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Review

A Review of the Biomass Valorization Hierarchy

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Abstract: The sustainability of the planet is based on reducing the use of fossil fuels and greenhouse gas emissions. The recovery of biomass waste puts economically valuable materials into circulation, which can successfully replace fossil fuels and which would otherwise be sent to landfills. Based on the review of several published works, we observe that the referenced processes to value biomass or biomass waste are not necessarily the most profitable and environmentally friendly. The most used methods to valorize biomass and biomass waste are mainly based on researchers knowledge and experience, neglecting some methods that are more appropriate or developing technologies. The valorization of biomass and biomass wastes should promote the production of products with the highest added value, and it must also be environmentally friendly and cost-effective. This manuscript proposes a hierarchy for the use of various valorization processes of biomass waste, from various agricultural activities, urban solids waste, food processing industries, and even wood industries. The proposed hierarchy is based on a number of recommendations aimed at increasing the use and valorization of biomass, in order to reach the objective of carbon neutrality and to comply with the principles of the circular economy.

Keywords: biomass waste; valorization; reduction; hierarchy; circular economy

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1. Introduction

European Union Directive No. 2018/851 (which reflects an update of Directive 2008/98/EC) reports that the term biowaste means biodegradable wastes from gardens and parks, dwellings, and facilities serving meals or selling food and similar wastes from food processing plants [1]. Biodegradable wastes, such as forest or agricultural waste, manure, sewage sludge, natural textiles, paper, or processed wood, were excluded from this cataloging. However, biomass is mainly obtained from plants and plant-derived compounds, whose main sources are forestry wastes and crops, and from animal and industrial residues, sewage, and municipal solid waste.

As early as 1999, the Landfill Directive [1] required EU Member States to reduce the amount of biodegradable municipal wastes they landfill by 35% by 2020, compared to

1995 levels [2]. This Directive allows for a partial reduction in the main environmental problems, consisting of the production of methane and carbon dioxide, which are greenhouse gases, and the generation of leachate, which can contaminate soils and groundwater. Based on this Directive, valuable materials are removed from the economy when recyclable or recoverable wastes are landfilled. Based on the EU's waste hierarchy, outlined by the European Commission, landfilling must be the final choice when it concerns waste treatments [2].

The main components of lignocellulosic biomass are non-carbohydrate polymers, like lignin and proteins, and carbohydrate polymers like cellulose and hemicellulose, which are sustainable, biodegradable, and non-toxic [3,4]. The conventional utilization of lignocellulosic biomass has been restricted to incineration for cooking and warmth, resulting in notable adverse environmental consequences such as desertification and land degradation. It is possible to recover and convert agricultural wastes like manure, straw, and winery waste into fertilizer, energy, and other materials that have positive effects on the environment and economy [5–7].

Biowastes from food waste, agriculture, and agro-industry sectors are increasing as a result of the demand for food, arising from the growth in the world's human population [8]. By 2050, there will be over ten billion people on the earth; therefore, agriculture still needs to find a sustainable path forward. This must be performed by lowering the amount of fossil fuels consumed due to the depletion of natural resources and reducing emissions and solid waste production [9].

Based on the UNEP's Food Waste Index 2024 report, around 1.05 billion tons of food waste were produced in 2022, corresponding to 19% of the total food production [10]. These food wastes would be enough for a billion meals a day, but they are often sent to landfills without any kind of recovery [11]. These losses of food also imply the loss of other resources, such as unnecessarily cultivating land, water use and contamination, and energy and labor resources [9]. Furthermore, 12% of the greenhouse gas emissions are attributable to agricultural activities [12].

Agricultural waste can contain fruit husks, seeds, roots, bagasse, and molasses as well as field residues like stems, stalks, leaves, and seedpods. Agro-industrial biowastes include paper industry wastes, food industry wastes (processing, packaging, and conservation), animal food processing wastes (dismantling, cutting, processing, and preparation), and municipal solid wastes (cleaning public spaces, pruning and clearing of trees and woods) [13]. Among the diversity of biomass waste available, organic leftovers from food processing facilities must be noted, which include, in their composition, fruit seeds, citrus peels, potato peels, coconut shells, wheat straw, rice husks, pomace, and so forth.

Millions of tons of food and agricultural waste are produced worldwide each year. Improper valorization and disposal of these wastes have a negative influence on the environment and the ecosystem. One way to mitigate the effects of biomass waste production is to valorize wastes by transforming them into value-added products that can be reintroduced into the market. However, to dispose of or treat biomass waste diverted from landfills, more environmentally friendly procedures need to be tested, evaluated, and implemented [14,15].

Woody crops and wastes, agricultural wastes, bagasse, waste paper, sawdust, municipal solids waste, food processing waste, and animal or cow wastes are all considered biowaste products. Similar to crop residues, these wastes represent a large potential resource for power generation and are useful in various contexts, particularly in poor and wealthy nations [11].

Concerning the actual tendency for the valorization of solid waste, the trend is to reduce the amount of waste produced or to define a possible reuse of it at the source.

This perspective is oriented towards the economic recovery of waste and will allow us to close the loop of the circular economy, contributing to a reduction in the environmental impact by reducing the production of greenhouse emissions due to the transportation and storage steps [9].

The different steps that encompass the treatment of solid waste, including biomass and biomass wastes, should be prioritized according to Figure 1. Inappropriate treatment or disposal of biowastes leads to environmental degradation, local air pollution, water and soil contamination, and climate change. Biomass burning releases carbon dioxide, methane, and nitrous oxide, the three most potent long-lived greenhouse gases [9]. Figure 1 shows that waste landfill should be the last step to consider in waste valorization. The recovery and reutilization of these biowastes through different methods (waste prevention, reuse, recycling, energy recovery, and disposal) have been tested all over the world. Biomass could be valorized through mechanic (washing, grinding, and pressing), biochemical (fermentation and enzymatic conversion), chemical (extraction of valuable organic compounds), and thermochemical procedures (converted into biochar, activated carbon materials, fuel, energy, and biopolymers) and through transformation into a composting product or into different products for applications such those presented in Figure 2.

Figure 1. Hierarchy on solids waste valorization.

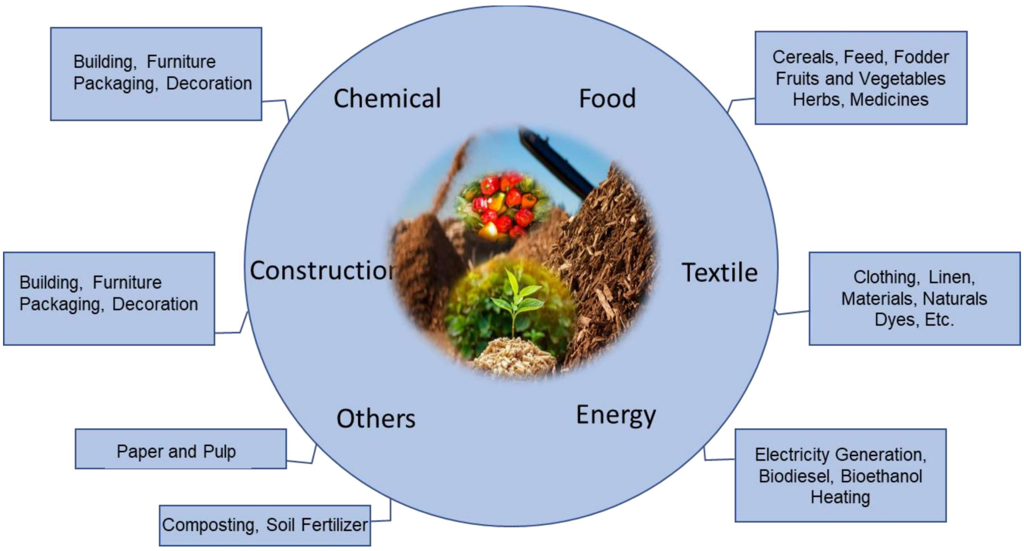

Figure 2. Possible competing uses for biomass, including biowastes.

The amount of biomass waste produced annually does not leave researchers, stakeholders, and responsible entities indifferent. The valorization of biomass waste through the production of compounds with economic value and potential for use in various industrial sectors presents itself as an added value in the reduction, treatment, and management of solid waste, both urban and agricultural.

The food waste value hierarchy was proposed by the US EPA in 2020, and source reduction in waste was the fundamental point. Even more, it was legislated that the Member States of the European Union should aim to achieve an indicative food waste reduction target of 30% by 2025 and 50% by 2030 to help achieve the Sustainable Development Goals [11].

The second phase was the use of excess food to feed people in need through the proper collection and distribution of excess food. It should be noted that food safety must be safeguarded if excess food is directed to feed people. Following the hierarchy proposed to valorize biomass waste, mainly food waste, is sometimes not profitable. Also, some researchers have concluded that following the proposed hierarchy for the valuation of food waste does not always allow for a reduction in environmental impacts [16].

Then, it was recommended to use the remaining food for animal feed and biomass recovery through polymer and composite production, energy, and adsorbent material production. Only at the end of the chain, it was recommended to compost or send the remnant food and biomass to burn or landfill [10,17]. The scheme presented in Figure 3 proposes a hierarchy for the valorization of organic waste from various sources, with the aim of reducing and extracting the maximum value from waste, promoting a reduction in the emission of greenhouse gases, and respecting the principles of the circular economy. The literature is rich in studies that explore the recovery/valorization of agricultural, agro-industrial, and also food residues through their transformation into valuable products. A brief description of different techniques used to transform and valorize different biomass types will be presented following the recommended hierarchy.

Figure 3. Proposed hierarchy of handling biomass waste.

2. Extraction of Valuable Products from Biomass

The extraction of bio-compounds from plants is the basis of research in the field of natural products. Various extracts of plants, such as flavanol, flavones, anthocyanins, pectin, phenolic acids, terpenes, tannins, coumarins, quinones, phenolic alkaloids, limonene, pinene, and essential oils, are increasingly being explored for different applications, in particular, in pharmaceutical, cosmetic, and agro-food chain processing [18–21]. The use of wet, dry, or fermentation techniques has been used for the obtention of several value-added compounds, such as flavonoids and essential oils, which have been directly extracted, for example, from food wastes and employed as flavoring agents in a variety of foods, including fruit juices [22].

Conventional extraction techniques (maceration, digestion, decoction, steam or hydro-distillation, pressing, infusion, percolation, liquid–liquid extraction, solid-phase extraction, coprecipitation, and Soxhlet extraction) are associated with higher cost, lower extraction efficiency, long processing time, higher temperature, and also with the use of a huge volume of toxic organic solvents [23,24]. Environmental concern trends have led several researchers to examine the use of green extraction techniques, such as pulsed electric field, enzyme digestion, extrusion, microwave heating, supercritical and accelerated solvent extraction, and also different solvents (ionic liquids, deep eutectic solvents, natural deep eutectic solvents, water, supercritical solvents, and bio-solvents) [25]. A green extraction method can include a reduction in energy consumption, the use of environmentally friendly solvents, and a reduction in or recovery of waste, allowing for safer and higher-quality products to be obtained [26,27].

In the health, pharmaceutical, and food sectors, the use of bioactive compounds, extracted from a diversity of biomass waste, is growing, as shown in Table 1. These compounds perform well in the prevention of several chronic diseases, as they have antimicrobial and immunological properties due to their natural antioxidant, stabilizer, emulsifier, thickener, and gelling properties [20,28].

Table 1. Examples of sets of agricultural waste, extracted compounds, and corresponding applications.

Waste	Extracted Compounds	Applications	Reference
tomato residues	phenolic compounds	antioxidant, antimicrobial, anticarcinogenic	[18]
pineapple peels	acetic acid	clear vinegar	[29]
orange peels	limonene		[21]
pine	pinene		[30]
agrowaste extracts	ferulic and syringic acid	compounds with antimicrobial and antioxidant potential	[15]
whey waste	red pigment	pigment	[31]
orange peels	limonene	exploited for food, pharmaceutical, and cosmetic industrial applications	[32]
agricultural by-products		antibiotics	[33]
pineapple waste	group of proteases	applications in food, textiles, and cosmetics	[34]
tomato residues	lycopene	applications in food, textiles, and cosmetics	[18]
citrus	pectin	interest in food, pharmaceuticals, and cosmetic	[35]
plant biomass	bioactive compounds	natural antioxidants in meat	[19]

3. Agricultural and Food Waste as Animal Feeding Product Sources

Based on the forecast of world population growth, already mentioned above, as well as an increase in the standard of living, it is expected that 1250 million tons of meat and dairy will be required by 2050 to meet the consumption needs of the population [36]. From this point of view, the recovery of agricultural, agro-industrial, and food waste through its direct use or its transformation into animal feed is undoubtedly a must-have.

It is a long-standing custom to feed animals directly with leftovers, especially those on farms. However, by using moisture-based, dry-based, or fermentation-based methods, food waste can be converted into animal feed without sacrificing its nutritional content [37]. Currently, by-products from the production and processing of food, or trash from food supply chains, make up about 30% of the feed given to cattle worldwide. A study performed by McBride (2021) already revealed that around 10% of the excess food in the US was used to feed animals, whereas the majority of this food waste came from groceries and manufacturing shops [38]. As far as the recovery of waste from livestock farms is concerned, the use of organic solid waste in the preparation of animal feed is well-known. Leftover meat considered unfit for human consumption is transformed into flour or bran that can be used to feed large animals or even pets [37].

Residues from agricultural and industry processing activities include fruits, harvested vegetables, grains, pomace, straw, peels, husks, stones, factory vegetable oil, and oleochemical residues. These materials are rich in carbohydrates, lipids, sugars, and inorganic compounds. However, organic crop leftovers, which include high concentrations of phytochemicals (phenolics, carotenoids) that have enormous potential in the food, pharmaceutical, and cosmetics industries, are used for animal feed due to their low availability, diversified composition, transportation, and other costs [36]. In reality, the cost of implementing more noble recovery processes redirects this waste to lower-value or lower-priority applications [39].

Through careful processing and handling, waste materials can be converted into nutrient-dense feed, such as the examples presented in Table 2, saving livestock farmers money and implementing a real circular economy approach.

Microbial fermentation, or solid-state fermentation, is referred to by Ritalia et al. (2017) [36] as an effective method for valorizing agro-industrial wastes through their transformation into a wide range of valuable bio-products. Microbial fermentation allows for the conversion of agro-industrial wastes into fermented and high-protein animal feed. The elements without nutritional input can be removed during the process, which increases animal digestion. From this perspective, solid fermentation allows us to obtain animal feed at lower prices and in a healthier way, which increases productivity [40]. However, some difficulties in the use of food waste as feed are related to farmers' benefits, waste composition, safety, costs, and their continued availability [18]. Yet, unpredictability in the nutritional content of some food agrowastes was mentioned as one of the limitations in their incorporation into animal diets [22]. However, the fraction with no nutritional value can still be directed to the thermochemical valorization process.

Table 2. Waste from agricultural and agro-industry activities used as animal nutrition sources.

Agricultural Waste	Application	Reference
olive cake	replacing beef cattle	[41]
fruit pomaces	broiler feed	[42]
grape marc and tomato pomace	feed dairy ewes	[43]
olive cake	Holstein dairy cattle	[44]
olive cake	deed cattle	[13]
cassava peels, cereal-grain waste	feed pigs, ducks, cattle	[45]
list of agricultural waste	micro protein for animal feed	[46]
list of agro-industrial waste	plethora of useful value-added bio-products	[40]

4. Biological Conversion of Biomass

Biomass and biomass wastes can be converted into by-products through biological processes, which include anaerobic digestion, fermentation, bioconversion, enzymatic hydrolysis, and bioremediation. The two most used methods to avoid biomass valorization are fermentation and anaerobic digestion [47].

During fermentation, microorganisms, such as bacteria and yeast, convert sugars into energy, producing derivatives such as ethanol, lactic acid, and carbon dioxide. Anaerobic digestion is a biological process generally composed of four main stages, i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Anaerobic digestion is carried out by microorganisms in the absence of oxygen, allowing for the conversion of hemicellulose,

cellulose, and starch into biogas, consisting of a mixture of methane, carbon dioxide, and a small amount of other gases [47].

Compared to chemical processes, biological techniques of biomass conversion are usually more sustainable and can help to reduce wastes, provide energy, and create valuable bio-products. However, the use of biological methods for the conversion of biomass presents some disadvantages, such as being time-consuming; the conditions for bacteria, yeast, fungi, and microorganisms to grow must be carefully controlled; and the methane produced must be separated from carbon dioxide before use. The costs can increase when the addition of enzymes is needed to improve the breakdown of lignocellulose constituents.

The bioconversion process allows for obtaining biofuels, bioplastics, and various chemicals, while enzymatic hydrolysis is mainly used to break down complex carbohydrates into simple sugars before being used in the fermentation process [48].

5. Conversion of Biomass and Biomass Waste into Biopolymers

The most prevalent types of plastics are thermoplastics, which include polyethylene terephthalate, polypropylene, low- and high-density polyethene, polystyrene, and polyvinyl chloride. The worldwide production of plastics reached the huge amount of 400.3 million metric tons in 2022 [49]. Synthetic plastics could reach a half-life of up to 1200 years; some of them are single-use, which contributes to a large amount of plastic waste. It must be noted that, for example, in the United States (which is one of the most developed countries in the world), in 2017, only 10% of the plastic waste produced was recycled, 14% was incinerated, and 76% was landfilled or ended up in water bodies [50,51]. It should also be noted that the use of stabilizers and antioxidants during the plastic process could reduce environmental degradation and extend their half-life. One of the main concerns is the quantity of small plastic waste that ends up in the oceans. By 2025, 150 million tons of plastic debris are predicted to be in the oceans, and there is a strong correlation between the origins of this material and the lack of an efficient waste recovery process [51].

Given this scenario, it is imperative to replace synthetic polymers with biodegradable biopolymers. This change could contribute to the valorization of biomass waste, a reduction in the use of raw materials of non-renewable origin, and an improvement in the environment by reducing the need for landfills and extending their lifespan, thus reducing the release of unpleasant odors that are accompanied by the emission of greenhouse gases. So far, bioplastics are one of the possible alternatives to conventional plastics that have been more enthusiastically offered on the market. Bioplastics are a polymer family whose carbon is typically obtained from organic resources, such as biomass, which improves the circular economy [52,53].

It must be clarified that there are three types of biopolymers: bio-based and biodegradable polymers, fossil-based but biodegradable polymers, and bio-based but non-biodegradable polymers [51]. Surprisingly, green resources, including corn, sugarcane, and biomass, are typically used to make non-biodegradable bioplastics [54]. The biodegradability of bioplastics is highly affected by their physical and chemical structure. On the other hand, the environment in which they are located plays a crucial role in their biodegradation (pH, temperature, moisture, oxygen content, and soil microorganisms). When bioplastics are constructed of monomers obtained from agricultural waste, the carbon footprint of the raw material and finished products is reduced. In actuality, people find it appealing when green plants are turned into plastics, and this is a major factor in the rising consumer acceptance of bioplastics [52].

Among the most widespread biopolymers made from renewable biomass sources are chitin, chitosan, alginate, cellulose, starch (pea starch and corn starch), and cyclodextrin [13,53]. Two of the most studied biodegradable polymers are polyhydroxyalkanoate, which is a polymer synthesized directly by living organisms, and polylactic acid, which is a polymer synthesized from bio-based monomers. Baranwal et al. (2022) presented a list with a diversity of raw materials from animal, plant, agricultural waste, and microorganism sources of origin (microalgae), which have been used to prepare biopolymers. The advantages and disadvantages between biopolymers of natural and synthetic origin were also presented by the same authors [53].

The scientific community has shown a great deal of interest in biopolymers and their derivatives because of their unique properties, which include being biodegradable, being biocompatible, having low toxicity, being renewable, and possessing a high tensile strength [54], as shown in Figure 4, which make them suitable for applications in several domains. They found applications as packaging materials and in agricultural activities, the food industry [55,56], and the pharmaceutical industry, such as drug delivery materials and regenerative medicine (medical implant organs) [57]. Even though bioplastics currently account for about 1% of the world's plastics business [58], their market segment is expected to grow to 35% by 2025 [59]. Bioplastics can be used for almost 90% of the current plastic usage. However, biodegradable bioplastics respond only to 35% of the applications [60].

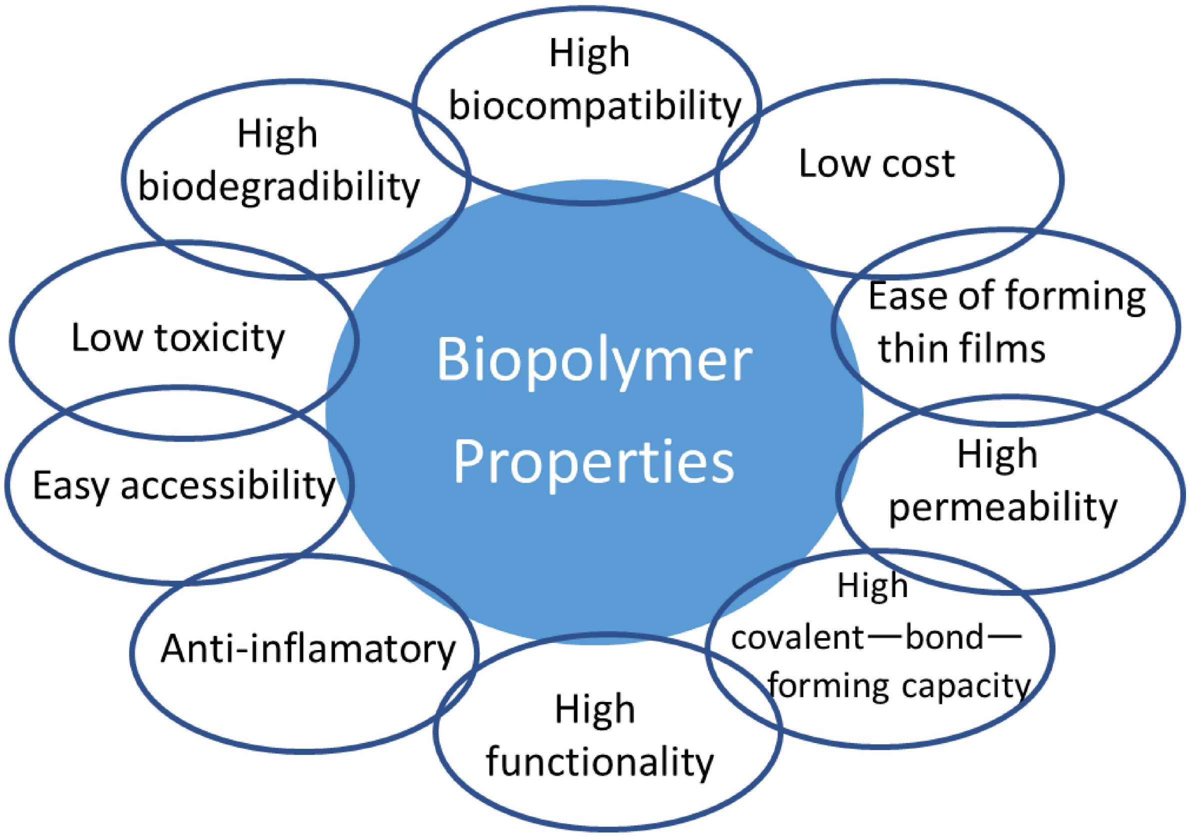

Figure 4. Key features of biopolymers.

Yet, the use of bioplastics has been linked to several environmental problems, such as greenhouse gas emissions and doubtful land use change. Manufactured bioplastics are still more expensive than synthetic plastics, which makes it difficult to implement them on the world market [61]. Due to their unique composition, bio-based polymer materials still perform worse than conventional petroleum-based materials in terms of cost (high energy consumption), competition with food production [62], and preparation process (consistency in impurities and unpredictability in waste feedstock composition) [63]. Also, the cultivation and production processes of bio-based but non-biodegradable polymers result in a high carbon footprint. Thus, these polymers are not more sustainable than synthetic polymers made from non-renewable resources.

Finally, the evaluation of the environmental impacts related to products made of various plastics is crucial for selecting suitable materials for sustainable development. Furthermore, more studies are necessary to better clarify the benefits of bio-based or biodegradable polymers over conventional polymers [64,65].

6. Biomass Applied as Green Construction Materials

With the growth of the world's population, there is a need to increase the construction or reconstruction of houses to create adequate living conditions for all people. Widespread worry about the detrimental effects of traditional building materials (cement, beams, rubble, lime, limestone, brick scraps) on the environment has led to an increased interest in eco-friendly or sustainable construction materials [66]. The major advantages reported for the use of direct agricultural waste on construction materials are their local availability, ease of use and build, less cost-effectiveness, increase in good isolation characteristics, and ease of recycling. From this perspective, residues from agricultural, logging, and agro-industrial activities have emerged as promising resources for the creation of new construction materials, such as the examples presented in Table 3. However, some disadvantages were also reported; the most important being the fragility of some materials. However, some studies have reported the introduction of biochar during cement production, which can improve concrete's tensile and compressive strengths [67].

Table 3. Examples of environmentally friendly and sustainable building materials made from agricultural and agro-industrial wastes.

Solid Waste	Application	Reference
empty fruit bunch with mesocarp fiber, sugarcane bagasse with coconut husk and with mesocarp fiber, coconut husk with an empty fruit bunch	roof board thermal insulation	[68]
sugar cane	improve durability and thermal properties of cement	[69]
mesocarp fiber	improve thermal properties of foamed concrete	[70]
agrowaste	bio-brickets	[71]
eggshell powder, sawdust powder, coconut husk powder	unfired clay blocks	[67]
eggshell waste	cement production	[72]

7. Thermochemical Conversion of Biomass into Combustibles

After the global energy crisis of the 1970s, which marked the beginning of the lack of petroleum supplies, attention was turned to the development of alternative fuels. Renewable biomass sources can be transformed into biofuel and can replace non-renewable fuels, which can contribute to a reduction in greenhouse gas emissions.

The increase in the use of fossil fuels contributed to climate change (greenhouse gas emissions, particularly, carbon dioxide), which ultimately inhibited economic growth. The development of renewable energy sources has gained more attention as a result of the declining availability of fossil fuel energy sources, their geographic distribution, which is concentrated in politically unstable nations, and the serious environmental problems associated with climate change. By 2030, the International Energy Agency (IEA) wants to see 6% of the world's energy come from renewable sources. Using heterogeneous catalysts, biofuel is a type of biodegradable alternative fuel that may be produced from a variety of vegetable and animal fat sources [73]. However, the EU's mandatory renewable energy, approved in 2023, defined an objective of 42.5% of the total amount of energy used for 2030 in Europe.

The use of biofuel has a neutral balance between the absorption of carbon dioxide, during biomass growth, and the production of carbon dioxide, during burning [74]. The use of bioenergy is crucial for slowing climate change and protecting the environment and energy sources. Reducing and recovering valuable resources for producing renewable energy will improve economic efficiency and have a beneficial social impact. Biomass waste valorization could be a way of creating income for people living in disadvantaged rural areas where biomass is abundant [75].

Waste from agricultural and industry processing activities and food wastes that cannot be recovered by other processes, due to the lack of regularity in supply, variability in their composition, difficulties in collecting and transporting them, the presence of contaminants, or even high costs of process implementation, can always be valued through their thermal valuation instead of being burned, buried, or sent to landfills.

In reality, several types of biomass, such as agricultural wastes, bagasse, waste paper, sawdust, municipal solids waste, food processing waste, and animal or cow waste, can be used to create heat, fuel, and electricity [76]. Biomass could be a source of renewable energy, and replacing fossil fuels could substantially limit their environmental impacts. The conversion of biomass into renewable energy sources depends on the renewable end-product required, the quality and quantity of biomass, and the cost of the process.

Over time, a wide range of conversion technologies (physical, thermochemical, biological, and hybrid systems) have been developed to transform biomass into different types of energy products. The physical process consists mainly of biomass size reduction and dehydration. Through cutting and grinding, mechanical crushing allows for particle size reduction, which influences temperature gradient changes in biomass during pyrolysis. The biological process requires the presence of microorganisms. If microorganisms break down organic materials in the absence of oxygen, the process is called biodigestion, and it will produce biogas, which can be used to produce energy. Fermentation consists of a process where yeast converts biomass into alcohol, which can be used as biofuel to power automobiles. On the other hand, thermochemical conversion is the most used way to thermo-valorize biomass and is frequently divided into five processes (torrefaction, liquefaction, pyrolysis, gasification, and combustion) [77].

The following sections will refer to thermochemical conversion processes of biomass. Figure 5 shows the temperature ranges of occurrence of the different thermochemical conversion processes.

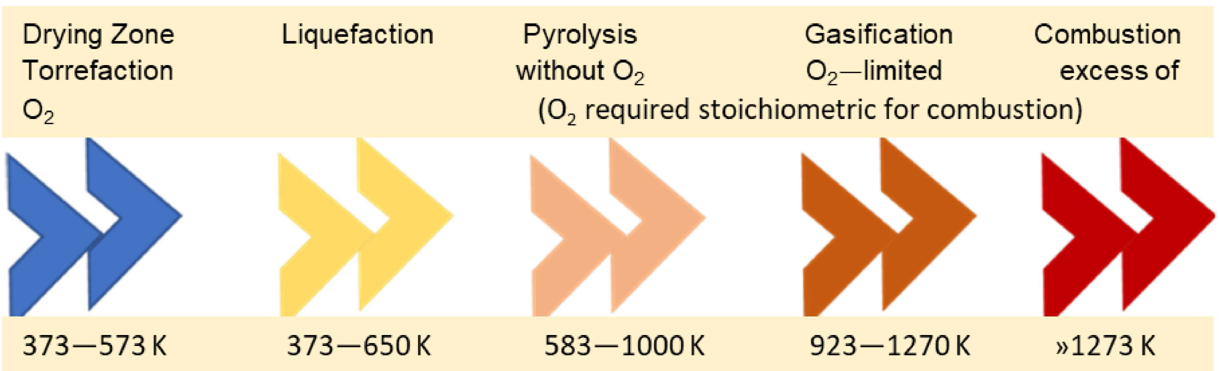

Figure 5. Temperature ranges of occurrence of the different thermochemical conversion processes.

7.1. Torrefaction

Torrefaction is the carbonization of biomass, which takes place in a near-inert atmosphere at low temperatures (473–573 K) and only partially pyrolyzes biomass. This pretreatment process makes biomass more coal-like for its use in steam generators. It also allows for a reduction in pollutant gas emissions in further thermochemical steps. The process also acts as a quality leveler for a multifuel feedstock [74]. The major attributes of this step are mass yield, energy yield, energy density, and degree of torrefaction.

7.2. Liquefaction

Thermochemical liquefaction of biomass can take place in the presence of a solvent (liquefaction) or without a solvent through direct pyrolysis. Liquefaction involves the conversion of biomass in the presence of a solvent (mainly water) at a moderate temperature (373 to 650 K) and moderate to high pressure (5–25 MPa) into a bio-granulate liquid or bio-crudes [73].

During liquefaction, biomass is fractionated into cellulose fibers, hemicellulose dehydration products, and lignin consisting of a relevant pre-treatment for improving gasification. Gasification converts organic materials like wood chips, agricultural waste, and other biomass into synthesis gas. However, biomass presents a relatively low bulk density, which is a disadvantage for storage and transportation issues. Bio-crude has a higher density and energy content than solid biomass and provides better transportation and storage capacities [78].

When compared with bio-oils produced through pyrolysis, bio-crudes present less oxygen and water content, less density, and more stability. However, petroleum and bio-crudes are not easily miscible because water is the primary solvent used in the liquefaction process [73].

7.3. Pyrolysis

Pyrolysis is the conversion process of specific biomass into solid (charcoal, char, or biochar), liquid (bio-oil), and gaseous (syngas) fractions through partial combustion at temperatures between 583 and 873 K, with an external heat source, and in the absence of oxygen [73,76]. Tshikovhi and Motaung reported that biomass pyrolysis can take place between 500 and 1000 K with the production of three combustible phases [79].

The ratio between the three products obtained will vary depending on the conditions used during pyrolysis [79]. If pyrolysis takes place at lower temperatures (573 to 773 K), the process is named carbonization, and it allows for the obtention of a solid phase (vegetable coal). If pyrolysis takes place at moderate temperatures (773 K), the process is named slow or conventional pyrolysis, and it allows for the obtention of three fractions almost in equal quantities. Slow pyrolysis requires a longer contact time, which represents a high cost, but it maximizes the amount of biochar that is produced. The first objective of slow pyrolysis is biochar production, reaching 60% of biochar and 30% of bio-oil [80]. If pyrolysis takes place at temperatures between 773 and 923 K, the process is called fast pyrolysis, and the reactions take place quickly and the contact time is shorter than in slow pyrolysis. As the pyrolysis temperature increases, the amount of the bio-oil produced increases [81], reaching 70% wt% and 15% of biochar [80]. Flash pyrolysis was also described as taking place at a temperature higher than 923 K, where the contact time is very short (<0.1 s). However, flash pyrolysis presents a disadvantage, such as it works under high pressure [5,80].

The volatile compounds produced during the pyrolysis process can be condensed (bio-oil) and used for heating and electricity generation purposes. The solid fraction is essentially composed of coal and inert material. The liquid phase is mainly composed of hydrocarbons, which can be used as synthetic combustibles. Bio-oil has a higher energy content and density than solid biomass, which is an advantage for transport and storage purposes.

Bio-oils usually include more water and oxygen content than bio-crudes. Here, again, bio-crudes are more thermally stable and have higher viscosities and lower densities than bio-oils. However, some experiments have demonstrated that bio-oils could partially replace fossil fuels in diesel engines, gas turbines, boilers, and furnaces for the production of heat and power or combined heat and power, despite having a lower calorific power than fossil fuel [82]. The gaseous phase, named syngas, is mainly composed of H_2, CH_4, CO, CO_2, and other elements in minor percentages, such as C_2H_4 and C_2H_6, depending on the original biomass used [83].

7.4. Gasification

As the name implies, the gasification process converts solid biomass into a gas, named synthesis gas or syngas, at a temperature range from 823 to 1873 K, leaving a solid named char. To produce synthesis gas, biomass gasification needs a gasifying medium, such as air, steam, or oxygen. Gasification takes place under controlled conditions concerning the presence of oxygen, i.e., it is in a stoichiometric deficit regarding the amount of biomass. Due to its availability and low cost, air is the most used gasifying medium [84]. As reported before, syngas is mainly composed of carbon dioxide, methane, and hydrogen in different proportions [76]. It was reported that when steam is used as a gasifying medium, the syngas presents a higher ratio of H/C [85].

When comparing solid biomass and bio-oil gasification, such as that obtained during the liquefaction process reported previously, the last one offers several advantages, including higher operating pressure and smaller equipment requirements. The reduction in ash and other pollutants is another advantage of gasifying bio-oils. Furthermore, because syngas from bio-oil gasification has less tar than solid biomass, it is cleaner.

Syngas can be used for direct heat, as fuel to generate electricity, or as a basis for a large number of products in the petrochemical and refinery industries, such as methanol, ammonia, liquid transportation fuels, kerosene, and chemicals [86]. For these reasons, gasification is more flexible than direct combustion. With its ability to adapt to market fluctuations and be implemented across many market segments, it provides a strong foundation for the transition to sustainable energy [73].

Syngas obtained through biomass gasification is a very promising renewable energy source that can partially substitute fossil fuels. This sets the stage for the global movement to promote the use of biofuels and other renewable energy sources in place of fossil fuels, which are the traditional energy sources. Among the various improvements made in the various pyrolysis methods used, the production of tar during biomass gasification is one of the main limiting problems of the mass production and use of syngas [87].

7.5. Combustion

Combustion is the thermal conversion of organic substances into gas and other subproducts, like slags, ores, and flying ashes, in the presence of oxygen with the production of heat. It is well known that the oldest and most widely used thermochemical conversion technique is biomass combustion. For thousands of years, people have used wood to cook and stay warm. Biomass burning, like maize stalks, wood chips, and switchgrass, has been popular in more recent years. Biomass fuels are significantly different from conventional fossil fuels like coal, which are used in combustion processes. The main components of biomass are carbon, hydrogen, and oxygen; other elements, such as nitrogen, potassium, chlorine, sulfur, and phosphorus, may be present but are undesirable as they are linked to ash and deposit formation, corrosion, and other undesirable problems [88,89]. These unique characteristics of biomass and low heating values provide some difficulties for the combustion process. However, combustion is recommended for biomass feedstocks that contain up to 50% or a maximum of 60% of water content [76,89,90].

There are three main steps involved during biomass combustion: drying, pyrolysis and reduction of unstable gases, and solid coal combustion [79].

Approximately 90% of the total renewable energy is obtained by the combustion of biomass. Combustion plants can operate on different types of biomass, i.e., wood, dry leaves, hard vegetable shells, rice husk, dried animal dung, etc. In the combustion process, which is an exothermic process, biomass and oxygen are combined in a high-temperature environment to form carbon dioxide, water vapor, and heat. When heat, fuel (biomass), and air are present in adequate ratios, combustion is self-sufficient due to the extra heat released from fuel, which allows burning to continue. A diversity of biomass residues used in different thermochemical processes to obtain energy products is included in Table 4.

It must be noted that the specific characteristics of the biomass fuel or fuels to be used heavily influence the design of the combustion devices and the selection of their operating parameters. However, the combustion of biomass (dry wood, dry leaves, hard vegetable shells, agricultural residues) when carried out inside a combustion chamber at high temperatures (800–1000 °C) allows for obtaining around 20 MJ/kg biomass of thermal energy [91].

Table 4. Thermochemical processes for biomass conversion.

Solid Waste	Process	Reference
olive tree waste	torrefactions	[92]
sorghum straw	torrefactions	[93]
pinewood sawdust	torrefactions	[94]
pequi fruit seeds	torrefactions	[95]
pine wood chips	gasification	[96]
solid waste and hazardous waste	gasification	[97]
rice straw	gasification	[98]
vineyard, tomato plant residues, canary pine needles, and pennisetum setaceum	gasification	[99]
biomass (e.g., agricultural, woody biomass waste)	gasification	[100]
algal biomass (microalgae)	liquefaction	[101]
Jatropha curcas seed	liquefaction	[102]
domestic sewage from ponds	liquefaction	[103]
pine wood shavings	liquefaction	[104]
citrus limetta or sweet lime	liquefaction	[105]
sugarcane leaves and tops	pyrolysis	[106]
waste biomass from coffee	pyrolysis	[107]
pinyon wood chips	pyrolysis	[108]
beech, poplar, spruce, and wheat straw	pyrolysis	[109]
rice husk	pyrolysis	[110]
winemaking industry wastes	combustion	[111]
tobacco	combustion	[112]
dairy waste	combustion	[113]

Woody biomass remains the predominant biomass fuel. Yet, combustion methods employ biogenic leftovers derived from industry, towns, and agriculture. Firewood has historically been the most often used fuel, but automated systems based on wood pellets or wood chips are gradually gaining popularity on the market [73].

When compared to their fossil counterparts, biomass combustion applications can cut life cycle greenhouse gas emissions by up to 90% (solid and gaseous bioenergy routes). The primary determinants of greenhouse gas balance are the emissions from the fuel supply chain and the overall efficiency of the system [78]. During the operating phase, greenhouse gas emissions are generally balanced out by the absorption of CO_2 from the atmosphere during biomass growth, thus making the process neutral in terms of greenhouse gas emissions [73,89].

The production of bioenergy from agricultural waste, food waste, and municipal waste can lead to sustainable waste recovery. The use of biomass to produce energy is becoming more and more popular throughout the world. Most of the time, either the CO_2 neutrality of sustainably produced biomass or the use of biomass wastes and residues serves as the impetus for biomass combustion. Nevertheless, the majority of bioenergy conversion facilities have numerous technological and financial constraints and are mainly in the research or pilot stage.

8. Biomass Converted into Adsorbent Materials

The increase in agricultural practices has led to an increase in the amount of agricultural waste, with a majority of it being burned or discharged, wasting resources and increasing pollution by releasing green gases into the atmosphere. The growth in the world's population leads to the overuse of water for personal or industrial uses and the influx of a greater volume of polluted and contaminated water. When released into the environment, pollutants harm the earth, soil, and surface and underground water. Reducing these effects on the environment can be achieved by using a variety of waste valorizing and treatment techniques. A mixture of physical, chemical, and biological techniques can be used to treat wastewater and remove different pollutants (nutrients, heavy metals, dyes, pesticides, and emergent pollutants). Among the various treatments mentioned in the literature, adsorption on a variety of adsorbents is highlighted for its high performance, being easy to apply and maintain. However, the cost of production of some adsorbents (activated carbon) is a limitation to their widespread use in the treatment of various effluents.

Biomass and biomass wastes from a diversity of usages find widespread applications as raw materials for the production of carbonaceous products, such as coke, biochar, and activated carbons (ACs). While ACs have well-defined porous structures and high superficial surface area, which provide them more potential applications as adsorbents, catalysts, and energy storage materials, biochar typically presents a less developed porous structure.

Waste biomass from agricultural or forestry activities can be used as an adsorbent to treat water and wastewater in its original form (wastes only submitted to the drying and grinding process), after acidic or basic modifications, and transformed into bio-based sorbents through the production of biochar or activated carbon.

8.1. Waste Biomass Applications Without Any Treatment

Biomass materials are cheap and abundant in the environment, as they are usually waste from agricultural or industrial activities. The direct application of agricultural waste (instead of being transformed into biochar or activated carbons), as adsorbent materials is undoubtedly a way to obtain low-cost adsorbents for removing pollutants from wastewater.

Most raw adsorbents made from different biomass sources have presented low adsorption capacities for dyes and organic pollutants. To increase the respective adsorption capacity, different modification techniques (acidic, alkaline, magnetization) have been used for this purpose [114]. Even so, the advantages and disadvantages of natural adsorbents to treat wastewater must be evaluated, considering the reduction in waste, implementation costs, product regeneration and reuse, and environmental sustainability [3,115]. The direct use of biomass to treat water presents great advantages, but the use of natural biomass without any treatment also has some harmful points. Natural biomass could release some soluble organic compounds into water bodies, which may contribute to increased pollution and the biological oxygen demand [3].

The effectiveness of agricultural wastes (orange peel, pomelo peel, lemon peel, banana peel, rice husk, wheat bran, pulse seed coat, coconut shell), and industrial waste materials (palm oil ash, red mud, tea factory waste, coffee waste, olive oil industry waste, fly ash, bagasse ash, blast furnace slag) for the removal of heavy metals, dyes, and organic pollutants were compiled by Singh et al. (2018) [116]. Different kinds of raw biomass were used to treat wastewater, as data presented in Table 5.

Table 5. Agricultural and forestry waste used in its original form for water treatment.

Raw Material	Applications	References
Review on the use of biomass-based adsorbents	Dye removal	[117]
Aloe vera	Biosorbents	[118]
Subble, Tectona Grandis, Adansonia digitata L., and bamboo flowers	Methylene blue	[119]
Chestnut thorn shell	Methylene blue	[120]
Apricot shells treated by NaOH	Cu^{2+}, Zn^{2+} and Pb^{2+}	[121]
Cashew nut shell	Red corant	[122]
List with a diversity of natural agrowastes	Mainly metal cations and dyes	[116,123]

8.2. Biochar Production

Agricultural and municipal wastes, which have a high lignocellulosic content, are among the many organic wastes that are exploited as feedstock to produce biochar. These wastes are collected from the environment and processed using various procedures to produce high-value carbon adsorbents, which can then be modified using further techniques. The primary objective of the preparation and modification methods is to create high-surface-area and high-pore-volume biochar that is chemically and thermally stable.

Biochar is a solid fraction mainly obtained from a direct pyrolysis process of biomass, in the absence of oxygen or under oxygen-limited conditions. It can also be obtained under microwave-assisted pyrolysis or through hydrothermal carbonization (in this case it is named hydrochar). However, it can also be obtained as a sub-product from the gasification process, largely used for obtaining energy.

8.2.1. Biochar Production Through Pyrolysis

Biochar is a solid fraction of the direct pyrolysis process, which takes place in the absence of oxygen or under oxygen-limited conditions, at a temperature ranging from 573 to 973 K [124,125]. Virtually all types of biomass, in their original form or after being processed, can be used as a feedstock for the production of biochar. Under controlled thermal conditions, biochar can be produced with a fine-grained structure and porous properties.

The main elements present in biochar are carbon, oxygen, nitrogen, and an inorganic phase named ash. Depending on the types of feedstock biomass used and the pyrolysis conditions, biochar's carbon portion might range from 30% to 60%. Biochar can be classified into three classes based on its carbon content: category 1, carbon > 60 wt%; category 2, carbon varying from 30 to 60 wt%; and category 3, carbon content < 30 wt%) [125].

It can have a diversity of applications, such as in agriculture to enhance soil fertility, nutrient absorption, and water retention; provide additional habitats for microorganisms; and improve soil health through the adsorption of pollutants. The use of biochar to treat wastewater will be discussed simultaneously with the applications of activated carbons.

8.2.2. Biochar Production Through Hydrothermal Processes

Hydrothermal liquefaction treatments (HTL) treat biomass at a moderate temperature, varying between 150 and 350 °C [126], and high pressure varying from 5 to 20 MPa. To produce solids (biochar), liquid water-immiscible (bio-oil), liquid water-miscible (aqueous phase fraction), and gaseous materials, biomass is subjected to depolymerization reactions under these conditions, including fragmentation, hydrolysis, dehydration, deoxygenation, aromatization, and repolymerization. The type of biomass and the HTL's operating conditions determine the final product's yield [127].

Depending on the operating temperature conditions, hydrothermal processes can be categorized as hydrothermal carbonation, hydrothermal liquefaction, and hydrothermal gasification. The use of HTL presents some advantages. The process is energy-efficient, presenting a higher energy output (5.89–7.91 MJ kg^{-1}) than other processes (fermentation, 2.5 to 3.9 MJ kg^{-1}). Moreover, more than 70% of the precursors are converted into biochar or can be recovered as a bio-oil [127]. Biochar has been produced from a diversity of biomass such as macroalgae (*Gracilaria gracilis*) [128], lignin and aspen wood [129], grass and olive stone [130], and sawdust [131].

Biochar production depends mainly on the amount of carbohydrates in the feedstock. A high amount of carbohydrates promotes a high biochar yield, yet the opposite was found concerning bio-oil production [132]. Biochar found applications as solid fuels and in the adsorption of pollutants, gas removal from gaseous effluents [133], and biological catalysts.

Biochar presents a high adsorption capacity regarding a diversity of pollutants, which includes nutrients. Because of its adsorbing and immobilizing qualities, biochar can prevent the leaching of soil nutrients, which promotes plant growth and water retention. Yet, its production cost is still a limitation for its disclosure.

Biochar performance in specific applications could be improved through common modification methods of textural and chemical properties. Modification methods used for this purpose include oxidation, acid, and alkaline treatment, physical activation, coating, and magnetization. The treatments allow for the introduction of acidic or basic functionalities on biochar surfaces, allow for an increment in surface area, micropore volume, and pore size dimensions, and can promote the introduction of cations to improve magnetization [3].

8.3. Activated Carbon Production

Activated carbons (ACs) are porous materials with unique physical, chemical, and textural properties. Activated carbons stand out in various applications due to their excellent properties, among them being the high surface area (which can reach 3000 m^2/g), the high porous volume (which can reach 2.5 cm^3/g), and the variable but adjustable pore sizes (which can range from ultra-micropores to macropores) [134].

Activated carbons can be produced from a diversity of precursors of organic and inorganic nature, such as wood, coal, polymers, and petroleum coke [135,136]. There are also various biomass types, such as chitosan, seeds, shells, rice husk, sawdust, etc., that are used in the production of ACs.

Biomasses are excellent precursors because they have a high carbon content, are available and less expensive, and are simple to transform into ACs [96,137]. Agricultural wastes are referred as the most commonly used biomass source for AC production due to their high cellulose and lignin percentages [138]. A list containing a diversity of biomass used in the AC production was presented by Heidarinejad et al. (2020) and Duan et al. (2021) [139,140].

The steps involved in producing ACs, such as choosing the precursor, carbonizing it, and activating it chemically or physically, directly affect the characteristics of the finished product. Among the methods of producing activated carbons, physical activation and chemical activation stand out, which are carried out using a variety of activating agents (physical activation, including air, CO_2, water vapor, and chemical activation, including KOH, H_3PO_4, K_2CO_3, $ZnCl_2$) at moderate to high temperatures [119,129,140]. A summary of these steps can be found in Figure 6.

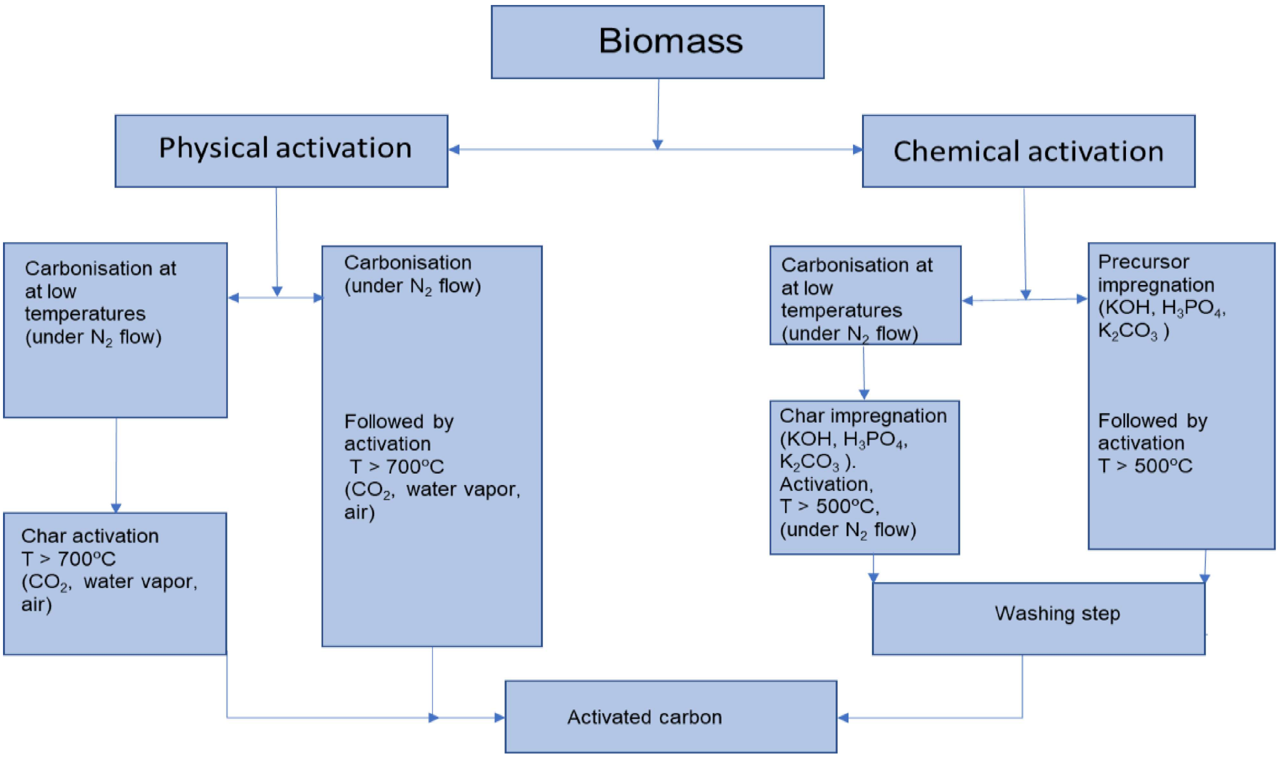

Figure 6. Activated carbon production conditions—physical and chemical activation.

Activated carbons have received great attention owing to their superior and efficient ability for catalysis uses [141], medicine, wastewater treatment, gas purification and capture [142,143], and solvent recovery. Their main application is related to the removal of dye, heavy metals, detergents, herbicides, pesticides [137], pharmacies, hydrocarbons, and emergent pollutants from aqueous media [122,144].

Undeniably, human activity, industrial emissions, and agricultural practices have a significant impact on wastewater production. All of these activities have changed the water cycle and produced a variety of contaminants, raising concerns throughout the world about how they may affect human health and animals in the future. Conventional methods to treat wastewater could include different steps such as precipitation, complexation, coagulation, flocculation, sedimentation, ion exchange, reverse osmosis, electrochemical processes, biological treatment, and adsorption. The demand for environmental protection increases annually, and adsorption processes gain importance in the treatment of a diversity of industrial effluents and in purification, separation, and recovery [145].

Because they are plentiful and inexpensive, some of the traditional green adsorbents, such as clay, bentonite, zeolite, and montmorillonite, are widely employed for the adsorption of pollutants from wastewater [146]. However, these adsorbents present limited adsorption capacity, which restricts their broad use. In this sense, activated carbons have become known as promising adsorbents for wastewater treatment.

Even more, ACs can be texturally and chemically modified, to improve their adsorption capacities [147,148]. Several AC modifications techniques, which include acidification, oxidation, metal impregnation, magnetization, are used to introduce a diversity of functional groups on their surface. It should be noted that the identification of the intended application for an AC is crucial to define the modification method to be implemented.

Finally, AC materials can be regenerated and reused several times. Nevertheless, because of their production cost and some difficulties in adsorbent regeneration or the need to dispose of end-of-life sorbents through methods other than disposal, their widespread use in wastewater treatment is sometimes restricted [149]. However, the adsorption process has received particular attention owing to its high efficiency, simplicity, and easy operation. Its operational and capital costs depend mainly on the adsorbent cost. Consequently, using low-cost and eco-friendly adsorbents, obtained mainly from biomass wastes, is the main challenge facing the broad implementation of the adsorption method in wastewater treatment processes [122]. Iwanow et al. (2020) presented a list of 51 papers that used different agricultural biomass wastes to produce ACs, with different functions and performances in a wide range of applications (straw, rice husk, bagasse, miscanthus, bamboo, cotton residues, nut shells, fruit pits, fruit seeds, fruits peels, coconut shells, olive stones, sunflower seed oil residues, coffee residue, corncobs, oil pal residues, etc.) [150].

9. Composting Product

Composting is a traditional, simple, economical, ecological, and conscious process that turns biodegradable compounds from a diversity of activities (agriculture, agro-industry, forestry, manure, food waste, and organic urban solid residues) into biofertilizers based on a sequence of biologically controlled steps. When employed as a waste valorization technique, composting reduces the negative impact of biodegradable waste on the environment and humans by reducing landfills and increasing its lifespan, which reduces the emission of bad odors, greenhouse gas emissions (nitrous oxide, methane, and carbon dioxide) [151], and groundwater contamination, aligning with the principles of a circular economy [39,152,153].

To transform biodegradable materials into a valuable fertilizer, the composting process typically consists of four stages, i.e., heating, high temperature, cooling, and maturation, which can take up to two months. The effectiveness of composting depends on several factors, such as temperature, aeration, moisture content, substrate consistency, the C/N ratio, material particle size, pH, and the degree of heap compaction [154]. To enhance composting speed up, agrowaste can be composted using techniques like vermicomposting and microbially enhanced composting. Because earthworms have an impact on nutrient mineralization, vermicompost applied to agrowastes typically has better nutrient bioavailability. When applied to soil, this increases the nutrients' accessibility to plants [39].

According to the EU Soil Strategy, 2021, transformed biomass materials serve as organic fertilizer, aid in replenishing depleted soil carbon pools, and enhance soil water retention capacity. These actions enable the closure of the nutrient and carbon cycles after receiving the proper treatment [155]. However, the process of composting organic solid waste is not very widespread. The drawbacks of composting include labor consumption, site–space occupation, extended composting times, and a lack of temporal adjustability [152].

Some researchers have concentrated their efforts on controlling and developing the composting procedure to accomplish the rapid composting process [152]. Among the parameters evaluated are feedstock mixtures, the addition of matured compost, ventilation, the addition of additives (black soldier fly larvae, biochar, bentonite, phosphate, inoculation) [153,156–159], and the use of pre-treatments with fungi [160]. However, further studies and trials are needed to take a safe and consolidated step in reducing the time needed to carry out safe and efficient composting [129]. The production and use of compost are no longer disseminated due to a lack of knowledge by consumers, farmers, and competent authorities about the advantages of using compost in agricultural practices [161]. On the other hand, the lack of an effective separation process of the organic and inorganic components of municipal solid waste, mainly at the local where wastes are produced, is a major brake in the implementation of the composting process, as presented in Figure 7.

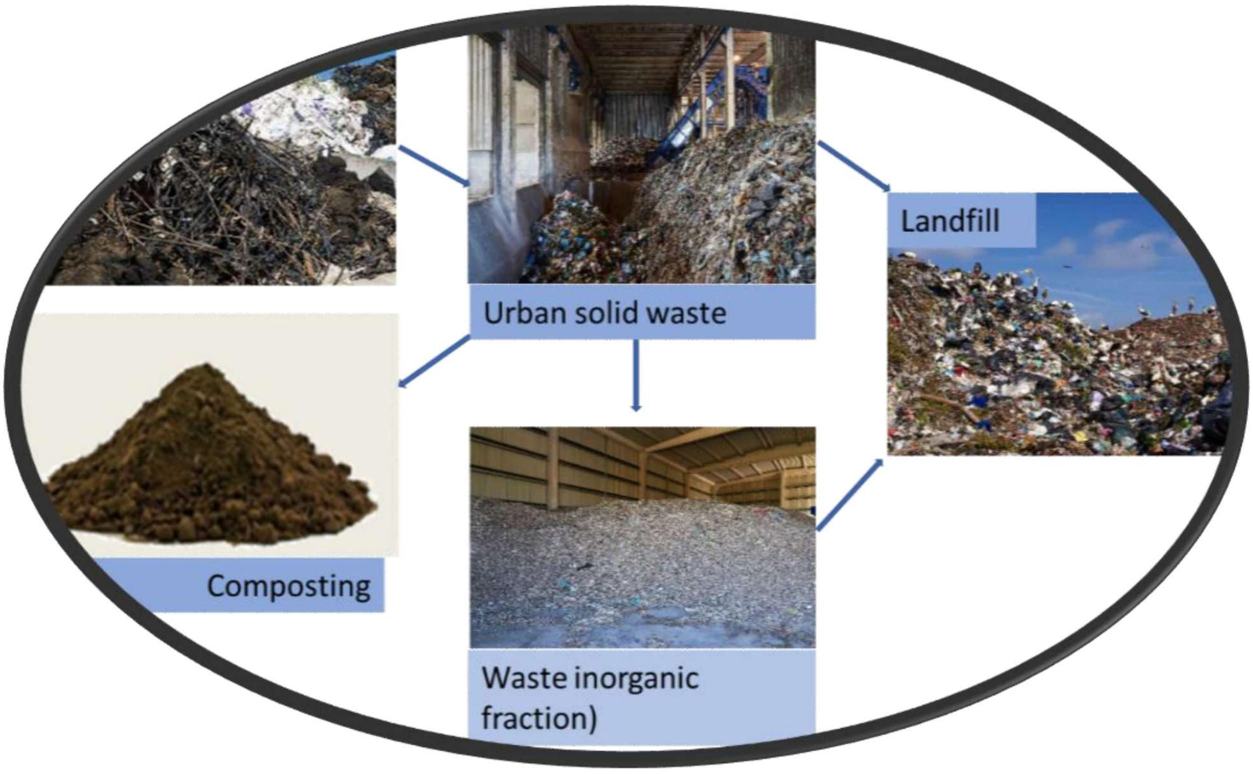

Figure 7. Separation and recovery of urban solid waste in a waste management unit.

To increase the use of composting, instead of landfilling the organic component of urban solid waste, municipal entities need to implement selective collection systems at the source. By removing biowaste from the waste undifferentiated fraction, the component that causes greenhouse gases is also removed from landfills, and all its potential is channeled for more efficient and safer systems, such as gas production and composting.

To better elucidate the biomass and biomass waste valorization hierarchy proposed, as presented in Figure 3, a bibliometric search was performed on the Elsevier database between 2008 and 2024. A first search was performed between 2008 and 2020 and a second search was performed between 2015 and 2024. The keywords used were the same in both searches (biomass, waste, recovery, and circular economy) and were found in abstract, authors keywords or indexed keyword, in the manuscript. Between 2008 and 2018, only 104 papers were found. Choosing the keywords that appear more than two times, the scheme presented in Figure 8 was drawn using VOSviewer 1.6.20 software.

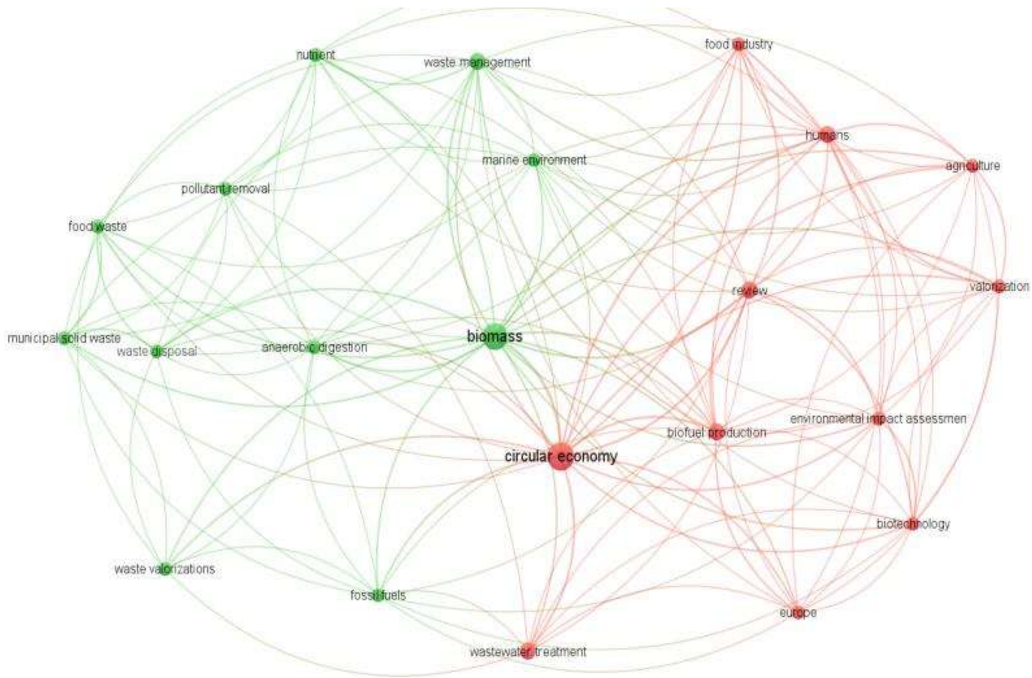

Figure 8. Network map of papers that contain keywords related to biomass, waste valorization, and circular economy, published between 2008 and 2020.

In Figure 8, the green map refers to the application of biomass using the most basic and traditional forms, that are essentially based on the elimination of biomass. The red map illustrates the beginning of the use of some practices that lead to the valorization of biomass, with emphasis on the energy valorization of biomass, and where the circular economy is already included.

The search performed for the period between 2015 and 2024 obtained 671 papers. Selecting only the keywords that appear more than 25 times, the scheme presented in Figure 9 was obtained. In this last period, the words "circular economy" and "valorization" stand out, highlighting the direction followed by the various works published with regard to the treatment and recovery of biomass and biomass waste.

In Figure 9, the yellow cluster is in the center and it is linked to all the other clusters, highlighting the growing dynamism and importance of the circular economy concept. The blue cluster encompasses the valorization of biomass through biochemical methods. The green cluster is more related to the biomass management, where the economic value of the various wastes is not yet highlighted. The purple cluster highlights the production of products with economic value, such as the production of compost and the production of energy compounds through heat treatment processes. The purple cluster also highlights the relationship between biomass valorization and the reduction of greenhouse gas production and climate change. After 2015, the terms biomass, circular economy, and valuation stand out in the network map obtained. Research and companies with an interest in the area of biowaste valorization must take every opportunity to withdraw all economic benefits from it.

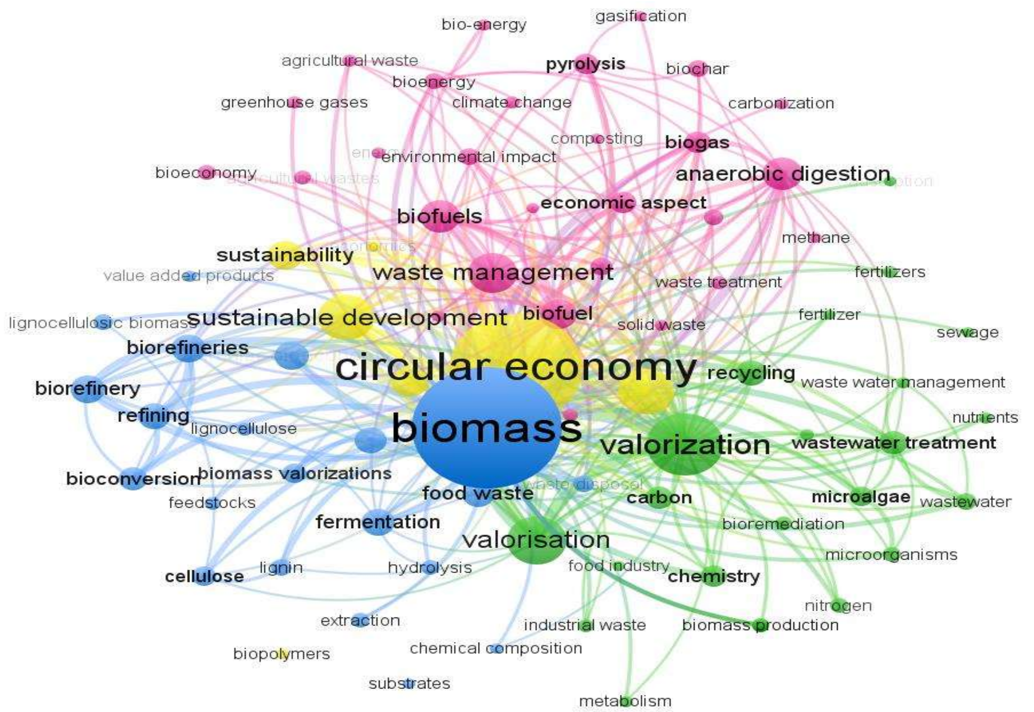

Figure 9. Network map of papers that contain keywords related to biomass, waste valorization, and circular economy, published between 2015 and 2024.

10. Conclusions and Future Perspectives

Based on the review of several published works, we observe that referenced processes to value biomass or biomass waste are not necessarily the most profitable and environmentally friendly. Researchers tend to recommend the use of some waste valorization methods based on their knowledge and experience, neglecting some methods that are more appropriate or developing technologies. The valorization of biomass should promote the achievement of the highest added value from biomass waste, especially waste from agricultural, agro-industrial, and food waste activities. It must also be environmentally friendly and cost-effective. In this sense, the biomass and biomass waste valorization hierarchy was then proposed.

Following the proposed hierarchy, the reader can identify, based on the characteristics of biomass (cellulose, hemicellulose, and lignin content), its availability, water content, inorganic contaminant content, cost, and desired final product, which biomass valorization process should be used in order to reduce the carbon footprint, the emission of greenhouse gases, wastes (with economic value) that are sent to landfill, and, of course, obtain the maximum benefits from them. The proposed waste recovery hierarchy is part of the Sustainable Development Goals' objectives and complies with the principles of the circular economy.

(1) The first process recommended is feeding people. However, it should be noted that food safety must be safeguarded if excess food is directed to feed people. Following the hierarchy proposed to valorize biomass waste, mainly food waste, is sometimes not profitable. Also, some researchers have concluded that following the proposed hierarchy for the valuation of food waste does not always allow a reduction in environmental impacts.

(2) Feeding animals is a way to valorize biomass waste. Unpredictability in the nutritional content and availability of some food and agrowaste was mentioned as one of the limitations in their incorporation into animal diets. In reality, the costs of implementing nobler recovery processes direct food waste to applications with lower added value or lower prioritization.
(3) Although some disposal methods are convenient, such as the use of biomass as fertilizer, they have environmental and economic costs. Biomass with a high cellulose content and fabric-forming ability is a suitable raw material for preparing cellulose-based products instead of being used as a fertilizer or being incinerated. Biomass with a high content of hemicellulose is more easy to biodegrade than cellulose. Finally, biomass with a high content of lignin, which is a crosslinked aromatic polymer, is the main challenge in lignocellulosic biomass valorization. Therefore, plant trunks are more difficult to biodegrade than other types of common straw. However, biomass containing a high amount of lignin can be used for biorefinery purposes [162].
(4) When compared to other techniques like incineration, thermal treatment, and microbiological fermentation, thermochemical valorization is recommended mainly if biomass resources come from a variety of sources and types. However, biomass and biomass wastes present some disadvantages when compared to fossil fuels, such as low energy density, high collection costs, presence of alkali metals, and relatively high nitrogen content [163].
(5) By employing biomass waste as a precursor to produce biochar and activated carbons, which can be successfully used as adsorbents in water and wastewater treatment, three different worries of solid and liquid waste valorization could be solved. When green technologies are adopted, AC costs are reduced, and liquid effluents can be treated and reused.
(6) A hierarchy to value biomass and biomass wastes is included in Figure 3. However, a more all-encompassing approach is necessary to value these wastes, which includes collaboration between different interdisciplinary players (scientists, social entities, industrial representatives, consumers, and policymakers).

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