; Noor, R.S.; Faheem, M.; Farhan, M.; Ameen, M.; Shaikh, S.A. Development and performance evaluation of small size household portable biogas plant for domestic use. *Biomass Convers. Biorefinery* **2022**, *12*, 3107–3119. [CrossRef]
39. Ellacuriaga, M.; García-Cascallana, J.; Gómez, X. Biogas Production from Organic Wastes: Integrating Concepts of Circular Economy. *Fuels* **2021**, *2*, 144–167. [CrossRef]
40. Agabo-García, C.; Pérez, M.; Rodríguez-Morgado, B.; Parrado, J.; Solera, R. Biomethane production improvement by enzymatic pre-treatments and enhancers of sewage sludge anaerobic digestion. *Fuel* **2019**, *255*, 115713. [CrossRef]
41. Mao, C.; Wang, Y.; Wang, X.; Ren, G.; Yuan, L.; Feng, Y. Correlations between microbial community and C:N:P stoichiometry during the anaerobic digestion process. *Energy* **2019**, *174*, 687–695. [CrossRef]
42. Kushkevych, I.; Vítězová, M.; Vítěz, T.; Kováč, J.; Kaucká, P.; Jesionek, W.; Bartoš, M.; Barton, L. A new combination of substrates: Biogas production and diversity of the methanogenic microorganisms. *Open Life Sci.* **2018**, *13*, 119–128. [CrossRef]
43. Schnürer, A. Biogas Production: Microbiology and Technology. *Adv. Biochem. Eng. Biotechnol.* **2016**, *156*, 195–234. [CrossRef] [PubMed]
44. McGenity, T.J.; Timmis, K.N.; Fernández, B.N. *Hydrocarbon and Lipid Microbiology Protocols*; Springer: Berlin/Heidelberg, Germany, 2016.
45. Nwokolo, N.; Mukumba, P.; Obileke, K.; Enebe, M. Waste to Energy: A Focus on the Impact of Substrate Type in Biogas Production. *Processes* **2020**, *8*, 1224. [CrossRef]
46. Rasit, N.; Idris, A.; Harun, R.; Wan Ab Karim Ghani, W.A. Effects of lipid inhibition on biogas production of anaerobic digestion from oily effluents and sludges: An overview. *Renew. Sustain. Energy Rev.* **2015**, *45*, 351–358. [CrossRef]
47. Rajagopal, R.; Massé, D.I.; Singh, G. A critical review on inhibition of anaerobic digestion process by excess ammonia. *Bioresour. Technol.* **2013**, *143*, 632–641. [CrossRef]
48. Westerholm, M.; Moestedt, J.; Schnürer, A. Biogas production through syntrophic acetate oxidation and deliberate operating strategies for improved digester performance. *Appl. Energy* **2016**, *179*, 124–135. [CrossRef]
49. Solowski, G.; Konkol, I.; Cenian, A. Production of hydrogen and methane from lignocellulose waste by fermentation. A review of chemical pre-treatment for enhancing the efficiency of the digestion process. *J. Clean. Prod.* **2020**, *267*, 121721. [CrossRef]

50. Ullah Khan, I.; Hafiz Dzarfan Othman, M.; Hashim, H.; Matsuura, T.; Ismail, A.F.; Rezaei-DashtArzhandi, M.; Wan Azelee, I. Biogas as a renewable energy fuel—A review of biogas upgrading, utilization and storage. *Energy Convers. Manag.* **2017**, *150*, 277–294. [CrossRef]
51. Perez-Esteban, N.; Vinardell, S.; Vidal-Antich, C.; Peña-Picola, S.; Chimenos, J.M.; Peces, M.; Dosta, J.; Astals, S. Potential of anaerobic co-fermentation in wastewater treatment plants: A review. *Sci. Total Environ.* **2022**, *813*, 152498. [CrossRef]
52. Abubakar, A.M.; Yunus, M.U. Reporting Biogas Data from Various Feedstock. *Int. J. Form. Sci. Curr. Future Res. Trends* **2021**, *11*, 23–36.
53. Bacenetti, J.; Lovarelli, D.; Ingrao, C.; Tricase, C.; Negri, M.; Fiala, M. Assessment of the influence of energy density and feedstock transport distance on the environmental performance of methane from maize silages. *Bioresour. Technol.* **2015**, *193*, 256–265. [CrossRef]
54. Huopana, T.; Song, H.; Kolehmainen, M.; Niska, H. A regional model for sustainable biogas electricity production: A case study from a Finnish province. *Appl. Energy* **2013**, *102*, 676–686. [CrossRef]
55. Bochmann, G.; Montgomery, L.F.R. 4—Storage and pre-treatment of substrates for biogas production. In *The Biogas Handbook*; Wellinger, A., Murphy, J., Baxter, D., Eds.; Woodhead Publishing Series in Energy; Woodhead Publishing: Cambridge, UK, 2013; pp. 85–103. ISBN 978-0-85709-498-8. [CrossRef]
56. Tucki, K.; Piatkowski, P.; Wojcik, G. Selected aspects from the analysis of the agricultural biogas plants sector in Poland. *Energy Mark.* **2016**, *122*, 54–58.
57. May, G.; Piekarski, W.; Kowalczyk-Juśko, A. Logistics of supplying raw material to an agricultural biogas plant. *Logistics* **2014**.
58. Jolliet, O.; Margni, M.; Charles, R.; Humbert, S.; Payet, J.; Rebitzer, G.; Rosenbaum, R. IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. *Int. J. Life Cycle Assess.* **2003**, *8*, 324–330. [CrossRef]
59. Muradin, M.; Foltynowicz, Z. Logistic aspects of the ecological impact indicators of an agricultural biogas plant. *Logforum* **2018**, *14*, 535–547. [CrossRef]
60. Dach, J.; Pulka, J.; Janczak, D.; Lewicki, A.; Pochwatka, P.; Oniszczuk, T. Energetic Assessment of Biogas Plant Projects Based on Biowaste and Maize Silage Usage. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2020; Volume 505, p. 012029.
61. Borek, K.; Romaniuk, W. Biogas Installations for Harvesting Energy and Utilization of Natural Fertilisers. *Agric. Eng.* **2020**, *24*, 1–14. [CrossRef]
62. Stanbury, P.F.; Whitaker, A.; Hall, S.J. *Principles of Fermentation Technology*; Elsevier: Amsterdam, The Netherlands, 2013; ISBN 978-1-4832-9291-5.
63. Stürmer, B. Feedstock change at biogas plants–Impact on production costs. *Biomass Bioenergy* **2017**, *98*, 228–235. [CrossRef]
64. Koryś, K.A.; Latawiec, A.E.; Grotkiewicz, K.; Kuboń, M. The Review of Biomass Potential for Agricultural Biogas Production in Poland. *Sustainability* **2019**, *11*, 6515. [CrossRef]
65. Nordberg, A.; Jarvis, A.; Stenberg, B.; Mathisen, B.; Svensson, B.H. Anaerobic digestion of alfalfa silage with recirculation of process liquid. *Bioresour. Technol.* **2007**, *98*, 104–111. [CrossRef]
66. Adekunle, K.F.; Okolie, J.A. A Review of Biochemical Process of Anaerobic Digestion. *Adv. Biosci. Biotechnol.* **2015**, *06*, 205. [CrossRef]
67. Shahriari, H.; Warith, M.; Hamoda, M.; Kennedy, K.J. Effect of leachate recirculation on mesophilic anaerobic digestion of food waste. *Waste Manag.* **2012**, *32*, 400–403. [CrossRef] [PubMed]
68. Weiland, P. Biogas production: Current state and perspectives. *Appl. Microbiol. Biotechnol.* **2010**, *85*, 849–860. [CrossRef] [PubMed]
69. Angelonidi, E.; Smith, S. A comparison of wet and dry anaerobic digestion processes for the treatment of municipal solid waste and food waste. *Water Environ. J.* **2015**, *29*, 549–557. [CrossRef]
70. Luning, L.; van Zundert, E.H.M.; Brinkmann, A.J.F. Comparison of dry and wet digestion for solid waste. *Water Sci. Technol.* **2003**, *48*, 15–20. [CrossRef] [PubMed]
71. Stolze, Y.; Zakrzewski, M.; Maus, I.; Eikmeyer, F.; Jaenicke, S.; Rottmann, N.; Siebner, C.; Pühler, A.; Schlüter, A. Comparative metagenomics of biogas-producing microbial communities from production-scale biogas plants operating under wet or dry fermentation conditions. *Biotechnol. Biofuels* **2015**, *8*, 14. [CrossRef] [PubMed]
72. Czubaszek, R.; Wysocka-Czubaszek, A.; Banaszuk, P. GHG Emissions and Efficiency of Energy Generation through Anaerobic Fermentation of Wetland Biomass. *Energies* **2020**, *13*, 6497. [CrossRef]
73. Abdelsalam, E.M.; Samer, M.; Amer, M.A.; Amer, B.M.A. Biogas production using dry fermentation technology through co-digestion of manure and agricultural wastes. *Environ. Dev. Sustain.* **2021**, *23*, 8746–8757. [CrossRef]
74. Jha, A.K.; Li, J.; Zhang, L.; Ban, Q.; Jin, Y. Comparison between Dry and Wet Anaerobic Digestions of Cow Dung under mesophilic and thermophilic conditions. *Adv. Water Resour. Prot* **2013**, *1*, 28–38.
75. Vogel, T.; Ahlhaus, M.; Barz, M. Optimization of the biogas production from grass by dry-wet fermentation. In Proceedings of the Eighth International Scientific Conference—Engineering for Rural Development, Jelgava, Latvia, 28–29 May 2009; LLU: Loma Linda, CA, USA, 2009.
76. Rocamora, I.; Wagland, S.T.; Villa, R.; Simpson, E.W.; Fernández, O.; Bajón-Fernández, Y. Dry anaerobic digestion of organic waste: A review of operational parameters and their impact on process performance. *Bioresour. Technol.* **2020**, *299*, 122681. [CrossRef]
77. Yu, Q.; Liu, R.; Li, K.; Ma, R. A review of crop straw pre-treatment methods for biogas production by anaerobic digestion in China. *Renew. Sustain. Energy Rev.* **2019**, *107*, 51–58. [CrossRef]

78. Shapovalov, Y.; Zhadan, S.; Bochmann, G.; Salyuk, A.; Nykyforov, V. Dry Anaerobic Digestion of Chicken Manure: A Review. *Appl. Sci.* **2020**, *10*, 7825. [CrossRef]
79. Rapport, J.L.; Zhang, R.; Williams, R.B.; Jenkins, B.M. Anaerobic Digestion technologies for the treatment of Municipal Solid Waste. *Int. J. Environ. Waste Manag.* **2012**, *9*, 100–122. [CrossRef]
80. Mata-Alvarez, J. *Biomethanization of the Organic Fraction of Municipal Solid Wastes*; IWA Publishing: Barcelona, Spain, 2003.
81. Kothari, R.; Pandey, A.K.; Kumar, S.; Tyagi, V.V.; Tyagi, S.K. Different aspects of dry anaerobic digestion for bio-energy: An overview. *Renew. Sustain. Energy Rev.* **2014**, *39*, 174–195. [CrossRef]
82. Anukam, A.; Mohammadi, A.; Naqvi, M.; Granström, K. A Review of the Chemistry of Anaerobic Digestion: Methods of Accelerating and Optimizing Process Efficiency. *Processes* **2019**, *7*, 504. [CrossRef]
83. Patinvoh, R.J.; Osadolor, O.A.; Chandolias, K.; Sárvári Horváth, I.; Taherzadeh, M.J. Innovative pre-treatment strategies for biogas production. *Bioresour. Technol.* **2017**, *224*, 13–24. [CrossRef]
84. Maneein, S.; Milledge, J.J.; Nielsen, B.V.; Harvey, P.J. A Review of Seaweed pre-Treatment Methods for Enhanced Biofuel Production by Anaerobic Digestion or Fermentation. *Fermentation* **2018**, *4*, 100. [CrossRef]
85. Cao, B.; Zhang, T.; Zhang, W.; Wang, D. Enhanced technology based for sewage sludge deep dewatering: A critical review. *Water Res.* **2021**, *189*, 116650. [CrossRef] [PubMed]
86. Kang, Q.; Appels, L.; Tan, T.; Dewil, R. Bioethanol from Lignocellulosic Biomass: Current Findings Determine Research Priorities. *Sci. World J.* **2014**, *2014*, e298153. [CrossRef]
87. Zhang, Y.-H.P. Reviving the carbohydrate economy via multi-product lignocellulose biorefineries. *J. Ind. Microbiol. Biotechnol.* **2008**, *35*, 367–375. [CrossRef]
88. Patinvoh, R.J.; Feuk-Lagerstedt, E.; Lundin, M.; Sárvári Horváth, I.; Taherzadeh, M.J. Biological pre-treatment of Chicken Feather and Biogas Production from Total Broth. *Appl. Biochem. Biotechnol.* **2016**, *180*, 1401–1415. [CrossRef]
89. Yoshida, S.; Hiraga, K.; Takehana, T.; Taniguchi, I.; Yamaji, H.; Maeda, Y.; Toyohara, K.; Miyamoto, K.; Kimura, Y.; Oda, K. A bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* **2016**, *351*, 1196–1199. [CrossRef] [PubMed]
90. Phillips, J.R.; Huhnke, R.L.; Atiyeh, H.K. Syngas Fermentation: A Microbial Conversion Process of Gaseous Substrates to Various Products. *Fermentation* **2017**, *3*, 28. [CrossRef]
91. Taherzadeh, M.J.; Karimi, K. Pretreatment of Lignocellulosic Wastes to Improve Ethanol and Biogas Production: A Review. *Int. J. Mol. Sci.* **2008**, *9*, 1621–1651. [CrossRef] [PubMed]
92. Brentrup, F.; Hoxha, A.; Christensen, B. Carbon Footprint Analysis of Mineral Fertilizer Production in Europe and Other World Regions. In Proceedings of the 10th International Conference on Life Cycle Assessment of Food, Dublin, Ireland, 19–21 October 2016.
93. Bharathiraja, D.B.; Sudharsana, T.; Jayamuthunagai, J.; Ramanujam, P.K.; Sivasankaran, C.; Iyyappan, J. Biogas production—A review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renew. Sustain. Energy Rev.* **2018**, *90*, 570–582. [CrossRef]
94. Liu, Z.-H.; Qin, L.; Jin, M.-J.; Pang, F.; Li, B.-Z.; Kang, Y.; Dale, B.E.; Yuan, Y.-J. Evaluation of storage methods for the conversion of corn stover biomass to sugars based on steam explosion pretreatment. *Bioresour. Technol.* **2013**, *132*, 5–15. [CrossRef] [PubMed]
95. Rentizelas, A.; Tolis, A.; Tatsiopoulos, I. Logistics issues of biomass: The storage problem and the multi-biomass supply chain. *Renew. Sustain. Energy Rev.* **2009**, *13*, 887–894. [CrossRef]
96. Ariunbaatar, J.; Panico, A.; Esposito, G.; Pirozzi, F.; Lens, P.N.L. Pre-treatment methods to enhance anaerobic digestion of organic solid waste. *Appl. Energy* **2014**, *123*, 143–156. [CrossRef]
97. Wan, C.; Li, Y. Fungal pre-treatment of lignocellulosic biomass. *Biotechnol. Adv.* **2012**, *30*, 1447–1457. [CrossRef]
98. Kumar, D.; Murthy, G.S. Impact of pre-treatment and downstream processing technologies on economics and energy in cellulosic ethanol production. *Biotechnol. Biofuels* **2011**, *4*, 27. [CrossRef]
99. Mao, C.; Feng, Y.; Wang, X.; Ren, G. Review on research achievements of biogas from anaerobic digestion. *Renew. Sustain. Energy Rev.* **2015**, *45*, 540–555. [CrossRef]
100. Li, H.; Li, C.; Liu, W.; Zou, S. Optimized alkaline pre-treatment of sludge before anaerobic digestion. *Bioresour. Technol.* **2012**, *123*, 189–194. [CrossRef] [PubMed]
101. Liew, L.N.; Shi, J.; Li, Y. Enhancing the solid-state anaerobic digestion of fallen leaves through simultaneous alkaline treatment. *Bioresour. Technol.* **2011**, *102*, 8828–8834. [CrossRef] [PubMed]
102. Chen, Y.; Cheng, J.J.; Creamer, K.S. Inhibition of anaerobic digestion process: A review. *Bioresour. Technol.* **2008**, *99*, 4044–4064. [CrossRef] [PubMed]
103. Montgomery, L.; Bochmann, G. *Pretreatment of Feedstock for Enhanced Biogas Production*; IEA Bioenergy: Paris, France, 2014; ISBN 978-1-910154-05-2.
104. Liu, D.; Liu, D.; Zeng, R.J.; Angelidaki, I. Hydrogen and methane production from household solid waste in the two-stage fermentation process. *Water Res.* **2006**, *40*, 2230–2236. [CrossRef] [PubMed]
105. Zheng, Y.; Zhao, J.; Xu, F.; Li, Y. Pretreatment of lignocellulosic biomass for enhanced biogas production. *Prog. Energy Combust. Sci.* **2014**, *42*, 35–53. [CrossRef]
106. Mshandete, A.; Björnsson, L.; Kivaisi, A.K.; Rubindamayugi, S.T.; Mattiasson, B. Enhancement of anaerobic batch digestion of sisal pulp waste by mesophilic aerobic pre-treatment. *Water Res.* **2005**, *39*, 1569–1575. [CrossRef]
107. Nah, I.W.; Kang, Y.W.; Hwang, K.-Y.; Song, W.-K. Mechanical pre-treatment of waste activated sludge for anaerobic digestion process. *Water Res.* **2000**, *34*, 2362–2368. [CrossRef]

108. Barber, W.P.F. Thermal hydrolysis for sewage treatment: A critical review. *Water Res.* **2016**, *104*, 53–71. [CrossRef]
109. Menind, A.; Normak, A. Study on grinding biomass as pre-treatment for biogasification. In *Agronomy Research*; Estonian Agricultural University: Tartu, Estonia, 2003; p. 155.
110. Skiadas, I.V.; Gavala, H.N.; Lu, J.; Ahring, B.K. Thermal pre-treatment of primary and secondary sludge at 70 degrees C prior to anaerobic digestion. *Water Sci. Technol.* **2005**, *52*, 161–166. [CrossRef]