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Methods for Treatment of Animal and Plant-Based Biomass Waste

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Abstract
In the work presented, effective methods of biomass processing for its reuse in the framework of the circular economy were determined. Based on various sources, a definition of biomass was obtained. The review covers preliminary operations, i.e., screening and grinding, as well as the methods of pressure and non-pressure agglomeration of plant and animal biomass, as well as the process of torrefaction of plant biomass. The analysis of the literature indicates various process and technological solutions for biomass processing, as well as provides numerous examples of the use of biomass in combination with other types of industrial waste and mineral additives. The activities undertaken as part of the work are consistent with the assumptions of the European Green Deal and are carried out in order to improve the management of waste streams (green productivity) and to increase the amount of recovered energy produced.

Keywords
biomass, agglomeration, torrefaction, waste management.

1. Introduction

In order to define what biomass is, it is not enough to provide one predetermined scientific definition. This is due to the fact that all legal texts, such as acts or regulations, establish their own definition of biomass. Very often, also sectors of the economy or even individual enterprises using or processing biomass create their own definitions.

The last amendment to the Polish Act of February 20, 2015, on Renewable Energy Sources (RES Act) defines biomass as biodegradable products, waste or other residues, the source of which is agricultural production, forestry production, fisheries, and aquaculture. Biomass also includes products resulting from its processing, such as pellets or biochar. In addition, the RES Act also includes biodegradable industrial and municipal waste, including waste from waste treatment installations, such as water treatment waste and sewage waste.

In turn, according to the current Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (EC Directive 2018/2001), biomass means products, waste or other biological by-products of agricultural activity, forestry, fisheries, aquaculture, and other related industries, including plant and animal matter and biodegradable waste (industrial and municipal) of biological origin.

In addition, both legal acts distinguish biomass of agricultural origin, i.e., the cultivation of energy crops, agricultural waste and agro-food processing, the source of which is agricultural production. The 2018/2001 EC Directive also distinguishes forest biomass (waste from forest management), biomass fuels (gaseous and solid) and biogas (gaseous fuels whose raw material is biomass). The RES Act divides the latter type of biomass into biogas (produced in waste processing installations, sewage treatment plants, and waste landfills) and agricultural biogas – obtained, for example, from the fermentation of agricultural products and by-products, animal manure, processing of agricultural products, forest biomass, and plant biomass).

Collating the above definitions into one, it is possible to define biomass as an organic substance, both of plant and animal origin, as well as products resulting from the processing of biomass, e.g., wood, slurry, manure, sewage sludge, energy plants, agricultural products (common corn, cereals, potatoes, beets), residues from the agro-food processing sector, and biofuels [1].

The following types of biomass can be distinguished:

– Forest biomass - firewood, branches, waste (needles, brushwood, bark, cuttings, etc.). Wood can also come from exploitation such as cutting in green areas, parks, roadsides. Additionally, the source of biomass production in this category is the wood sector, i.e., sawmills, furniture manufacturers generating various types of wood waste (sawdust, dust, shavings, etc.).
– Biomass of agricultural origin - agricultural products, waste, and other residues of agricultural activity (leaves of arable crops, silage), cultivation of energy crops (rape, flax, hemp and other oil plants, willow, miscanthus). They can be converted into gaseous fuels in biogas plants, burnt or used to produce briquettes.

– Organic waste - all the residues generated during animal husbandry, as well as agro-food production and processing, such as liquid manure, manure, molasses, fruit pomace, and slaughterhouse waste. This type of biomass also includes kitchen waste, shop waste and sewage sludge [2].

Every year, agriculture and the agro-food industry [3-4] generate over 10 million tonnes of waste, which is subject to management. The latest data, but only for biodegradable waste, was presented by the National Waste Management Plan 2022. In 2011-2013, the amount of waste in group 02, i.e., agriculture, horticulture, hydroponics, fishing, forestry, hunting and food processing, was 12.5 million tonnes. However, according to Daniel et al. [3], the problem of improper waste management appears more and more often. Moreover, the efficient and environmentally safe conversion of such by-products into, for example, food ingredients and/or new products will help to reduce the waste stream.

The most common types of waste generated by agriculture and various sectors of the food industry include potato pulp produced in the production of potato starch, buckwheat husk from the production of groats in cereal plants, rapeseed pomace from the production of rapeseed oil, herbal waste generated during drying, packing and segregating dried herbs, etc. These wastes are often used to a small extent, which is a problem for a given enterprise.

The uncontrolled decomposition of waste from agriculture and the agro-food industry (PRS) generates significant amounts of pollutants, including hazardous compounds and substances. Currently, it is becoming necessary to develop new, rational systems for processing waste from food production and processing [5-6].

According to the data of Statistics Poland for 2019 [7], although 56% of generated municipal waste was intended for recovery (including 25% for recycling), at the same time 43% of generated municipal waste was landfilled. However, only 1% of generated municipal waste was designated for neutralisation by incineration, but without energy recovery. Moreover, only 27% of municipal waste landfills are equipped with degassing installations with energy recovery. The above data clearly indicate that it is necessary to convert biomass waste into energy and / or useful products [8].

The aim of this study is to review the methods of biomass processing for its reuse in the circular economy and is the initial phase of works in the field of minimising the environmental burden and reusing environmentally harmful industrial waste.

2. Methods of Biomass Management

2.1. Preliminary operations

2.1.1. Screening

In biomass processing, the particle size of this material is of crucial importance. Therefore, it is necessary to determine the grain size composition of the biomass. The individual grain fractions of biomass are difficult to separate due to their physical properties, e.g., irregular shapes, high bed humidity, tendency to aggregate into agglomerates, etc. These properties intensify the phenomenon of blocking sieve openings and, as a result, decrease the efficiency and effectiveness of the screening process. It has been observed that for this type of material the phenomenon of blocking screen openings [9-13] occurs mainly in screens with low dynamics of screen movement, e.g., in rotary screens and drum screens. For this reason, for effective screening of biomass, vibrating screens should be used, especially those with a double frequency of vibrations [14-15]. The dynamic nature of the vibrating motion of these screens reduces the number of blocked screen openings and ensures the high efficiency of this process.

2.1.2. Grinding

The primary purpose of the comminution process is to reduce the size of the feed material to increase the specific surface area of the product. The shredded raw material can be used in further technological processes to obtain an appropriate final product that meets specific quality requirements.

The processes of shredding biomass structures require the use of significant energy inputs, and the typical devices used by industry include mills [16-17]. The selection of the device operation parameters depends on the physicochemical properties of the raw material and the required particle size composition of the mill product. The results of the research conducted so far indicate that the description of the grinding process carried out on a laboratory scale together with an attempt to adapt it further to an industrial scale require considering many, often mutually exclusive factors. This is due to the complexity of the destruction mechanisms of the structure (fibres) of the biomass and a large number of process parameters affecting the final product [18].

Changing one or more process parameters may have a positive effect on the grain size composition of the grinding product, while at the same time adversely affecting the energy inputs of the process [19-21]. In most cases, obtaining satisfactory process results was achieved as a result of introducing changes to the existing structures, searching for such operating conditions of the devices (by changing the process conditions) at which satisfactory economic results would be obtained. This applies to structures operating on an industrial and laboratory scale [22]. Modern computer simulation methods allow for the analysis of processes considering a large number of variable parameters, providing a basis for the construction of very complex mathematical models [23-24]. However, insufficient knowledge on the nature of the grinding process of biological materials does not allow for the construction of a model that would meet both the technological requirements and Taylor criteria [25]. It should be noted, however, that many researchers dealing with the description of the grinding process obtained significant results of their works [26-31].

The production technologies that use the comminution process to obtain the appropriate starting material for further processing [32-33] include, among others, gasification technology and sequestration.

2.2. Pressure agglomeration

One of the methods of managing various types of waste of plant origin is their processing in the process of pressure agglomeration into granules or briquettes, which is confirmed by numerous scientific studies [34-42]. In the production of fuel in the form of pellets or briquettes, more and more often, apart from wood waste, other waste materials are used, e.g., waste from the fruit and vegetable industry.

According to Azargohar et al. [43], currently one of the possible solutions to improve the quality of pellets is co-pelletisation, i.e., mixing two or more raw materials. In the case of producing pellets from alternative raw materials, the general trend is to use the addition of wood materials, for example sawdust, to improve the quality of the pellets obtained [43]. This increases the lignin content in the granulate, which improves its quality, mainly in terms of calorific value, bulk density, durability, and ash content [43-44].

According to Harun et al. [45], co-pelletisation has been one of the most frequently studied methods of producing fuel pellets in recent years. In their research, they produced granules from mixtures of reed, timothy (*Phleum pratense L.*), millet (*Panicum virgatum L.*) with pine and spruce sawdust. They showed that mixing pine sawdust with other types of biomass reduces the energy demand during compaction, which will result in the reduction of pellet production costs [45].

Liu et al. [46] produced granules from blends of bamboo and spruce sawdust. In their research, they found that adding pine sawdust to bamboo was an effective way to improve the bulk density of granules. After adding 40% pine sawdust to bamboo, it increased the bulk density of the granules from 0.54 g / cm3 to 0.60 g / cm3, which allowed to meet the quality requirements. The pellets obtained from such a mixture had a slightly lower calorific value, which, however, could meet the requirements of DIN 51731 (> 17500 J / g) [46].

Garcia et al. [47] produced fuel pellets from mixtures of pine sawdust with many alternative agricultural raw materials and assessed the quality of the pellets obtained in accordance with ISO standards for industrial pellets. As part of the research, they found [47] that pellets made of mixtures of pine sawdust with the addition of almond shells and olive pits added in the amount of 30 wt%, as well as pellets with the addition of waste cones in the amount of up to 15 wt% allows to produce pellets of class I1.

Arranz [48] showed that the addition of olive waste and grape marc to Pyrenean oak waste increased the calorific value and bulk density of the pellets obtained. This was confirmed by the research of Miranda et al. [49], who thickened the waste olive flesh produced in the production of oil in a mixture with other waste. They found [49] that adding olive pomace to the waste of Pyrenean oak provides a more effective compaction of the mixture, and also improves the kinetic strength of the granulate obtained and reduces its ash content.

Chou et al. [50] optimised the process of obtaining fuel briquette from rice straw and rice bran in the piston-matrix compaction process, showing that with the growth of rice bran content in the thickened mixture, the briquette strength and its calorific value increase, and the energy needed for thickening briquette decreases. According to Nasrin et al. [51], who studied the physical properties of briquettes from biomass waste produced in the production of palm oil, the homogenisation of the compacted material, i.e., the grinding and mixing of seed nests, fibres and grains improves the quality properties of the briquette obtained, while the increasing energy outputs needed to produce it. Celma et al. [52], producing granules from industrial post-production tomato waste, found that the granulate density, its hardness and kinetic strength depend on the initial moisture of the biomass, as well as on further activities related to the reduction of moisture after compacting and the storage time of the granulate obtained.

Stahl and Berghela [53], producing fuel pellets from a mixture of sawdust and turnip post-production waste (expeller) from the production of turnip oil, found that the energy consumption of the pelletising process decreases with an increase in the content of turnip waste in the thickened mixture; but unfortunately the mechanical strength also decreases, as well as the density of the granulate obtained. The results show that in experimental studies, the composition of the compacted mixture should be selected in such a way as to strive for a compromise between the reduction of energy consumption and the durability of the pellets obtained. Similar results were obtained by Nielsen (2009), who used the addition of turnip waste (pomace) to various types of sawdust in the industrial production of pellets. During the research, Nielsen [54] noticed a decrease in energy consumption during the pelleting process with an increase in the addition of turnip pomace with a simultaneous decrease in the mechanical durability of the pellet obtained. According to Öhman et al. [55], the quality of biomass pellets can be improved by adding hydrolytic post-production waste from lignocellulose ethanol production. As a result of the increase in the addition of post-production waste from the production of ethanol from lignocellulose to biomass, the calorific value of the pellet increased, the ash content decreased, the fuel tendency to slag decreased and the emission of fine particles to the atmosphere during combustion was reduced compared to pellets from biomass alone.

Stolarski [56] described an experiment of producing pellets from grain sorting (waste from an elevator) in a mixture with oak sawdust (50%:50%) and from waste from the production of apple juice (100%). According to Wandrasz

[57-58], the composition of formed fuels (created in the thickening process) may include waste, e.g., waste from oilseed processing: rapeseed pomace, sunflower husk, or walnut shells (so-called biological combustible substances BSP). Obidziński [59] investigated the effect of the content of potato pulp (post-production waste from the production of potato starch) in a mixture with oat bran on the energy consumption of the pelleting process and the quality of the granulate obtained in terms of its use as a fuel. It was found that increasing the content of potato pulp in the mixture with oat bran from 15 to 25% resulted in a decrease in the power demand of the granulator by approx. 41% (from 3.69 to 2.18 kW) and a decrease in the kinetic strength of the granulate determined by the Holmen method.

In another work, Obidziński [60] determined the effect of the content of potato pulp (15, 20 and 25%) in a mixture with buckwheat husk and the conditions of the granulation process on the energy consumption of the granulation process and on the quality of the granulate obtained (density and kinetic strength, its heat of combustion, calorific value, and ash content) in terms of its use as feed or fuel. As a result of the research, it was found that the addition of mashed potatoes in the amount of up to 15% to the granulated buckwheat husk allows to obtain granules of high density and kinetic strength. Obidziński et al. [61], as a result of the research conducted, confirmed the usefulness of potato pulp as a valuable binder for thickening buckwheat hulls, allowing to obtain high-quality granules. Obidziński with associates [62] also made an attempt to assess the suitability of onion husk waste as a material for the production of solid fuels in the form of granules (pellets). Due to the low susceptibility to thickening of onion shells, the addition of a binder in the form of potato pulp (waste with high starch content) in the amount of 10%, 15% and 20% was applied and granulated. The waste was subjected to elemental analysis, determining the content of C, H, N, S, Cl and their heat of combustion and calorific value. The highest quality pellets (obtained from a mixture containing 10% potato pulp) were burned in a low-power boiler with a retort grate, and the content of CO, CO_2, SO_2, NO and HCl in the flue gas was determined. The emission values obtained from the combustion of onion husk granules exceed the requirements of the EcoDesign Directive, especially in the case of CO. In another study, Dolżyńska et al. [63] presented the results of research on the usefulness of agri-food waste in the form of cherry stones and rye bran as raw materials for the production of solid fuels (pellets) obtained in the agglomeration pressure process. With an increase in the content of rye bran from 10 to 20% in the mixture with cherry seeds, the power demand of the granulator decreases and the kinetic strength of the granules increases, the density of the granules increases and a slight decrease in the heat of combustion and calorific value (approx. 1.7%) can be observed. Obidziński et al. [64] presented the results of the pelletisation (agglomeration) of post-harvest tobacco waste as a raw material for the production of fuel pellets. The pellets obtained were characterised by a high density above 1000 kg/m^3 and a kinetic strength above 97%.

In another study, Dołżyńska et al. [65] analysed the potential and usefulness of agri-food waste (in the form of plum seeds) as a solid fuel. Crushed plum stones containing 10, 15 and 20% rye bran were pelleted. The pellets obtained with a 20% addition of rye bran were of the highest quality. Unground plum pits and pellets were burned in a 25 kW retort boiler to determine changes in NO, SO_2, CO, CO_2, HCl and O_2 concentrations in the afterburning flue gas. The results collected indicate that plum pellets with the addition of rye bran can be an effective replacement for wood pellets in prosumer installations, meeting the requirements of the Ecodesign Directive for CO and NO.

Research related to the production of solid fuel in the form of briquettes from waste remaining in the production of bananas (banana peels) was presented in the works [66-68]. Similar studies on the production of fuel briquettes (on a hydraulic press under pressure to compact at 18 MPa) from waste in the form of banana peels were carried out by Oliveira Maia et al. [69] and Sellin together with associates [70]. The works [69-70] show that briquettes from banana waste have a calorific value and physical and chemical properties similar to other types of biomass used as a raw material for the production of fuels.

According to Szyszlak-Bargłowicz and co-authors [71], the process of pelleting miscanthus biomass often encounters problems related to the low durability of the pellets obtained and high energy expenditure. The solution to the problem is the use of an additive to crushed miscanthus, post-production residues from the production of coconut oil in the form of crushed coconut. The results obtained show that the energy consumption of the miscanthus biomass pelleting process can be significantly reduced by adding the remains of shredded coconut as a biocomponent. With the addition of coconut up to 30%, a granulate was obtained with a kinetic strength of over 95%, a density of over 1200 kg/m^3 and a bulk density of over 417 kg/m^3, with a simultaneous reduction in energy expenditure for the granulation process by 44% [71].

Woo et al. [72] produced fuel pellets from a mixture of waste coffee grounds (SCG) and pine sawdust (PS). They showed that increasing the proportion of coffee grounds (SCG) in the pellet increased its calorific value due to the high content of C, H and oil in the coffee grounds and the increase in ash and sulphur content (due to the high content of sulphur in the coffee grounds). Analysis of the particle size distribution of the raw materials showed that the coffee grounds' particles are smaller than the pine sawdust particles; thus, the durability of the pellets decreases in proportion to the increasing content of coffee grounds. Pellets with 10 wt.% of coffee grounds and 90 wt.% pine sawdust met the quality sulphur standards of class 1 wood pellets, demonstrating the suitability of coffee grounds as a raw material for the production of biofuel pellets.

2.3. Non-pressure agglomeration

The methods of biomass processing by methods other than pressure granulation also include non-pressure agglomeration, also called disk [73] and drum granulation. Among others, tanning shavings, constituting biomass of animal origin, can be the raw material in this method of biomass processing. Various forms of solid waste are produced in the processes of leather dressing (chemical processes and mechanical operations that shape the structure of the leather) - these are both biologically unstabilised waste (untanned headstocks, strippers) and waste resulting from the proper tanning process (shavings, unusable splits), as well as dust (from dyeing and finishing processes). Strings are often used in the production of leather composites [74-75], but they pose a number of problems in transport and storage. These problems can be solved by the granulation of this waste, together with mineral additives that support subsequent processing processes. Optimisation of the granulation processes of waste tarts has shown that the best quality granules are obtained from shavings mixed with a binding liquid (water glass solution). Too dry shavings do not granulate well. An additional advantage of the method proposed is the possibility of using other by-products, such as gypsum, molasses (from a food product), etc. The agglomerate formed in the disc granulation is durable, mechanically stable, as well as easy to transport and store [76]. The potential application area of the granules produced involves the production of composite materials based on crushed collagen fibres and their use in agriculture as soil improvers or a fertiliser additive [77-78].

The literature on the subject also provides examples of non-pressure agglomeration of saturation (defecosaturation) mud, which is a by-product of sugar production, and more precisely the purification process of raw beet juice. The management of post-natural mud is not an easy task from an environmental and technological point of view, compared to other sugar by-products such as molasses or pulp. Attempts were made to disc-granulate the post-saturation mud [79]. The research conducted showed that post-saturation mud is a material that can easily be granulated with the use of any moisturising liquid.

The process of non-pressure agglomeration can also be used for the granulation of mineral resources used in the production of agricultural fertilisers and as an additive to plant biomass waste. Siuda et al. [80] examined Jurassic lime flour mined in the Sławno mine (Poland) and waste gypsum (sulfogypsum) obtained from the Bełchatów Power Plant (Poland). The study focused on the optimisation of the gypsum-lime fertiliser granulation process carried out using one-stage technology on a disc granulator and compared it with the effects of two-stage agglomeration. A mixture (1:1 ratio) of waste sulphogypsum and lime flour was used in the study. Such a weight ratio ensured the maximum use of sulphogypsum waste while maintaining good mechanical properties of the granulate. The granulated bed was moistened with a lignosulfonate solution.

The research showed that the expected granulation effect can be obtained with each of the methods analysed. A more preferred method involves two-stage granulation, which allows to obtain results comparable to one-stage granulation, but with a lower moisture content of the granulate obtained. The quality of the granulate obtained, its strength and granulometric composition meet the operational requirements, regardless of the granulation technology selected. In addition, the use of multi-stage granulation makes it possible to obtain a product with properties comparable to disk granulation with a much lower moisture of the bed, thanks to which it is possible to reduce the costs of drying the agglomerates obtained. During the research it was also found that molasses and magnesium lignosulfonate can also be used interchangeably in the granulation process of the lime-gypsum mix. However, it should be remembered that in order to obtain granulate with satisfactory parameters, a lower weight of lignosulfonate than molasses is needed. The final stage of the work was to verify the concept of granulation of a two-stage gypsum-lime mixture on an industrial scale [80].

Non-pressure agglomeration of waste biomass can also be used in seed coating processes. Ławińska and her colleagues carried out research on the management of tannery waste in seed production [81-82]. As part of it, collagen hydrolysates obtained from waste of the leather industry were used as a binding liquid enabling the formation of an envelope of legume seeds. Also used as a shell component were dolomite and chalk flour. Coating was carried out on a 0.5 m diameter disc granulator, under optimal process conditions, i.e., at a speed of 45 rpm and plate inclination angle of 45^{o}. As a result of the research, it was determined that collagen hydrolysates in the granulation process create a durable coating for seeds; they also protect them against soil pathogens and improve plant growth and condition (also in drought conditions).

Waste products of biomass such as potato starch solutions can also be used in non-pressure agglomeration processes in the form of a binding liquid. Obraniak conducted a study of limestone flour granulation on a disc granulator using a 3 to 6% solution applied directly to the bed for 1 to 12 minutes [83]. The fine-grained bed was drip-wetted using a hydraulic sprinkler, and the wetting liquid reservoir was mounted 2.5 meters above the sprinkler outlet. The test results showed that although the starch solution extends the time of granulation of the lime flour, the granulate obtained in the process is more resistant to abrasion.

2.4. Biomass torrefaction

Torrefaction is a process of the preliminary thermal processing of biomass to bring it closer to the properties of coal, especially in terms of improving its milling. In this process, a solid product is obtained, i.e., a homogeneous torrefaction with physicochemical properties that are more advantageous when it is used as a fuel for the power industry, as compared to raw biomass. Comparing torrefaction with other methods of the thermochemical conversion of biomass, it takes place at the lowest temperature (200-300°C) and in anaerobic conditions. The remaining processes take place under various temperature and oxygen conditions. Carbonisation, pyrolysis and liquefaction take place at temperatures from 200 to 1000°C, but oxygen-free, while gasification and combustion take place at temperatures from 600 to 1500°C and with the necessary supply of oxygen.

When analysing the torrefaction process in terms of temperature distribution over time, five phases can be distinguished:

- Preheating, in which the biomass is preheated (temperature rise) until reaching the drying stage of the biomass (evaporation of moisture).
- Pre-drying, in which water is evaporated from the biomass at a constant rate and temperature (slight fluctuations) until a critical humidity is reached and the rate of water evaporation reduced.
- Drying and intermediate heating, in which processes the temperature of the biomass increases to 200°C and the water released. In turn, there is resistance to mass and heat transfer in biomass particles. After this stage, the biomass is practically devoid of moisture. Weight loss also occurs at this stage as light organic compounds (e.g., terpenes) can evaporate.
- Torrefaction, at this stage the biomass is actually torrefied. This phase begins after exceeding 200°C and ends when the temperature drops below 200°C. This step includes, in addition to a period of constant temperature, a heating period and a cooling period. Degassing (weight loss) begins during the heating period, continues during the constant temperature period, and stops during or after the cooling period.
- Cooling of the solid product, in which the solid product is still cooled to a predetermined end temperature. There is no further weight reduction during the process; however, the reaction products adsorbed may partially evaporate [84].

Torrefaction can be conducted in pulverized coal boilers without the need to change the carburising and furnace systems of the boiler [85]. Biomass torrefaction is a promising technology for the conversion of lignin-cellulose biomass to a coal-like solid fuel with good milling properties. In a typical biomass torrefaction process, both the mass and chemical energy of the raw material are lost. However, taking into account the mass-to-energy ratio, an increase in the concentration of chemical energy of the fuel is observed [86]. In the process of torrefaction, the biomass loses its moisture almost completely, thanks to which it gets rid of the ballast, which lowers the costs of its transport. Moreover, thanks to the increased resistance to atmospheric and biological factors and its hydrophobic nature, it is possible to store larger amounts of fuel compared to raw biomass [87]. The torrefaction of biomass causes an increase in the carbon content and in energy parameters (heat of combustion and calorific value) of the thermally processed biomass [88].

Torrefaction is a universal process as it enables the processing of various types of biomass for the production of various bio-products, depending on the selection of temperature parameters, e.g. torrefying miscanthus at 257°C, we obtain bio-fuel for the energy industry. By torrefying the same biomass, but at 300°C, the end product will be biochar for use, inter alia, in agriculture as an additive to fertilisers. On the other hand, miscanthus torrefied at a much higher temperature (525°C) will produce active biosorbents/activated carbon used to remove heavy metals from car exhaust gases and from waste gases from coal-fired power plants [89]. The same results can be achieved by torrefying biomass other than energy crops, e.g., oat straw, straw and corn cob waste, pine sawdust or dried sewage sludge [90]. Piersa et al. showed that with optimal temperature selection (between 320–350°C), plant biomass (pine wood) and organic biomass (sewage sludge) can be torrefied. These raw materials can be used both for the production of biofuels, but also for bio-carbon as an additive to fertiliser mixtures [91]. As demonstrated by Romanowska et al., the appropriate temperature of torrefied biomass (*Salix viminalis L.* fertilised with cyanobacteria and Chlorella microalgae) is the most important factor in the commercial production of solid biofuels [92]. The authors of the work [93] draw similar conclusions when analysing the torrefaction of Jerusalem artichoke fertilised with ecological waste from the biofermentation of maize grain to methane. As research has shown, thanks to the low cultivation costs of this biomass, thermal energy from the solid biofuel produced requires approx. 25% less expenditure than in the case of traditional fertilisation. Szufa et al., while studying the torrefaction of agricultural biomass (oat and maize straw), indicated that the temperature of the biomass torrefaction process had a greater impact on the torrefaction of maize and oat straw compared to the time spent in torrefaction. Moreover, they found that temperatures between 290 and 330°C are the most optimal roasting temperatures for this type of biomass [94]. This is also confirmed by research on the optimal parameters of the torrefaction process of oat and maize straw. They proved that torrefaction in the temperature range between 250 and 350°C improved the properties of the solid biofuel produced by reducing the O/C ratio and increasing the gross calorific value [95]. It should also be noted that different types of biomass may have a different, more effective torrefying temperature. The authors of the work [96], examining energy plants (willow, mallow and Jerusalem artichoke) determined it in the range of 245-250°C with a residence time in the range of 12-14 minutes. Exceeding these values leads to too much carbonisation of energy crops and causes volatile loss of matter. Moreover, exceeding the recommended temperature of the torrefaction process results in unnecessary energy and fuel consumption as well as expense, which may make the process or installation unprofitable. The appropriate temperature range is from 242 to 244°C, with a residence time of 12-13 minutes in the reactor. These parameters gave a 30% weight loss and the highest calorific value (for such weight loss). They can also be used as a constraint in the design of torrefaction installations.

Torrefied biomass has also been used, among others, in co-combustion and co-gasification for the production of heat, electricity and syngas. Recently, torrefied biomass has also been studied for various applications, such as soil improvement and adsorbents to remove pollutants for carbon sequestration, and even the development of negative CO_2 emission technology. The overview of torrefaction systems still does not indicate the optimal pre-treatment, reactor, or post-treatment. The course of the process depends on the type of raw material used, the effect in the form of end products or its cost. Besides, to achieve higher heat efficiency, higher productivity, homogeneous products and better temperature control, several technologies need to be considered. Moreover, it is necessary to conside economic analysis as a tool to assess the commercialisation potential of the integrated torrefaction process. Previous studies show that non-oxidative torrefaction gives a promising result in terms of the quality of biochar, but it may also pose investment challenges. Therefore, further research and development is needed to develop oxidative torrefaction to enable the profitable production of biochar. Torrefaction also provides environmentally friendly pre-treatment of biomass for bioenergy production by improving its calorific value, while at the same time resulting in relatively lower greenhouse gas emissions compared to other pre-treatment methods and thermochemical processes. It is considered a negative emission technology due to the absorption of carbon from the biomass, considering the life cycle of the torrefied biomass. Future research should therefore focus on life cycle assessments of different microalgae species to produce torrefied biomass. In addition, future work should include an assessment of the impact of heavy metal contamination during the torrefaction of various biomass feedstocks in order to properly define the risks associated with the effects on human health and the environment. It has also been found that biochar is a good alternative adsorbent for acid gas removal [98].

When analysing the list of technologies available on the market, i.e., biomass torrefaction reactors, they can be divided according to the way the substrate is heated into two main groups - reactors with indirect and direct heating. Indirectly heated reactors can be divided into rotary and screw (auger) reactors. On the other hand, with direct heating, it can be additionally divided into three subgroups due to the oxygen content in the heating medium:

- reactors in which the heating medium does not contain oxygen,
- reactors in which the heating medium contains a small amount of oxygen,
- other.

The first group of machines includes screw, rotary, microwave, vibrating, stepped, belt, and moving floor reactors. This group of reactors is used most often. Torrefaction reactors differ mainly in solutions related to the following:

- material flow,
- substrate heating mechanism,
- source of heat,
- treatment of torgas.

Each type of reactor has its advantages and disadvantages. Some of the solutions are cheap, easy to build and operate, while others show problems related to material flow and heat transport, which contributes to uniform heating of the substrate. Some of the devices proposed work well on a laboratory scale, while others on an industrial scale. The torrefaction and gasification processes are carried out in many ways and with the use of various solutions of heat transfer and biomass conversion technology.

3. Conclusions

The above-presented process and technological solutions for the processing of both plant and animal biomass (e.g., in the form of waste from the leather industry) confirm its great potential as a source of renewable energy, but also as an effective way of managing waste that is harmful to the environment in terms of its quantity and chemical composition and unfavourable physical properties. The methods presented indicate the multidirectional possibility of shaping the properties of end products obtained from waste biomass, both through the selection of their composition as well as the optimisation of process and apparatus parameters for its processing. In addition, it is possible to combine waste biomass generated by various industries with other production residues that are both solid and liquid. These methods indicate an unlimited number of possible system configurations for biomass processing. According to the authors, work in this area should be focused in particular on waste-free methods and those reducing energy expenditure. For this reason, the authors have started work to develop and verify a model of the migration of waste components to the environment using granulation processes by optimising the composition of the agglomerates produced and selecting process parameters for burdensome waste, including the leather, tanning, agro-food, mining, chemical and other industries.

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