agronomy

Review

Biomass Waste Conversion Technologies and Its Application for Sustainable Environmental Development—A Review

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Abstract: With the global population continuing to increase, the demand for food and energy has escalated, resulting in severe environmental pressures. Traditional methods of food and energy production have left a significant footprint on the environment, primarily due to the emission of greenhouse gases and a notable surge in waste production. Nevertheless, scientists have recently focused on developing sustainable solutions by managing biomass waste and converting it into useful products. Various biomass conversion technologies, including pyrolysis, gasification, and fermentation, have emerged to transform waste materials into valuable commodities like biofuels, fertilizers, and chemicals. These technologies present an alternative to conventional energy production methods and decrease reliance on non-renewable resources. Furthermore, the by-products generated through biomass conversion, such as biochar, possess utility as valuable soil amendments. This review emphasizes the potential of biomass conversion technologies in providing sustainable solutions for waste management, food and energy production, and reducing negative environmental impacts while providing valuable by-products for agricultural use. The focus is on Lebanon, which is facing a waste and energy crisis, with an aim to encourage and promote sustainable practices by highlighting different green waste management technologies. Focusing on the application of biochar in soil, our goal is to provide cost-effective and eco-friendly solutions to various agricultural and environmental challenges in Lebanon. This includes using biochar from biomass waste as a soil amendment to boost crop yields, remediate soil pollution, reduce soil drought stress, and address other related issues.

Keywords: biomass; valorization; conversion; environment; waste management; soil amendment

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1. Introduction

The global population growth rate is increasing dramatically. The current global population has surpassed three times its mid-20th century figure, according to the United Nations. Presently, there are approximately 8 billion people worldwide, with projections indicating continued growth in the coming years. Projections suggest that the global population will reach approximately 9 billion by 2037 and expand to around 10 billion by 2058 [1].

The expansion of the world's population can be attributed to various factors, including improved healthcare, sanitation, and nutrition, leading to reduced infant and child mortality rates, thus enabling more individuals to reach reproductive age and contribute to population growth. Additionally, factors such as increased life expectancy, urbanization, and elevated migration rates have also played significant roles in this global demographic phenomenon [2]. The need for food and energy is rising correspondingly, and thus the agri-food sector and food production are growing to provide food security for all populations. Figure 1 represents the worldwide vegetable production volumes in million kilograms in 2014–2026; the graph shows clearly the increase in production over the years with an estimation for more increase. As the future demand for food is expected to be higher, larger areas of crop cultivation and yields will increase as well [3].

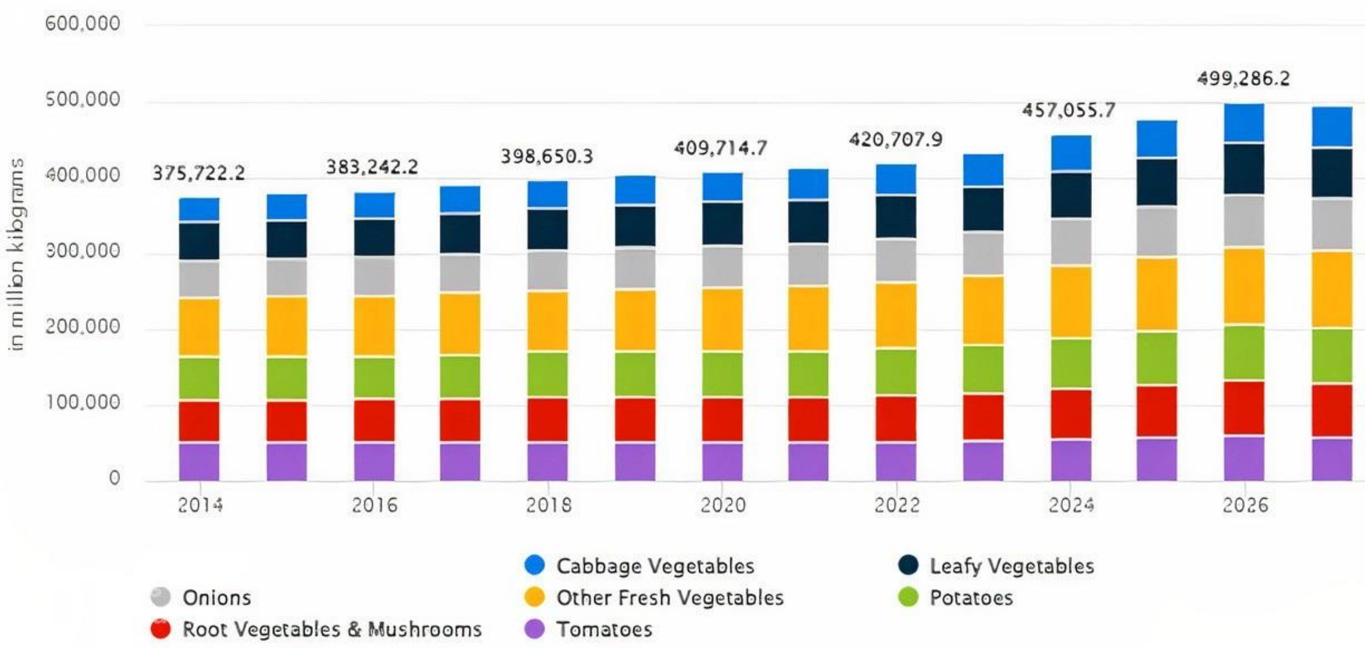

Figure 1. Worldwide vegetable production volumes in million kilograms, 2014–2026 [4].

It is no secret that agriculture is an invaluable part of the global economy, whether it is to provide food for the population, or to produce raw materials for non-food purposes, regardless of the economy of the country. Economic expansion depends significantly on agriculture: comprising approximately 30% of the global gross domestic product (GDP) in some of the least developed nations [5]. Furthermore, meeting the food demands of the rising population will require a 51% increase in food production, as per predictions [6].

Water, food, and energy are interlinked focal points for promoting sustainable development, with increasing demands for each of them. However, food production significantly contributes to environmental pollution through its various stages, from production to marketing. In 2015, food production emissions accounted for 34% of the total greenhouse gas (GHG) emissions globally, reaching 18 Gt CO_2eq per year [7]. Animal products' production, including animal feed production, represents 29% of the water footprint of the worldwide agricultural sector, and it occupies 80% of all agricultural land. Figure 2 represents CO_2 emissions for selected broad food categories, with meat products having the highest emissions. Agriculture also leads to species loss, habitat loss, and ocean and freshwater eutrophication. The impact of food production on the environment is substantial, and it is imperative to address it to meet our climate targets [8–10].

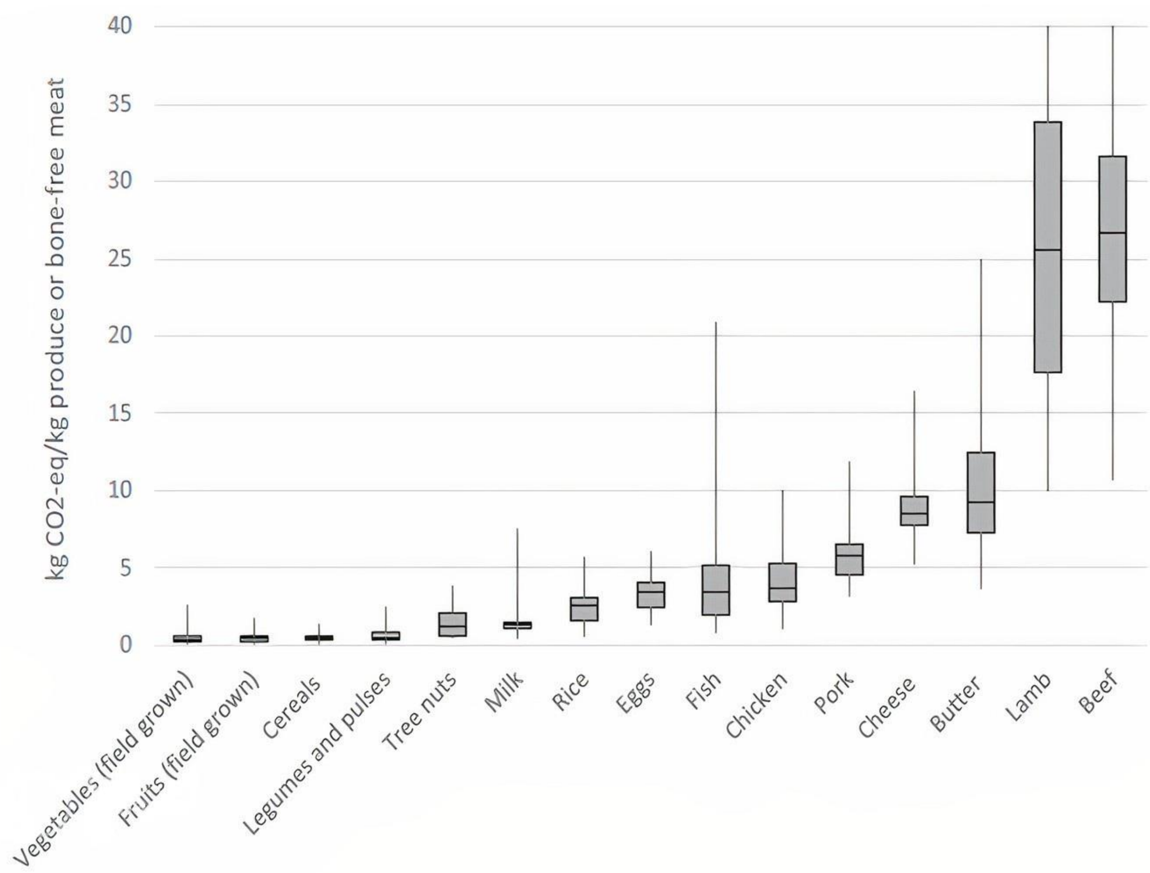

Figure 2. CO_2 emissions for variety of food categories [11].

Owing to the critical role of nitrogen supply in enhancing plant growth, crop yield, and quality, as well as improving the nutritional content of plant-based food products for both animal and human consumption, the utilization of nitrogen-containing chemical fertilizers has seen a notable rise. However, this has raised environmental concerns as volatile losses such as ammonia (NH_3) or nitrous oxide threaten air, soil, and water quality, global ecosystems, and climate change. Consequently, it was approximated that synthetic nitrogen fertilizers accounted for 12% of the yearly average of 5180 million tons of greenhouse gas emissions linked to agriculture between 2010 and 2014 [12,13].

According to Ishangulyyev et al. (2019), approximately one third of the global food production is lost or wasted [14]. Kojima and Ishikawa (2013) also found that food waste and loss have detrimental environmental effects through landfill decomposition and greenhouse emissions from open-air burning [15]. Landfilling and burning are still the most common waste disposal methods.

Unless waste food is upgraded, bioconverted, or reutilized, it represents a loss of valuable biomass and nutrients. Nonetheless, the escalating energy consumption is another significant requirement accompanying the growth of the population, alongside the demand for food. Energy consumption globally has experienced a significant increase over the past few decades, with usage surging from 8588.9 million tons (Mtoe) in 1995 to 13,147.3 Mtoe in 2015 [16].

Fossil fuels currently provide the majority of the world's energy, representing 80% of the global consumption, and this demand is expected to increase by 48% in the next two decades due to population growth. The oil and gas sector encounters a substantial challenge in fulfilling this increasing demand. While fossil fuels are cheap and widely available, they have a significant environmental impact, contributing to global warming. To tackle this issue, there is a necessity for the advancement of environmentally friendly and sustainable energy solutions, like biofuels, derived from renewable biomass waste, with the potential to diminish greenhouse gas emissions [17–19].

Biomass waste conversion via green technologies enables the problem of energy demand and organic waste management to be solved (Figure 3).

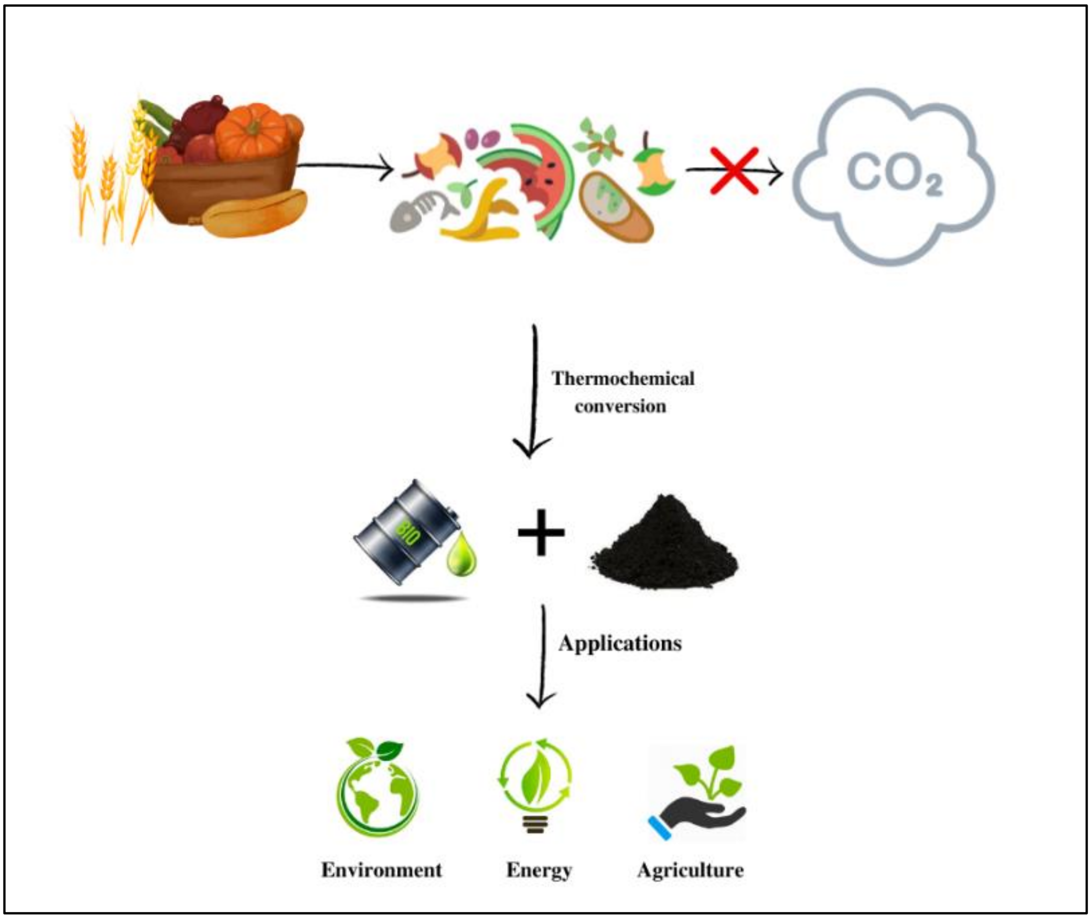

Figure 3. Biomass conversion into higher value products.

This review article aims to present green solutions to address various challenges related to population growth, such as the increasing demand for food and energy. These industries exert a notable environmental footprint, including the emission of pollutants and the generation of waste materials. In response, the article provides an overview of different green technologies, including biomass conversion technologies, as solutions for green energy production and biomass waste management.

It is worth highlighting the growing attention towards biomass conversion technologies and their practical uses. A striking illustration of this trend is the substantial number of publications, nearly 494,922 in total between 2003 and 2022, as depicted in Figure 4. In 2003, there were approximately 4035 publications, whereas, by 2022, this figure had surged to 71,222 publications, marking a remarkable increase of about 1664.8%. This data underscores the escalating interest in this field, which holds particular relevance for Lebanon. The country is grappling with significant challenges in both clean energy production and waste management. The review aims to promote green solutions for these challenges and generate interest in the application of biomass conversion technologies, such as pyrolysis, for sustainable practices in Lebanon and beyond.

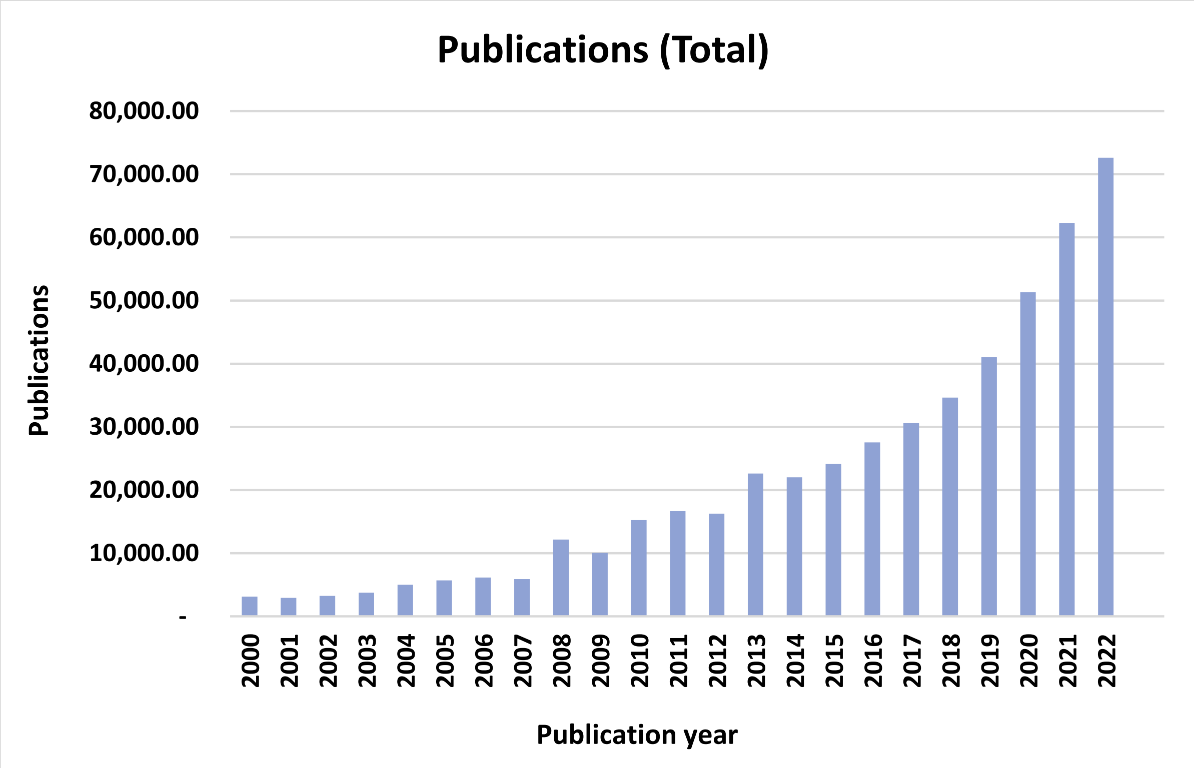

Figure 4. Representation of the number of published publications (Key words: Biomass conversion technologies AND their applications) in each year, with a total of 494,922 publications between 2003 and 2022. Data generated using Dimensions.ai search engine and plotted using Origin software (v.10).

Overall, this article's primary objective is to concentrate on the utilization of pyrolysis and its application in enhancing soil quality using the abundant biomass waste resources found in Lebanon. Simultaneously, it aims to offer insights into diverse eco-friendly technologies and their possible uses. These endeavors are geared towards fostering sustainable practices and mitigating the adverse environmental consequences associated with human activities.

2. Biomass Waste

Biomass is defined as organic matter originating from living plants that can be naturally replenished or renewed. Pang (2016) reported that the fundamental components comprising the structural composition of biomass include cellulose, hemicellulose, and lignin [20]. Biomass waste is challenging to quantify due to its diverse and dynamic waste streams and the lack of consistent data collection methods. It consists of lignocellulosic and food materials, which vary in composition and quantity based on geographical location; climate; and economic and social conditions. Roughly 50% of global waste is organic and can be considered biomass [21].

However, biomass waste is rapidly increasing and generates approximately 140 Gt of waste globally each year as per reports, causing significant disposal and governance issues [22].

Moreover, managing biomass waste sustainably is crucial due to its significant environmental and economic impacts. The burning or disposing of biomass waste in the field or landfills has low efficiency and causes severe environmental pollution. Thus, finding sustainable ways to manage biomass waste is gaining interest [23]. Figure 5 represents an estimation of the quantity of waste burned by country, where these quantities are the highest in some part of Asia (China and India).

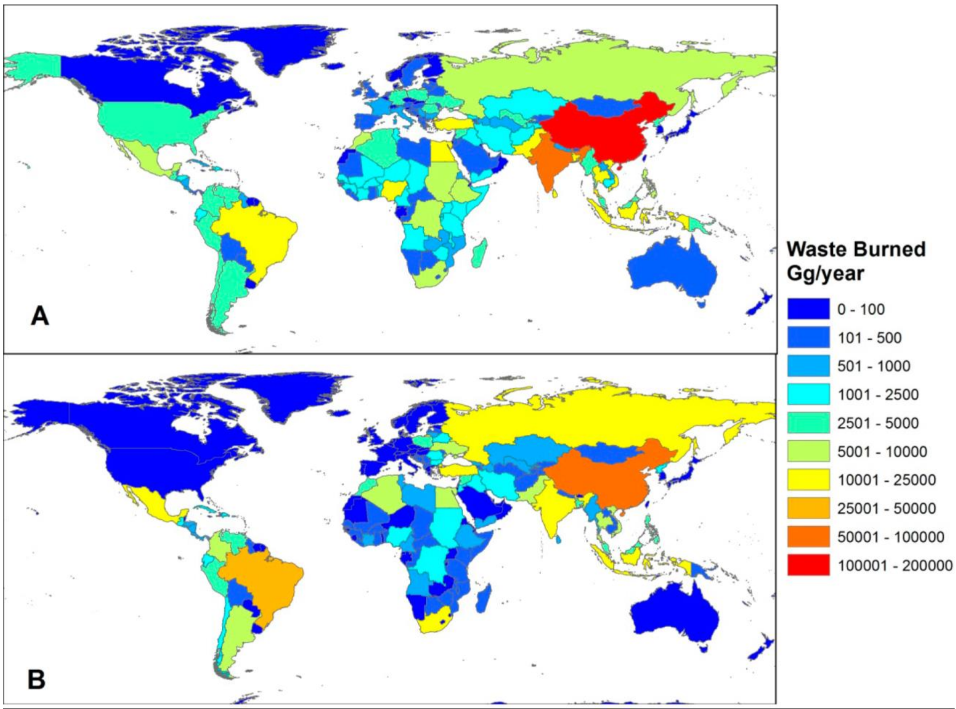

Figure 5. Estimated quantity of waste burned by country, residentially (**A**) and in dumps (**B**) Reprinted with permission from Ref. [24]. Copyright 2014, American Chemical Society.

The presence of landfills gives rise to environmental concerns, primarily because they can lead to the contamination of surface and groundwater through leachate. Additionally, landfills generate greenhouse gas emissions during the decomposition of organic waste, which poses risks to air quality, human well-being, and plays a role in exacerbating climate change. Nevertheless, biomass has served as a fuel source for centuries, and while its combustion can result in the emission of pollutants, notably greenhouse gases, with CO_2 being the predominant component (as illustrated in Figure 6), there exists the potential for its transformation into biofuels via thermochemical methods. These processes present a more environmentally sustainable substitute for fossil fuels [25–28].

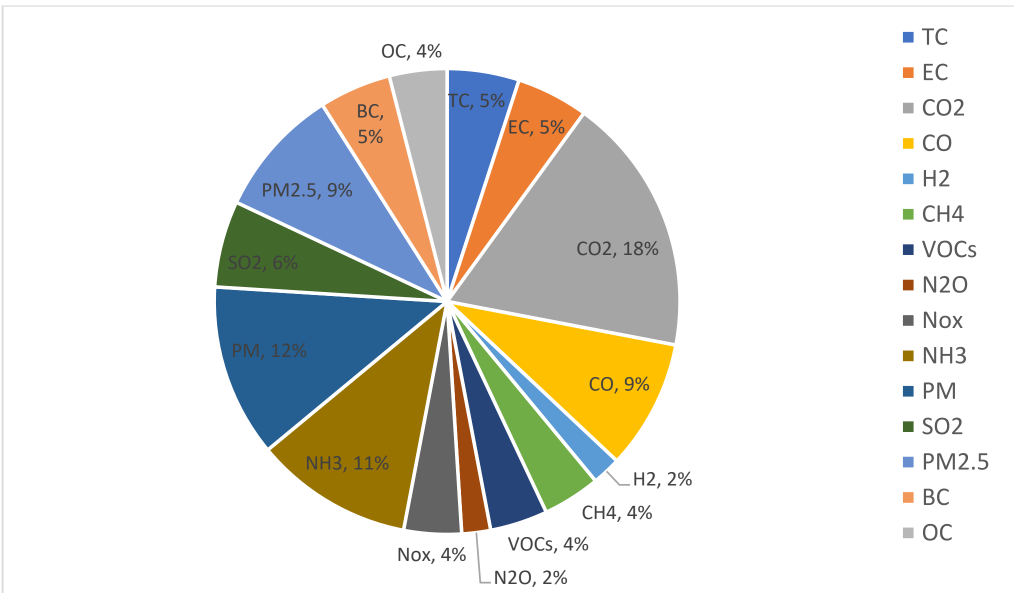

Figure 6. Worldwide contributions of biomass burning emissions products [29].

Spotlight on Lebanon

Lebanon is a small nation situated in the Eastern Mediterranean, encompassing a total land area of 10,452 square kilometers. Its population has reached about 6 million people [30]. Lebanon heavily relies on fossil fuels for its energy needs, with fuel oil generating 95% of its electricity. Despite private generators contributing a third of the total electricity production, the country is plagued by electricity shortages due to aging infrastructure, inadequate investment, and limited resources. Unfortunately, the high fuel consumption has led to environmental degradation and air pollution. In 2018, the primary energy supply was 8.57 Mtoe, mostly from oil and natural gas for Lebanon [31–33].

Looking at the situation from another angle, energy crops emerge as a potential solution to Lebanon's energy crisis, capitalizing on its abundant agricultural land, which is well-suited for bioenergy production. However, it is crucial to emphasize that the cultivation of energy crops can potentially lead to adverse impacts on groundwater resources, both in terms of availability and quality [34]. This issue becomes particularly worrisome in Lebanon, a country already exceptionally vulnerable to the consequences of climate change and ongoing droughts. Consequently, the pursuit of alternative solutions remains a pressing and ongoing priority.

However, in addition to the energy crisis, Lebanon is also experiencing a waste crisis, causing environmental and economic issues due to the lack of a sustainable waste management plan. Despite spending an average of $420 million per year on solid waste management, Lebanon's waste management strategy, according to Human Rights Watch, is not sustainable and significantly more expensive than that of other countries such as Jordan and Tunisia, which invest between $48 and $54 million per year in this issue.

Lebanon generates over 2.04 million tons of municipal solid waste per year, with organic waste being the largest fraction, at more than 52%. This is due to the growth of the food industry and the culture of overconsumption. Additionally, dry and wet waste generated by the processing industry presents challenges in terms of storage, transportation, and processing [35,36].

Also, Lebanon is known for its wide variety of crops, which result in a diversity of biomass. The total cultivated area is 277,169 ha out of which 58,600 ha of olive trees, 77,100 ha of other fruit trees, 69,600 ha of cereals, and 41,700 ha of vegetable crops [37]. Given that biomass is a renewable energy source and considering Lebanon's energy crisis and abundance of diverse biomass waste, it prompts us to consider optimal ways to utilize these wastes for energy and biomaterial production.

3. Biomass Conversion Technologies

Addressing the need for a sustainable resolution to manage the increasing volume of biomass waste generated by the agri-food industry has stood as a key research focus for scholars over recent decades [38]. Biomass waste management and conversion are becoming increasingly popular due to the negative impact biomass waste has on the economy, the environment, and human health. However, recent research has shown that biomass waste can be converted into valuable resources with high efficiency and low cost, which can save money and conserve natural resources [39]. Biomass conversion is the process of converting organic matter from biomass into usable forms of energy and high-value products.

Biomass can be converted into several useful forms of energy and biochemicals using different processes and technologies [40,41]. Broadly, biomass conversion technologies fall into two categories: biochemical and thermochemical [42]. The selection of a specific conversion technology is influenced by several variables, including the type of feedstock and its moisture content, as well as the quality and quantity of biomass feedstock, its availability, the desired end products, economic considerations like profitability and market accessibility, and environmental considerations [43]. Rosendahl, L. (2010) explains that biomasses are also classified according to their water content when used for energy purposes [44]. Therefore, high-moisture biomass would not be appropriate for technologies that require prior drying, but instead would be appropriate for technologies that benefit from water content.

3.1. Biochemical Conversion

According to C. William et al. (2020), biochemical conversion is described as the process of converting biomass using enzymes from bacteria or other microorganisms to transform biomass into gaseous or liquid fuels, such as biogas or bioethanol [45]. This transformation occurs through anaerobic digestion, fermentation, or composting processes. Hydrogen, biogas, ethanol, acetone, butanol, and organic acids can be produced from biomass by selecting different microorganisms in the process of biochemical conversion as reported by Chen and wang (2016) [46]. By choosing different microorganisms, two types of butanediol can be produced, including 2,3butanediol, 1,4butanediol, isobutanol, xylitol, mannitol, and xanthan gum [47].

3.1.1. Anaerobic Digestion

Anaerobic digestion (AD), as detailed by Kumar and Ankaram (2019), is a method that transforms organic substances in an environment devoid of oxygen [48]. This process leads to the production of methane-rich biogas and involves a sequence of interrelated stages, including hydrolysis, fermentation, acetogenesis, and methanogenesis, as outlined by Sangeetha et al. (2020) [49]. During AD, microbes break down the organic components of waste to produce biogas that is composed of 40–65% methane (CH_4), 35–55% CO_2, and other trace gases like hydrogen (H_2) and H_2S. Additionally, the process yields a nutrient-rich residue known as digestate, which can be used as a soil conditioner or source of C, N, and P, as reported by Ghosh et al. (2020) and Wang and Lee (2021) [50,51]. The biogas generated can be used directly for heat and energy generation or upgraded into fuels and other value-added products, as reported by Ge et al. (2014) and Xu et al. (2018) [52,53]. However, the AD process has limitations such as its slow process, the foul odor release, and the lack of quality of digestate which makes it unsuitable for agricultural use.

3.1.2. Fermentation

According to Patra, D et al. (2022), fermentation is the process by which microorganisms (yeast or bacteria) convert biomolecules (glucose) into alcohol or acid under anaerobic conditions [54]. These products can yield fuels and various industrial bioproducts. Food and agricultural waste comprise a variety of sugars, with some being readily fermentable into ethanol and other products, while others, like cellulose, hemicellulose, starch, and protein, require additional processing before fermentation can commence. Conventional ethanol fermentation typically occurs within a temperature range below 35 °C, as indicated by Galbe and colleagues in their 2011 study [55].

Fermentation Products

The process of microbial fermentation converts sugars produced from biomass waste such as lignocellulosic waste, as explained by A.K. Chandel and co-authors in 2018 [56]:

- Biofuels like ethanol (the most prevalent), butanol, acetone, iso-butanol, lipids, and more.
- Organic acids such as lactic acid.
- Carbon dioxide.
- Hydrogen gas (H_2).

Ethanol production involves distillation and dehydration to increase the concentration of alcohol and achieve the necessary purity for use as a fuel for vehicles. The solid by-product resulting from fermentation, as exemplified in the case of sugar cane, can serve as livestock feed. Additionally, by-products like bagasse can be utilized as fuel for boilers or further processed through gasification [57].

Fermentation Feedstocks

The range of fermentation feedstocks for ethanol production is extensive and includes a variety of options. Among the most prevalent choices are cereal grains, sugar cane, and sugar beets, collectively known as first-generation feedstocks. However, due to concerns about food sustainability, lignocellulosic feedstocks, considered as a second-generation feedstock, have been developed as an alternative to overcome the limitations of first-generation bioethanol, as reported by Rodionova et al. (2022), and algal biomass as a third-generation feedstock, as reported by Timothy J. Tse et al. (2021) [58,59]. Lignocellulosic biomass, as highlighted by Wu et al. (2020), generally comprises cellulose (40–60%), hemicellulose (10–40%), and lignin (15–30%) [60]. Extracting sugars from these feedstocks for ethanol production is more challenging. Nevertheless, when compared to starch- and sugar-based feedstocks, cellulosic feedstocks offer a range of advantages, as stated by Kumar et al. (2012) and Youngs and Somerville (2012) [61,62]. These materials are abundant in agricultural countries, making them affordable and readily available for industrial-level plants. Moreover, since cellulosic feedstocks are not used for human consumption, they do not compete with the food supply.

Limitations of Fermentation

There are several challenges that restrict the use of fermentation, as reported by Sindhu et al. (2016) [63] such as

- Challenges in the process of deconstructing lignocellulosic biomass into functional components like sugars and lignin.
- The need for energy-intensive pretreatment processes to separate the complex biomass into its individual components.
- A significant proportion of the cost of processing lignocellulosic biomass for energy production comes from the pretreatment step, which can be more than 40%.

Extensive efforts have been made to develop new technologies that are efficient, cost-effective, and environmentally friendly for various types of biomasses, including lignocellulosic biomass. Noteworthy progress has been made in this field in the past decade, such as the use of specialized microorganisms or enzymes, the optimization of fermentation conditions, co-culturing different microorganisms, and the genetic modification of microorganisms, which are aimed at overcoming the limitations of lignocellulosic biomass fermentation. These methods can be employed collectively to improve the effectiveness of fermenting lignocellulosic biomass. However, despite these advancements, there are still significant gaps between novel findings and practical applications. For instance, attempts to integrate a pretreatment such as facilitating the efficient breakdown of biomass by enhancing the permeability and surface area availability of polysaccharides for enzymatic hydrolysis, hydrolysis, and fermentation processes into a single, more efficient step have not yet been widely implemented in the industry. Further efforts are required to bridge the gap between groundbreaking research and the real-world implementation of cost-effective and eco-friendly technologies for biomass conversion [64,65].

Table 1 shows the general comparison between anaerobic digestion and fermentation, in which it appears that the difference lies in the final product and its application.

Table 1. A general comparison of AD and fermentation [66].

Anaerobic Digestion	Fermentation
Organic MSW and agricultural waste are the most suitable as feedstock	Organic MSW and agricultural waste are the most suitable as feedstock
Process occurs in the absence of oxygen	Process occurs in the absence of oxygen
Final products: methane and digestate	Final products: acid or alcohol (ethanol, lactic acid, etc.) and a nutrient-rich residue
The biogas can be used to produce heat or electricity	Bioethanol can be used as clean fuel for transportation

3.1.3. Composting

Composting comprises only 5.5% of the total waste treatment methods used globally, while open dumping comprises the largest share, of 33% (Figure 7) [67].

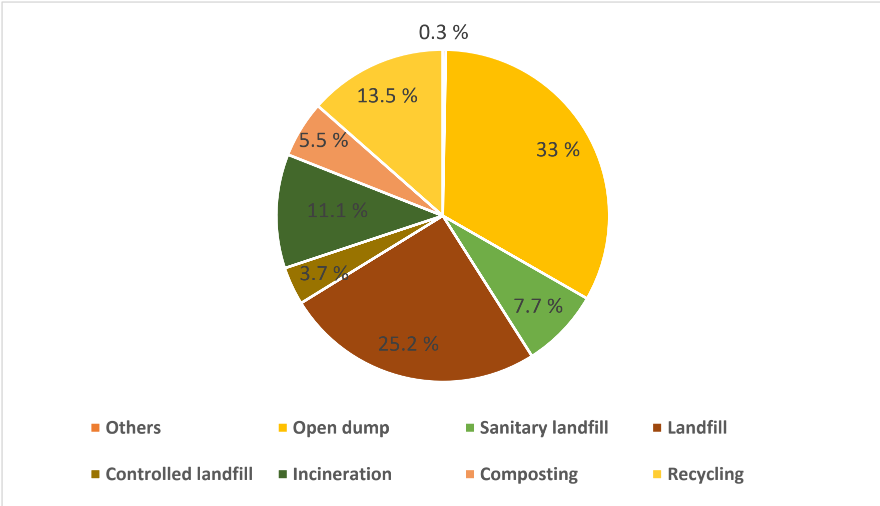

Figure 7. Share of the different waste management options in the global treatment and disposal of waste (%) [67].

A study conducted by Mazzà et al. in 2020 revealed that, in Lebanon, 8% of municipal solid waste (MSW) was recycled, 9% was composted, 51% was landfilled, and 32% was sent to open dumps in 2010 [68].

The study also found that over 52% of the waste in Lebanese bins is organic, and roughly 30% of the total mixed MSW can be diverted and transformed into a biologically stabilized material [68]. Additionally, the study reports that there was a total of 16 composting plants in Lebanon in 2014, with four under construction, three constructed, and nine operational. The study also notes that composting primarily takes place at the Coral plant.

Figure 8 represents the weakness and the strength of composting in addition to the threats and opportunities. In brief, composting can be a good practice to reduce organic waste but it requires a lot of standards to be followed during the process to avoid having low quality products or causing any harm during the process.

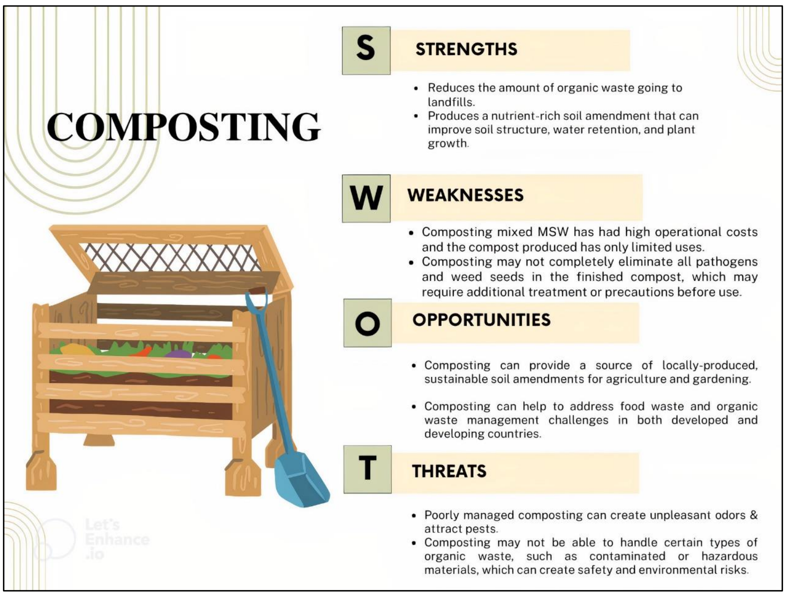

Figure 8. Strengths and weaknesses of composting according to keener (2010) [69].

3.2. Thermochemical Conversion:

Thermochemical processing employs controlled heating or oxidation to convert biomass into energy and chemical products. This approach presents various benefits compared to conventional methods, such as diminished greenhouse gas emissions and the capacity to generate electricity independently of an external power source, as noted by Mahinpey and Gomez (2016) [70]. The process involves elevated temperatures ranging from 300 to 1300 °C, the utilization of cost-effective and recyclable catalysts, rapid reaction rates, short reaction durations, and adaptability regarding feedstock composition and structure. Additionally, thermochemical conversion is not affected by the recalcitrance of biomass [71]. A variety of biomass waste materials, including food waste, agricultural residues, algae, forestry residues, and more, can be employed as suitable feedstocks for thermochemical conversion. Nevertheless, the selection of the thermochemical process hinges on the moisture content of the biomass waste. Therefore, there are two main categories of thermochemical conversion: dry (not aqueous) techniques and hydrothermal techniques. In dry thermochemical conversion, as the temperature increases, the biomass primarily undergoes structural destruction, decomposing into condensable vapors and gaseous molecules. In contrast, hydrothermal techniques produce a solid product at mild conditions (below 280 °C and self-generating pressure) [72].

Three primary pathways for thermochemical conversion are combustion, gasification, and pyrolysis, in addition to hydrothermal treatment (HTT) such as hydrothermal carbonization, liquefaction, and gasification [73,74].

3.2.1. Direct Combustion

Combustion converts biomass into heat, water, and carbon dioxide through an exothermic reaction in the presence of oxygen in open air or excess air. This process, one of the earliest uses of biomass conversion, involves the hydrocarbons in biomass and oxygen reacting together. However, improper oxygen quality can lead to incomplete combustion, releasing pollutants such as CO, NO_X, SO_2, and particulate matter into the atmosphere [75].

In the process of combustion, a solid fuel particle is introduced into a high-temperature environment, in which it undergoes drying and devolatilization, ultimately forming a residual char. Subsequently, this residual char is oxidized by substances like O_2, CO_2, and H_2O, leaving behind an ash residue, as discussed by Hupa, M. et al. (2017) [76]. Typically, direct combustion takes place in a furnace, steam turbine, or boiler, within a temperature range spanning from 800 to 1000 °C. This method is particularly suitable for biomass materials with a low moisture content (below 50%), as outlined by Lam, M. K et al. (2019) [77].

3.2.2. Gasification

As per the insights provided by AlNouss et al. (2019), biomass gasification (BG) is a transformative process that turns biomass into valuable products, including biofuels, biochar, syngas, power, heat, and fertilizer [78]. Simultaneously, it contributes to reducing the necessity for environmentally harmful waste disposal methods. This technology employs a controlled process that involves heat, steam, and oxygen to convert biomass into hydrogen and other products while employing a gasifying agent, which can be air, oxygen, steam, carbon dioxide, or a combination of these. The choice of gasifying agent impacts the heat content of the resulting syngas. For gasification, the optimal moisture content for biomass falls within the range of 10% to 15% according to Gao et al., 2023 [79].

Sikarwar and Zhao (2017) also highlight how biomass gasification alters the carbon-to-hydrogen mass ratio, resulting in a higher hydrogen fraction and an increased calorific value in the produced gaseous product [80]. However, it is important to note that while biomass gasification holds the potential to generate a fuel gas suitable for power generation or synthesis gas applications, the volatile components in biomass often contain tar, which is a complex mixture of aromatics, as discussed by Tasaka et al. (2006) [81]. Figure 9 provides an overview of the advantages and disadvantages associated with biomass gasification.

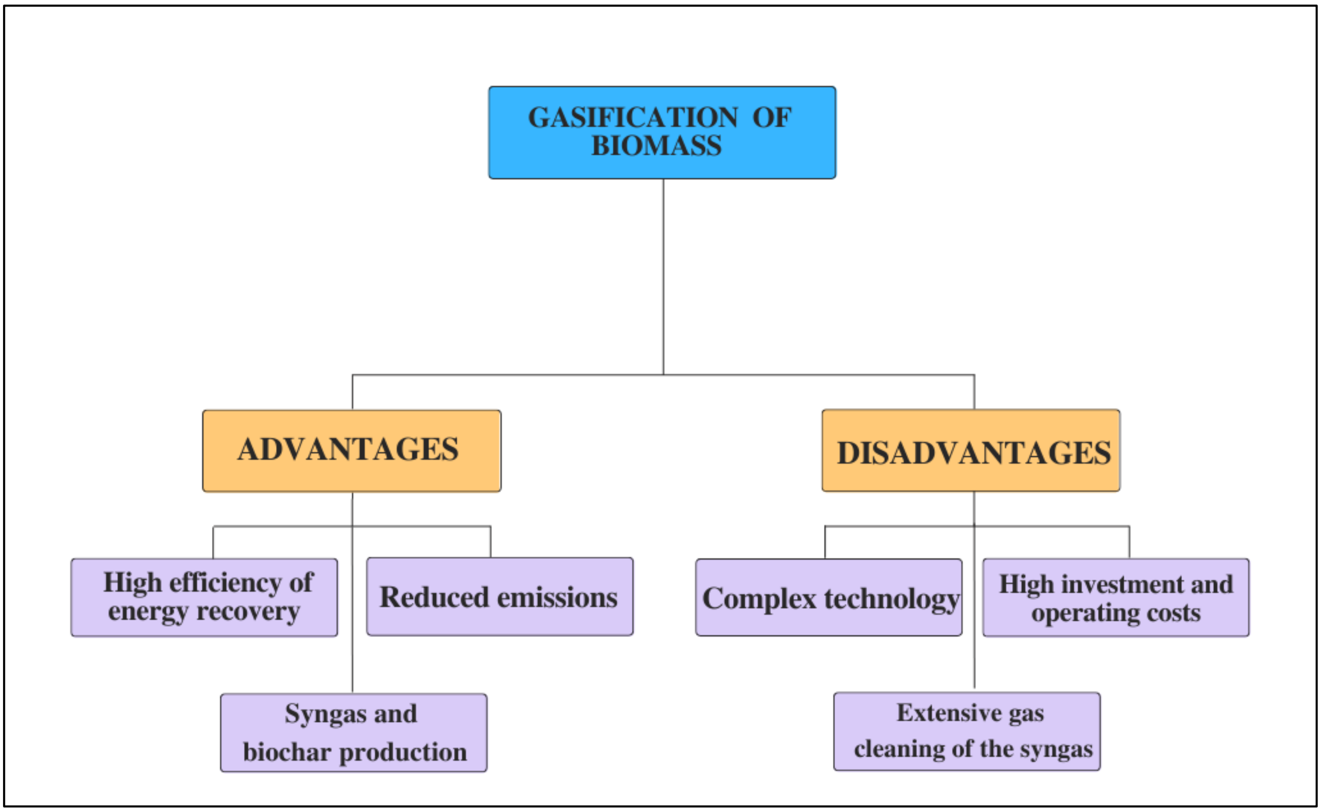

Figure 9. Advantages and disadvantages of biomass gasification according to Walling et al. (2019) [82].

3.2.3. Pyrolysis

Pyrolysis is a process that subjects molecules to high temperatures within an oxygen-free environment, causing chemical decomposition and the formation of smaller molecules, as elucidated by Palmer (2013) [83]. The thermal breakdown of biomass via pyrolysis is a complex phenomenon involving a range of reactions, including dehydration, isomerization, dehydrogenation, aromatization, charring, and oxidation, as discussed by Rasul et al. (2012) [84]. These reactions give rise to various products, including steam, carbon oxides, aliphatic and aromatic hydrocarbons, pitch (tar), polymers, hydrogen, and coal, as indicated by Saravanan et al. (2021) [85]. These products are categorized as biochar, bio-oil, and biogas/syngas.

In comparison to other thermochemical methods like gasification, combustion, and liquefaction, pyrolysis distinguishes itself by its lower energy requirements, greater energy recovery, and a diverse range of output products, as highlighted by Angin et al. (2013) [86]. The characteristics of pyrolysis products heavily depend on process parameters such as temperature, heating rate, residence time, and the size and nature of the biomass particles, as explained by Egbosiuba (2022) [87]. Table 2 illustrates the distinct characteristics of gas mixtures obtained through conventional pyrolysis from various biomass sources. Notably, different types of biomass lead to variations in gas mixture characteristics, particularly in terms of calorific value.

Additionally, pyrolysis can be categorized into two main types, slow and fast pyrolysis, determined by the temperature and heating rate applied, as noted by Hu et al. (2021) [88]. Slow pyrolysis excels in biochar production (Table 3), while fast pyrolysis is tailored for bio-oil production [89,90]. Consequently, the intended outcome of the process plays a pivotal role in selecting the appropriate type of pyrolysis. Figure 10 illustrates how the pyrolysis temperature significantly influences the yields of different pyrolysis products.

Table 2. Characteristics of gas mixture which were obtained by method of conventional pyrolysis from different types of biomasses [91].

Raw Material		Wood	Peat	Straw Husk	Sunflower Litter	Chicken Sludge	Sewage
Calorific value * (MJ/kg)	Q_h	13.2	10.5	9.1	7.9	7.8	11.1
	Q_l	12.0	9.5	8.2	7.2	7.2	9.9
Degree of energy conversion **		0.18	0.16	0.14	0.16	0.14	0.13
Adiabatic temperature of combustion (°C)		1860	1730	1720	1640	1710	1770

* Q_h = heat rejected to high T°C medium; Q_l = heat input from low T°C medium. ** "Degree of energy conversion" is the efficiency of transforming one type of energy into another.

Table 3. Operating conditions and main products in pyrolysis types [92].

	Residence Time	Heating Rate	Temperature	Main Products
Slow	Days	Very show	400 °C	Char
Conventional	5–30 min	20–100 °C/min	450–650 °C	Liquid, gas, char
Fast	0.5–5 s	1000 °C/s	450–650 °C	Liquid

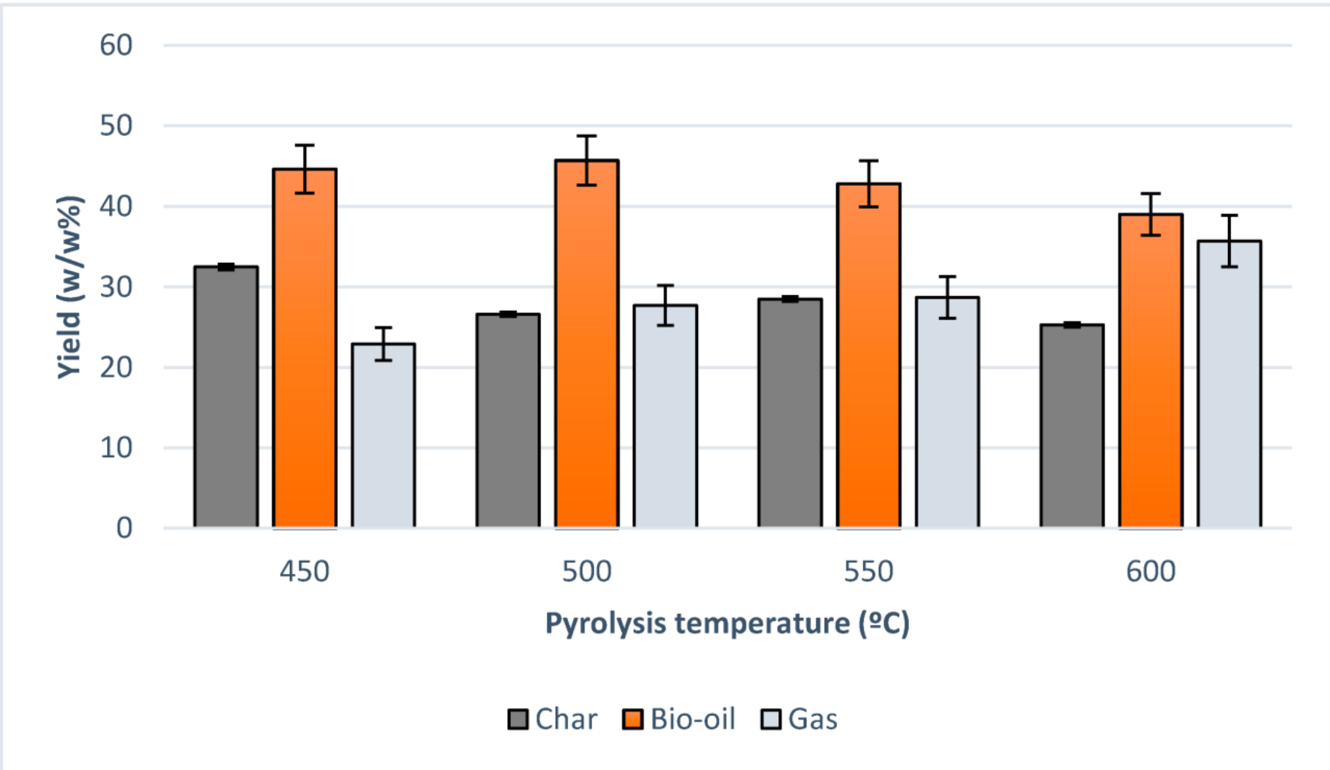

Figure 10. Relative amount of the end constituents during pyrolysis process of biomass at different temperatures [93].

Figure 11 depicts the advantages and disadvantages, as well as the opportunities and challenges associated with pyrolysis for biomass treatment. In summary, pyrolysis is a promising approach for converting organic waste into more valuable products. However, it still presents initial cost challenges.

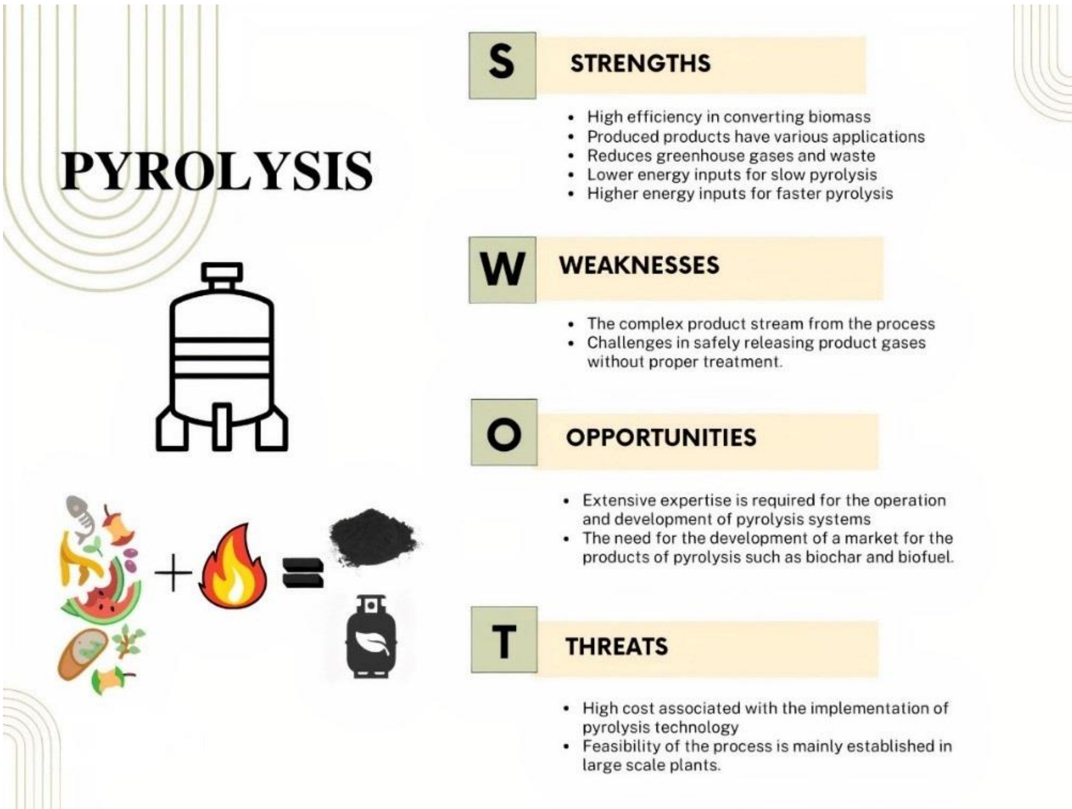

Figure 11. Pyrolysis strengths and weakness according to Jha, S. et al., 2020 [94].

3.2.4. Hydrothermal Carbonization

Kumar and Ankaram (2019) explain hydrothermal carbonization (HTC) as a thermochemical process that uses hot, compressed water to pretreat biomass with a high moisture percentage (75–90%) [48]. In this procedure, the temperature typically falls within the range of 180–280 °C, while the pressure is maintained between 2–6 MPa, with a duration spanning from 5 to 240 min, as noted by Arellano et al. (2016) [95]. In addition to being able to process biomass with a high moisture content without predrying, HTC also has low carbonization temperatures (180–350 °C), and it can minimize air pollution by dissolving nitrogen oxides and sulfur oxides in water [96]. Figure 12 summarizes the biomass conversion technologies that were mentioned in this section and Table 4 summarize the major difference between thermochemical and biochemical conversion.

Table 4. A general comparison of thermochemical and biochemical processes [97].

Thermochemical	Biochemical
Effectively applied to almost any biomass feedstock	Involves the use of microbes, enzymes, and/or chemicals
No pretreatment	Pretreatment is essential
Relatively higher productivity due to completely chemical nature of reaction	Productivity is limited due to biological conversion
Multiple high-value products possible using fractional separation of products	Normally limited to one or few products and would require additional microbes, enzymes for more products
Independent of climatic conditions	Mostly susceptible to ambient temperature, anaerobic digester
Complete utilization of waste/biomass	Production of secondary wastes such as biomass sludge
Less reaction time	High reaction time

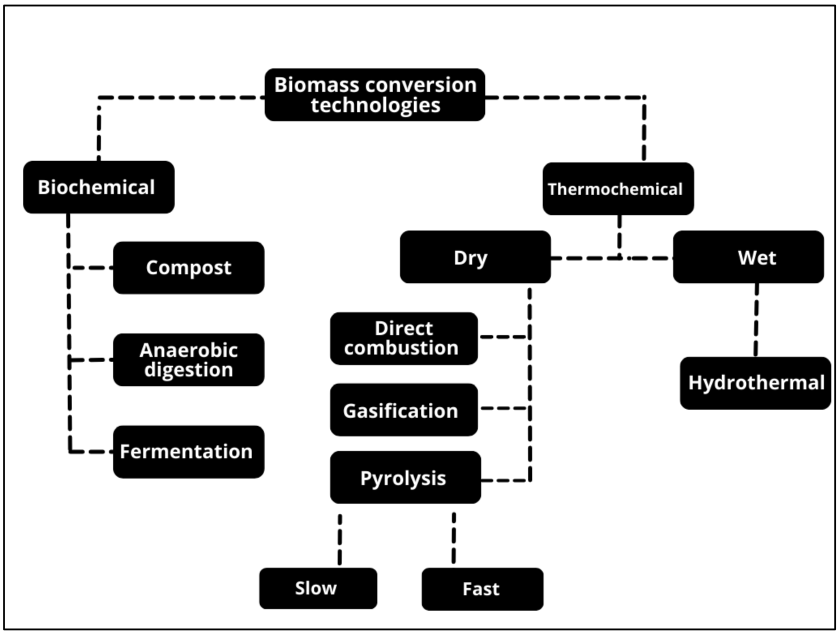

Figure 12. Biomass conversion technologies.

To sum up, the decision between biomass conversion technologies, whether it is biochemical conversion or thermal conversion, hinges on several factors such as the intended use, logistical considerations, and the availability of specific biomass resources. Each situation presents its distinct set of pros and cons that need to be taken into account.

4. Hydrochar and Biochar

Subcritical water activates the hydrochar production process by carbonizing it hydrothermally at temperatures between 180 °C and 260 °C [98]. Apart from its distinct physical, chemical, and biological properties, hydrochar exhibits characteristics such as an elevated specific surface area and pore volume, greater mineral content, the capacity to mitigate nitrogen oxide emissions, an enrichment of surface functional groups, and enhanced efficiency in fixing CO_2, as highlighted by Sharma et al. (2021) [99]. The agronomic and environmental benefits of biochar have sparked significant interest due to its porous structure and tunable functionality [100]. Difference between hydrochar and biochar are listed in Table 5.

Table 5. Difference between hydrochar and biochar [101].

	Hydrochar	Biochar
Temperature	Low: 180–260 °C [98]	High: between 300 °C and 1000 °C [102]
Residence time	Short	Long
Pressure	High: 10–25 MPa [103]	Low
Moisture content	>10%	<10%
Characteristics	Non porous—core shell, alkali rich surface	Porous and aromatic rich surface
	Low in fixed and total carbon content Energy efficient process	High in fixed and total carbon content High ash content
	High HHV	Low HHV

5. Application of Chars

Biochar is considered the principal product since its qualities allow it to be used as a solid fuel; an adsorbent for extracting pollutants from water/wastewater streams, such as phosphorus from agricultural runoffs; and a soil amendment [104]. Adsorption for water and air pollutants, activated carbon, anaerobic digestion promoter/catalyst, construction material, agriculture and horticulture use such as soil conditioning, compost additive, carbon sequestration, and so on, are all potential applications for biochar [105]. Because we are more interested in biochar applications as soil amendments, we will go into this application in further detail:

5.1. Yield Improvement

Several studies have shown that incorporating biochar into the soil can enhance plant growth and increase yield. In a study, banana peel biochar was prepared at 400 °C temperature for 2 h and was added to soil to grow plants. They found that adding 2% or 3% biochar to the soil helped the plants grow, but the difference was not significant enough to be considered meaningful. They also found that the biochar was high in potassium [106].

Moreover, Choudhary et al. (2023) found that using biochar made from invasive weeds in combination with inorganic fertilizers can improve the yield and quality of oats [107]. The biochar helped increase the plant height and number of tillers, as well as improve the nutrient availability and soil water-holding capacity. This could provide a good strategy for managing invasive weeds. Specifically, the study found that using 75% of regular fertilizer and 10 tons of biochar per hectare resulted in an 8% increase in green fodder yield, a 7.8% increase in dry fodder yield, a 6% increase in crude protein, and a reduction of 5.7% and 6% in acid detergent fiber and neutral detergent fiber, respectively, when compared to using only regular fertilizer.

As per a meta-analysis conducted by Ye et al. (2020), utilizing exclusively inorganic fertilizers resulted in a 26% boost in yield [108]. In contrast, the combination of biochar and inorganic fertilizers led to a more substantial 48% increase in yield when compared to the scenario where no fertilizers were employed. These studies encompassed the utilization of biochar produced within the temperature range of 400–550 °C.

Similarly, the research conducted by Frimpong et al. (2021) demonstrated that the utilization of a blend of biochar and compost or biochar in conjunction with NPK enhanced both soil nutrients and crop tissue nutrients [109]. They applied 10 tons of biochar per hectare, which was abundant in carbon but relatively lacking in nutrients. The compost employed was nutrient-rich and served as a readily available source of carbon. This combination of biochar and compost resulted in a remarkable 75.3% increase in maize yields. Figure 13 indicates that the highest levels of available phosphorus were observed in cases where biochar was used in combination with compost and NPK (nitrogen, phosphorus and potassium fertilizer mix), followed by instances where biochar and compost were combined. This observation substantiates the assertion that adding biochar alongside other amendments contributes to the enhancement of soil nutrient levels.

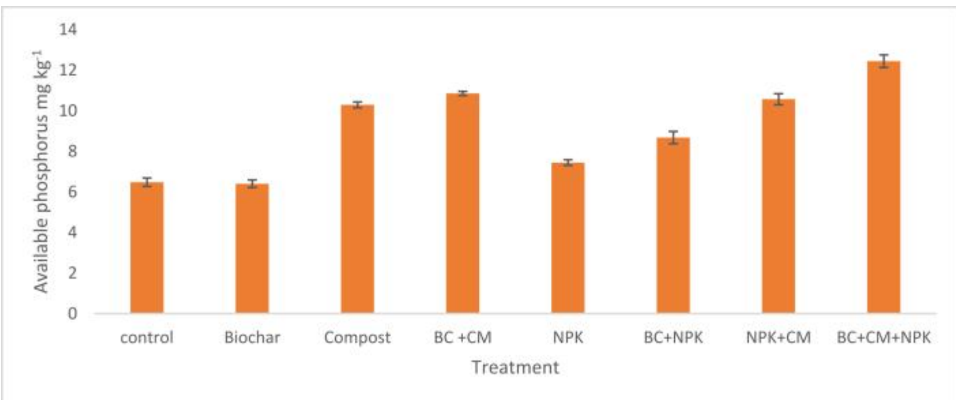

Figure 13. Total organic carbon (%) and total nitrogen (%) contents in soils amended with biochar, compost, and NPK, solely or in combination. BC: biochar, CM: compost, NPK: inorganic fertilizer [109].

Furthermore, in their study, Knoblauch et al. (2021) observed that the application of a single dose of biochar, derived from organic waste sourced from a biogas plant, at a rate of 3.4 tons per hectare and heated to 650 °C, had a positive impact on corn yield. After a two-year period, they noted a significant increase of 33–37% in the corn yield when compared to control plots [110]. Additionally, their findings indicated that the biochar application led to a reduction in the availability of potentially harmful trace elements such as Zn, Pb, Cd, and Cr in the soil. Moreover, the study revealed that the application of biochar resulted in an even more substantial increase in the yield of winter crops, with gains ranging from 52–72%. However, it is worth noting that the positive effects of biochar application diminished over time.

Another study found that lettuce plants grown in soil with biochar made from manure at 550 °C for 1.5 h in a prototype pyrolysis kiln with a capacity of 15 kg had increased biomass. The biochar was added to the topsoil (0–25 cm depth) at a rate of 5% before planting, and the topsoil was made up of 52% sand, 21% silt, and 27% clay, with 0.6% total organic matter, a pH of 8.74, and an electrical conductivity of 0.84 mS cm^{-1} [111].

Joseph (2020) found that using biochar made from fresh dung in the soil increased soil carbon, fruit yield, tree diameter, and height [112]. Trees planted with biochar had 18–26% greater growth rates than the control, with an average tree diameter of 145.4 mm and tree height of 3.7 m. The fruit count from the biochar row was 97% greater in 2018 (Figure 14). The biochar was applied in two halves, with the first half applied at a depth of 500 mm and a 250 mm layer of subsoil placed on the biochar.

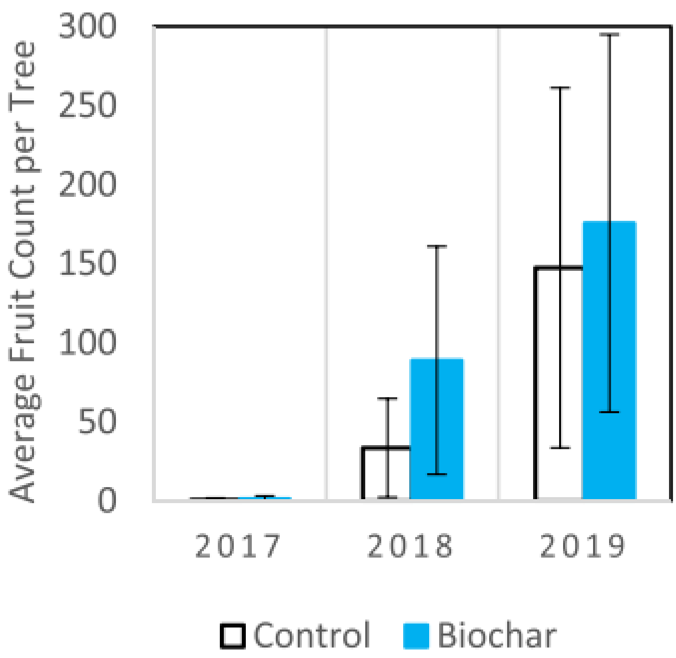

Figure 14. Average fruit yield count per tree as a function of year of picking [112].

Furthermore, a global meta-analysis has found that the application of biochar to soils can lead to significant improvements in crop yields and reductions in pollution. Specific studies conducted in the locations of Jokioinen, Qvidja, Viikki-1, and Viikki-2 in Finland found that using biochar resulted in increases of 65% in crop yield and reductions of 43% in greenhouse gas emissions. The use of spruce biochar in Qvidja also led to increases in plant biomass, plant nitrogen uptake, and crop yield, as well as a reduction in nitrogen leaching. This is attributed to the biochar's high specific surface area, which allows it to retain nitrogen in the soil, making it a more efficient and sustainable method of fertilization. The specific soil types in these locations were Stagnosol, Cambisol, and Umbrisol, characterized by poor drainage, a high organic matter content, and a good water-holding capacity, respectively. The biochar used in these experiments was produced by pyrolyzing chipped forest residue at 450 °C and the application rate was 30 t ha^{-1} with five replicates [113,114].

Therefore, from an economic standpoint, incorporating biochar as a soil amendment under optimal conditions can enhance crop yields, subsequently boosting income for both farmers and agribusinesses.

5.2. Nutrient Retention

Biochar possesses an extensive surface area, enabling it to effectively absorb and retain essential nutrients like nitrogen, phosphorus, and potassium. As a result, it plays a role in mitigating nutrient leaching, which occurs when these essential elements are washed away from the soil due to rainfall or irrigation. This nutrient retention property of biochar contributes to a reduction in the demand for fertilizers, which are not only costly but also carry adverse environmental consequences.

The incorporation of biochar derived from pine tree waste, produced at 650 °C, into soil has the capacity to enhance both the total carbon content and the availability of phosphorus in the soil. In specific soil types, namely, sandy clay loam and clayey soils, the introduction of biochar at a rate of 20 Mg per hectare resulted in an increase of 24.9–28.7 g per kilogram of soil in total carbon, along with a rise of 43.9–79.5 mg per kg of soil in available phosphorus. Additionally, when biochar is co-applied with NP fertilizer, it has the potential to improve short-term phosphorus availability, as indicated in the research conducted by Romero et al. (2021) [115].

Furthermore, in a study conducted by Wu et al. in 2012, they employed various temperatures (300, 400, 500, 600, and 700 °C) and residence times (1, 2, 3, and 5 h) to create biochar from rice straw [116]. The resulting biochar underwent comprehensive analysis using a range of analytical techniques. The study's findings revealed that the pyrolysis temperature had a more pronounced impact on the chemical composition and structure of the biochar compared to the residence time, particularly when produced at a low heating rate. Biochar derived from rice straw and generated at 400 °C exhibited high alkalinity and cation exchange capacity, in addition to notable levels of available phosphorus and extractable cations. These characteristics indicate that biochar produced from rice straw holds promise for applications as a fertilizer or soil amendment.

The objective of the research conducted by Zhang, M et al. (2021) was to investigate the impact of incorporating biochar, which was produced by subjecting biomass to a temperature of 550 °C for a duration of 2 h into soil, specifically in relation to the retention of nitrogen fertilizer [117]. The study found that when compared to not adding biochar, the application of biochar increased the retention rate of nitrogen fertilizer by a significant amount, ranging from 49.84% to 95.23%. The results also showed that using higher rates of biochar (2% and 4%) was even more effective in improving the retention of nitrogen fertilizer. Additionally, the study observed that the utilization of biochar contributed to a reduction in nitrogen loss from the soil. Without the application of biochar, the nitrogen loss was observed to be 88.17%, while the application of biochar reduced the nitrogen loss by 4.77% to 50.16%. This indicates that the addition of biochar can help to retain more of the nitrogen fertilizer applied to the soil, leading to improved crop growth and yield. In addition, it was found that adding Moutai lees biochar, a type of biochar that is produced from the fermented residue (lees) of a traditional Chinese liquor called Moutai, to yellow soil improves soil nutrition and microbial environment by increasing the total nitrogen and nitrate contents but decreases the microbial biomass nitrogen content. The study found that Moutai lees biochar at 4% is effective in increasing the nitrogen fertilizer retention rate and decreasing the risk of nitrogen leaching losses in yellow soil. The study also revealed that the application of biochar changes the bacterial community structure and the relative abundance of nitrogen-related microorganisms in yellow soil [117].

Furthermore, a study by Tangmankongworakoon (2019) found that biochar made from coffee residue (BCR) can be a useful material for soil amendment [118]. The biochar was made by heating coffee residue at a temperature between 350–550 °C for 45 min using a biomass kiln. The study found that the BCR biochar had a pH of 9.9, electrical conductivity of 1.66 dS/m, nitrogen ratio of 3.1, phosphorus ratio of 1, potassium ratio of 1.7, organic matter ratio of 19.5, and C/N ratio of 28.9%. The study concluded that BCR can be used not only as a source of fuel but also as a suitable material for soil amendment due to its ability to improve nutrient absorption and reduce nutrient leaching, leading to improved crop yields.

In conclusion, it can be affirmed that by enhancing nutrient retention, biochar contributes to the reduction in nutrient leaching, thereby mitigating soil and groundwater contamination from fertilizers. Simultaneously, it enhances nutrient availability to plants, leading to a decreased requirement for fertilizers. This dual effect reflects both economic and environmental benefits.

5.3. Water Retention

The impact of biochar on soil properties can vary depending on the soil's texture. Generally, it reduces bulk density (BD) by approximately 9%. However, its effect on the water-holding capacity (FC and WP) is most pronounced in coarse-textured soils, where it increases by 51% and 47%, respectively. In medium-textured soils, the increase is moderate, at 13% for FC and 9% for WP. In fine-textured soils, the effect on the water-holding capacity is minimal or slightly decreased. Furthermore, biochar substantially enhances the available water (AW) in coarse-textured soils, surpassing the improvements observed in medium- and fine-textured soils by 45%.

These findings suggest that biochar may offer greater advantages when applied to coarse-textured soils. In summary, biochar has the potential to enhance soil properties, with its effects varying based on soil texture. It generally reduces soil density, making it less compact and more porous. Soil density indicates the degree of soil particle compaction, with denser soils having less space for air and water movement. A reduction in soil density provides more room for air and water to permeate, benefiting plant growth by enabling deeper root penetration, improved access to water and nutrients, and enhanced water infiltration and drainage [119].

5.4. Reduce Greenhouse Gases (GHG) Emissions

In a global meta-analysis, it was observed that the application of biochar to soils resulted in a significant average reduction of 38% in soil N_2O emissions. The study identified that the application rate of biochar was the most influential variable in determining its potential for mitigating emissions [120].

Another study has suggested that the utilization of orange peel biochar can serve as an effective means for waste disposal, while simultaneously enhancing the fertility of soil. The study found that applying 2% orange peel biochar made at 350 °C for 3 h to the soil reduced greenhouse gas emissions by 59.2% for N_2O and 29.3% for CO_2. It was also discovered that over time, the soil pH, organic carbon, nitrate nitrogen, and enzyme activity increased [121].

Through its capacity to decrease greenhouse gas emissions, biochar emerges as a technology capable of mitigating climate change and mitigating its adverse effects.

5.5. Reduce Heavy Metals Availability

Joseph and Pan (2018), in their meta-analysis, found that the addition of biochar to soils resulted in a reduction in Cd, Pb, Cu, and Zn accumulation in plant tissues by approximately 38%, 39%, 25%, and 17%, respectively [122]. This reduction was particularly noticeable in coarse-textured soils. However, the impact of biochar on the uptake of heavy metals by plants varied depending on factors such as soil characteristics, the type of biochar used, plant species, and the type of contaminant. The study also revealed that the effect of biochar on Pb uptake was highly sensitive to soil pH. Specifically, decreases of 40%, 44%, and 20% in Pb uptake were observed in acidic, neutral, and alkaline soils, respectively.

Table 6 provides an overview of the distribution of biochar feedstocks and the pyrolysis rates derived from the studies analyzed.

Table 6. The distribution of biochar feedstocks and the rates of pyrolysis derived from the studies under review are presented. The feedstock sources encompass a variety of materials, including manure, crop residue, cobs, sludge, locusts, and shells [119].

Feedstock	**Percentage (in 174 Publications)**
Wood	43.4
Straw	45.7
Others	10.9
Pyrolysis speed	
Slow	79.2
Fast	20.8

Nonetheless, heavy metals do not constitute the sole category of pollutants that can be addressed through remediation. There are other pollutants, such as organic contaminants, in which biochar can serve as a remediation method. This applies to substances like pesticides, pharmaceutical products, as well as industrial products including solvents and additives. Research has shown that biochar is effective in combatting these pollutants. When biochar is introduced into agricultural soils, it can diminish the mobility, transport, and bioavailability of pesticides, while also reducing their microbial uptake. Furthermore, it has the capacity to promote soil microbiota and enhance pesticide degradation, as demonstrated by Ogura et al. (2021) [123]. In a study by Yang et al. (2010), the addition of 1% of biochar at 850 °C led to a 52% reduction in Chinese chive's uptake of fipronil and an 81% reduction in chlorpyrifos uptake [124].

In summary, when biochar is added to soil, it enhances the soil fertility through several mechanisms. It improves nutrient retention and increases the soil's capacity to hold water. These combined effects lead to healthier soil, better plant growth, and ultimately higher agricultural yields. Furthermore, the use of biochar can contribute to mitigating soil degradation and contamination and decreasing the reliance on synthetic fertilizers, aligning with environmentally sustainable agricultural practices.

5.6. Carbon Sequestration

The adverse effects of climate change, driven primarily by the emission of greenhouse gases like CO_2, have significantly impacted agriculture by causing droughts and land degradation. In response to this challenge, biochar has emerged as a promising tool for carbon sequestration. Biochar effectively captures CO_2 from the atmosphere and stores it in the soil. Subsequently, biochar serves as a valuable carbon source for the soil, playing a pivotal role in promoting soil health and enhancing productivity.

By capturing carbon from the atmosphere, biochar serves as a carbon storage mechanism. This process leads to an increase in soil organic carbon content, which is essential as an energy source for soil microorganisms. These microorganisms, in turn, play a crucial role in boosting plant growth and overall agricultural productivity.

In the study conducted by Yang et al. (2019), they observed a remarkable rise in the soil organic carbon levels of up to 26.7% in paddy soil [125]. Additionally, there was a substantial increase of up to 40.8% in the soil microbial biomass carbon. Moreover, Fawzy et al. (2022) reported in their study that 1 ton of biochar can embody 2.68 tCO2e [126].

Therefore, in addition to its role as a soil amendment, which aids in retaining nutrients and moisture, immobilizing pollutants, reducing emissions, and enhancing soil physical health, biochar also plays a significant role in mitigating climate change (Figure 15).

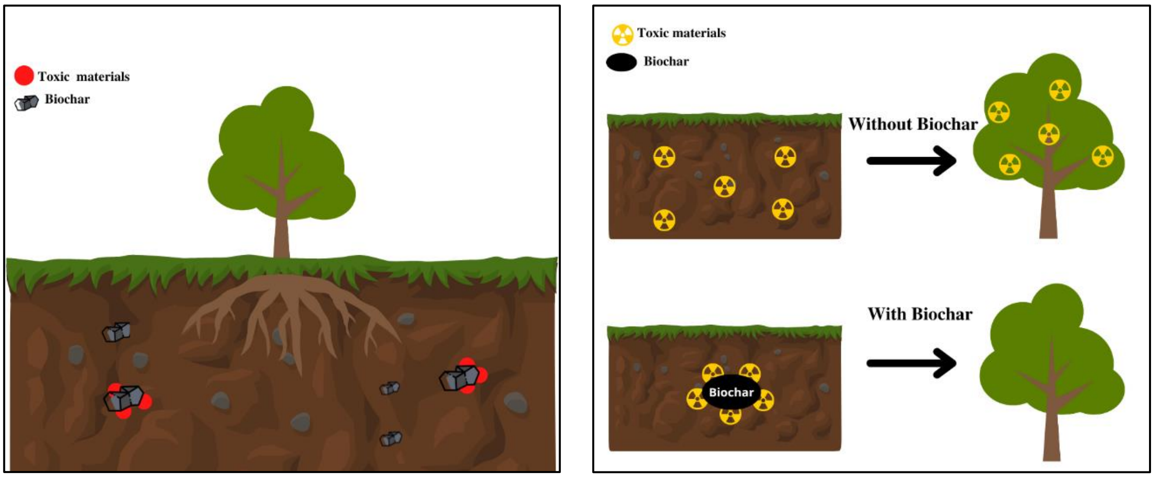

Figure 15. Biochar adsorbs heavy metals and toxic materials from soil.

Biochar and hydrochar have more applications other than soil amendment; some applications are mentioned below in Table 7.

Table 7. Biochar and hydrochar applications.

Application	Hydrochar	Biochar	References
Soil amendment	The use of Hydrochar made from Chlorella vulgaris microalgae in a soil column system for growing rice resulted in a 13.5–26.8% increase in grain yield	Adding 10 or 40 tons of wheat straw biochar per hectare to unfertilized soil led to a 12% and 14% increase in rice yields, respectively. In soil that received nitrogen fertilization, the same additions resulted in an 8.8% and 12.1% yield increase.	[127,128]
	Introducing 0.5% or 1% hydrochar to the soil led to enhanced plant growth, although there was an initial lag. The enhancement was attributed to the increased soil moisture retention capacity of the soil.	The use of poultry litter biochars at a rate of 10 tons per hectare resulted in a 42% increase in the dry matter yield of radish.	[129,130]
Removal of pollutants	Applying 5% of sewage sludge hydrochar to the soil reduced the amount of Cd that was available to plants by 52.29%, preventing cabbage from absorbing the metal from the soil.	The addition of Concarpus biochar greatly decreased the concentration of heavy metals in the shoots of maize plants, with the highest reduction of 60.5% for manganese.	[131,132]
Energy production	-	The yield of high-grade biofuels produced through the pyrolysis process can range from 21.9% to 75%, depending on the temperature of the process, the type of biomass used, and the type of reactor used.	[133]
Carbon sequestration	Because hydrochar contains more easily decomposable carbon, it is less efficient as a carbon sequestering agent in soil than biochar made by pyrolysis.	Biochar can sequester up to 1.67 mmol/g of CO_2 when prepared at 300 °C and used as an additive in mortar mixtures.	[134,135]
	-	It was estimated that the implementation of biochar has the potential to decrease 9% of Europe's total emissions.	[136]

An illustrative summary of this section is visually presented in Figure 16.

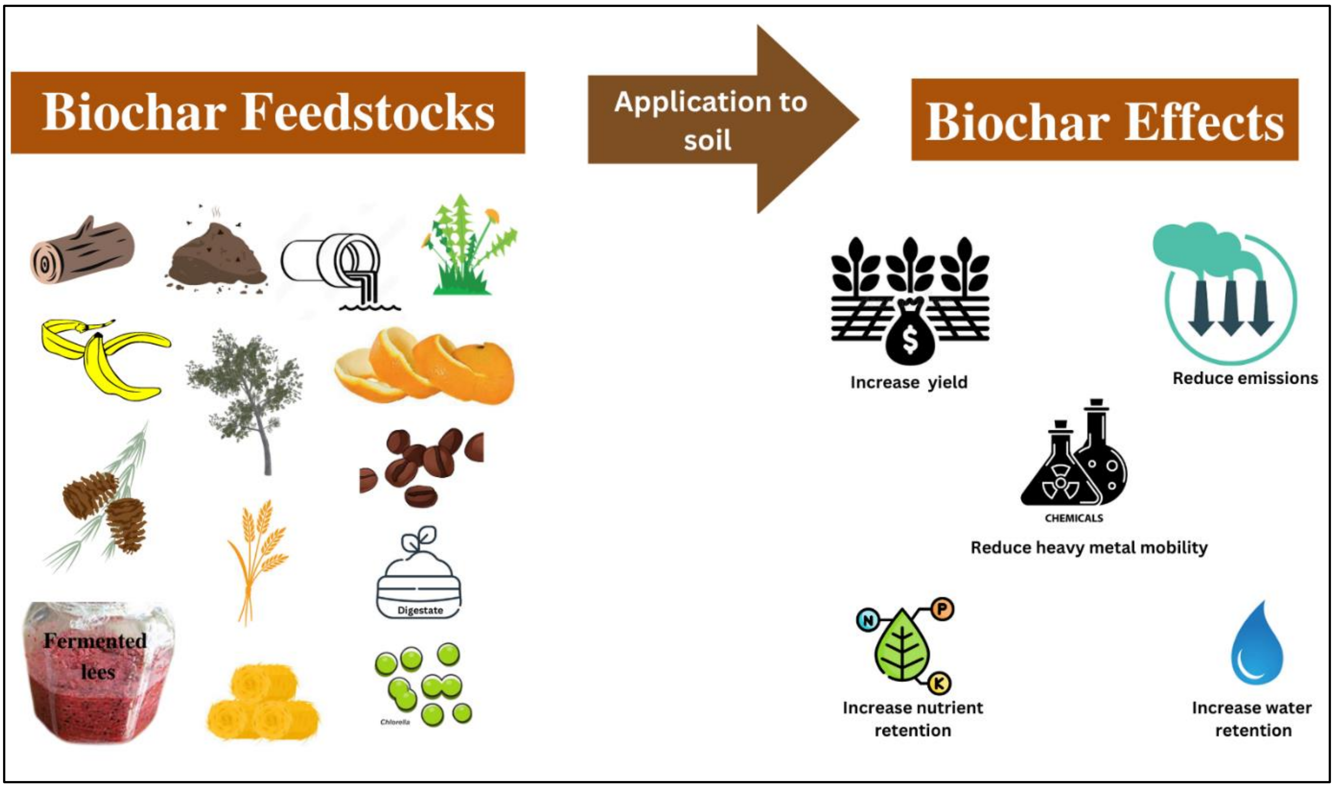

Figure 16. Biomass feedstock for biochar production and soil application with their effects that was covered in this section.

5.7. Industrial Application of Biochar

The review by Gąsior and Tic (2017) highlights the versatile nature of biochar and its potential to serve various purposes beyond its traditional applications in energy, agriculture, and wastewater treatment [137]. Its excellent insulating properties, ability to absorb moisture, and capacity to protect against electromagnetic radiation make it an ideal material for use in residential spaces, particularly as an insulating material and for moisture control. When combined with gypsum, clay, lime, or cement mortar, biochar can enhance the properties of plastering mortars due to its ability to absorb water and its low thermal conductivity.

Biochar has also captured the interest of numerous industries (Figure 17), including metallurgy, electronics, chemicals, textiles, and pharmaceuticals, due to its exceptional properties. The global market for biochar-based products includes a wide range of applications, such as microbiological preparations, animal feed supplements, paints and dyes, semiconductors, batteries, cosmetics, pharmaceuticals, food preservatives, and additives to textiles for functional clothing. Biochar can even be used as a filling material for pillows and mattresses.

In the field of material science, the use of carbonaceous materials is a well-established practice. However, the utilization of expensive carbon materials is limited to specialized applications. As a result, researchers are exploring innovative ways to use biochar as a renewable and cost-effective alternative to non-renewable carbon materials. This area of research and development is gaining popularity, as biochar has the potential to deliver exceptional end results. Ongoing studies continue to explore the vast potential of biochar in numerous fields.

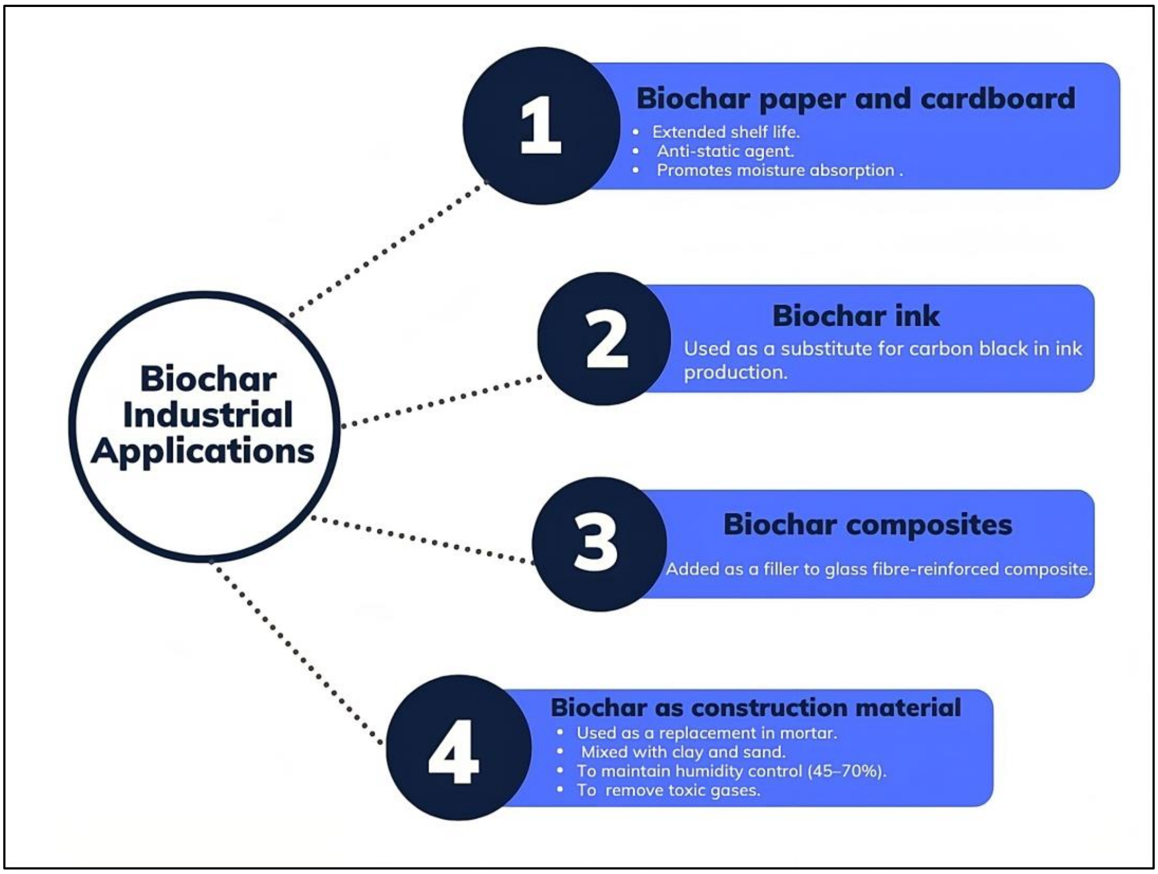

Figure 17. Emerging biochar applications according to Garcia, B. et al. (2022) [138].

6. Conclusions

This review highlights the potential of anaerobic digestion, pyrolysis, gasification, and hydrothermal liquefaction as means of converting biomass residues into valuable products such as biofuels and biochar, which can address various energy and environmental concerns. These technologies offer the benefits of producing high-value products, generating energy, reducing greenhouse gas emissions, and improving energy efficiency, while mitigating the environmental impact of conventional energy and food production methods.

Biochar serves as a multifaceted solution in the realm of soil improvement. Its capacity to act as a soil amendment, preserving nutrients and moisture, immobilizing pollutants, reducing emissions, and enhancing soil structure and health, underscores its pivotal role in sustainable agriculture. Beyond its soil-enhancing benefits, biochar also emerges as a potent ally in the battle against climate change, further amplifying its significance in the agricultural and environmental sectors.

However, the thermochemical process involved in biomass conversion remains complex and time-consuming, and there is a need for further research to enhance efficiency, scalability, and economic feasibility.

Recent advances in machine learning offer a promising solution for optimizing biomass conversion processes, especially in the area of biomass pretreatment. By leveraging AI, more efficient and eco-friendly pretreatment methods have been developed, making biomass a sustainable and viable source for producing biofuels and other high-value products. Additionally, machine learning can improve the process of characterizing biochar for various applications, such as carbon sequestration and soil amendment.

Despite the progress made in assessing the economic feasibility of using agricultural biomass for energy and higher value products, there are still logistical challenges associated with biomass collection, transportation, and storage. Further analyses are needed to optimize models that account for practical issues like biomass deterioration rates and equipment availability. It is recommended to integrate economic and environmental analyses to achieve a comprehensive assessment of biomass conversion to bioenergy and higher value products. Future models should also consider different carbon regulatory policies to balance environmental and economic goals. In summary, these technologies offer immense potential in addressing pressing environmental and energy challenges.

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References

1. Chamie, J. Population growth diversity continuing in the twenty-first century. In *Population Levels, Trends, and Differentials*; Chamie, J., Ed.; Springer: Berlin/Heidelberg, Germany, 2022; pp. 413–427. [CrossRef]
2. Gu, D.; Andreev, K.; Dupre, M.E. Major trends in population growth around the world. *China CDC Wkly.* **2021**, *3*, 604–613. [CrossRef] [PubMed]
3. Godfray, H.C.J.; Aveyard, P.; Garnett, T.; Hall, J.W.; Key, T.J.; Lorimer, J.; Pierrehumbert, R.T.; Scarborough, P.; Springmann, M.; Jebb, S.A. Meat consumption, health, and the environment. *Science* **2018**, *361*, eaam5324. [CrossRef] [PubMed]
4. Statista. Fresh Vegetables-Worldwide: Statista Market Forecast. 2022. Available online: https://www.statista.com/outlook/cmo/food/vegetables/worldwide#revenue (accessed on 16 September 2023).
5. Uddin, M.M.M. What are the dynamic links between agriculture and manufacturing growth and environmental degradation? Evidence from different panel income countries. *Environ. Sustain. Indic.* **2020**, *7*, 100041. [CrossRef]
6. van Dijk, M.; Morley, T.; Rau, M.L.; Sulser, T.B.; Lipper, L.; Wiebe, K. A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. *Nat. Food* **2021**, *2*, 494–501. [CrossRef]
7. Crippa, M.; Solazzo, E.; Guizzardi, D.; Monforti-Ferrario, F.; Tubiello, F.N.; Leip, A. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nat. Food* **2021**, *2*, 198–209. [CrossRef] [PubMed]
8. Kroyer, G. Impact of food processing on the environment—An overview. *LWT Food Sci. Technol.* **1995**, *28*, 547–552. [CrossRef]
9. Giovannucci, D.; Scherr, S.J.; Nierenberg, D.; Hebebrand, C.; Shapiro, J.; Milder, J.; Wheeler, K. Food and Agriculture: The future of sustainability. *SSRN Electron. J.* **2012**. [CrossRef]
10. Everwand, G.; Cass, S.; Dauber, J.; Williams, M.; Stout, J. Legume crops and biodiversity. In *Legumes in Cropping Systems*, 1st ed.; Murphy-Bokern, D., Stoddard, F.L., Watson, C.A., Eds.; CABI: Oxon, UK, 2017; pp. 55–69. [CrossRef]
11. Clune, S.; Crossin, E.; Verghese, K. Systematic review of greenhouse gas emissions for different fresh food categories. *J. Clean. Prod.* **2017**, *140*, 766–783. [CrossRef]
12. Peoples, M.B.; Giller, K.E.; Jensen, E.S.; Herridge, D.F.; Bourion, V.; Kumar, S.; Li, L.; Mpepereki, S.; Mulholland, M.; van Kessel, C.; et al. Quantifying country-to-global scale nitrogen fixation for grain legumes: I. Reliance on nitrogen fixation of soybean, groundnut and pulses. *Plant Soil* **2021**, *469*, 1–14. [CrossRef]
13. Sutton, P.; Wallinga, D.; Perron, J.; Gottlieb, M.; Sayre, L.; Woodruff, T. Reproductive Health And The Industrialized Food System: A Point Of Intervention For Health Policy. *Health Aff.* **2011**, *30*, 888–897. [CrossRef]
14. Ishangulyyev, R.; Kim, S.; Lee, S.H. Understanding Food Loss and Waste—Why Are We Losing and Wasting Food? *Foods* **2019**, *8*, 297. [CrossRef]
15. Kojima, R.; Ishikawa, M. Prevention and Recycling of Food Wastes in Japan. 2013. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwiQ8r-H58SCAxU6qFYBHVRECKoQFnoECBgQAQ&url=https%3A%2F%2Fs3b3b3a1c9c7aa7a9.jimcontent.com%2Fdownload%2Fversion%2F1371618475%2Fmodule%2F7050419389%2Fname%2F%25E6%2597%25A5%25E6%259C%25AC%25E3%2581%25AE%25E9%25A3%259F%25E5%2593%2581%25E3%2583%25AA%25E3%2582%25B5%25E3%2582%25A4%25E3%2582%25AF%25E3%2583%25AB%25E6%25B3%2595%25E3%2580%2580%25E3%2583%259D%25E3%2582%25B9%25E3%2582%25BF%25E3%2583%25BC%25E3%2582%25BB%25E3%2583%2583%25E3%2582%25B7%25E3%2583%25A7%25E3%2583%25B3%25EF%25BC%25882013%25E5%25B9%25B45%25E6%259C%258831%25E6%2597%25A5%25EF%25BD%259E6%25E6%259C%25881%25E6%2597%25A5%25EF%25BC%2589%25E3%2583%259C%25E3%2583%25B3.pdf&usg=AOvVaw13MRKyZxEm9xtsscZSCsog&opi=89978449 (accessed on 16 September 2023).
16. Ahmad, T.; Zhang, D. A critical review of comparative global historical energy consumption and future demand: The story told so far. *Energy Rep.* **2020**, *6*, 1973–1991. [CrossRef]
17. Moodley, P. Sustainable biofuels: Opportunities and challenges. *Sustain. Biofuels* **2021**, 1–20. [CrossRef]
18. Rafiee, A.; Khalilpour, K.R. Renewable Hybridization of Oil and Gas Supply Chains. In *Polygeneration with Polystorage for Chemical and Energy Hubs*; Academic Press: London, UK, 2019; pp. 331–372. [CrossRef]
19. Esmaeili, H.; Nourafkan, E.; Nakisa, M.; Ahmed, W. Application of nanotechnology for biofuel production. In *Emerging Nanotechnologies for Renewable Energy*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 149–172.

20. Pang, S. Fuel flexible gas production: Biomass, coal and bio-solid wastes. In *Fuel Flexible Energy Generation*; Woodhead Publishing: Amsterdam, The Netherlands, 2016; pp. 241–269. [CrossRef]
21. Kaltschmitt, M.; Janczik, S. Biomass to power is on the rise globally. *Renew. Energy Focus* **2015**, *16*, 174–176. [CrossRef]
22. Tripathi, N.; Hills, C.D.; Singh, R.S.; Atkinson, C.J. Biomass waste utilisation in low-carbon products: Harnessing a major potential resource. *Npj Clim. Atmos. Sci.* **2019**, *2*, 35. [CrossRef]
23. Zhou, C.; Wang, Y. Recent progress in the conversion of biomass wastes into functional materials for value-added applications. *Sci. Technol. Adv. Mater.* **2020**, *21*, 787–804. [CrossRef] [PubMed]
24. Wiedinmyer, C.; Yokelson, R.J.; Gullett, B.K. Global emissions of trace gases, particulate matter, and hazardous air pollutants from open burning of domestic waste. *Environ. Sci. Technol.* **2014**, *48*, 9523–9530. [CrossRef] [PubMed]
25. Fekete, B. Biomass. In *Climate Vulnerability*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013; pp. 83–87. [CrossRef]
26. Lou, X.F.; Nair, J. The impact of landfilling and composting on greenhouse gas emissions—A review. *Bioresour. Technol.* **2009**, *100*, 3792–3798. [CrossRef] [PubMed]
27. Zhao, H. Biomass burning emission and impacts on air pollution in China. In *Asian Atmospheric Pollution*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 335–347. [CrossRef]
28. Fajobi, M.O.; Lasode, O.A.; Adeleke, A.A.; Ikubanni, P.P.; Balogun, A.O. Investigation of physicochemical characteristics of selected lignocellulose biomass. *Sci. Rep.* **2022**, *12*, 2918. [CrossRef]
29. Giglio, L.; Randerson, J.T.; van der Werf, G.R. Analysis of daily, monthly, and annual burned area using the fourth-generation global fire emissions database (Gfed4): Analysis of Burned Area. *J. Geophys. Res. Biogeosci.* **2013**, *118*, 317–328. [CrossRef]
30. World Bank. The Role of Food and Agriculture for Job Creation and Poverty Reduction in Jordan and Lebanon. 2018. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwi6obv56MSCAxV7rlYBHaBjDjAQFnoECBMQAw&url=https%3A%2F%2Fdocuments1.worldbank.org%2Fcurated%2Fen%2F325551536597194695%2Fpdf%2FAgricultural-Sector-Note-Jordan-and-Lebanon.pdf&usg=AOvVaw3_pYF-uqd4JahTj6W5QmEE&opi=89978449 (accessed on 16 September 2023).
31. Wehbe, N. Optimization of Lebanon's power generation scenarios to meet the electricity demand by 2030. *Electr. J.* **2020**, *33*, 106764. [CrossRef]
32. Julian, M.; Bassil, N.; Dellagi, S. Lebanon's electricity from fuel to solar energy production. *Energy Rep.* **2020**, *6*, 420–429. [CrossRef]
33. Ersoy, S.R.; Terrapon-Pfaff, J.; Ayoub, M.; Akkouch, R. Report. Sustainable Transformation of Lebanon's Energy System. Friedrich-Ebert-Stiftung. 2021. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwitn5mH6cSCAxU8k1YBHfQfBOwQFnoECBMQAQ&url=https%3A%2F%2Flibrary.fes.de%2Fpdf-files%2Fbueros%2Fbeirut%2F19294.pdf&usg=AOvVaw3vHB8hRJE3Y5Xs5l__n6X-&opi=89978449 (accessed on 16 September 2023).
34. Nobre, R.C.; Nobre, M.M. Groundwater and Health Implications of Biofuels Production. *Environ. Impact Biofuels Cap* **2011**, *7*, 123–136. [CrossRef]
35. SWEEP-Net. Country Report on the Solid Waste. 2014. Available online: https://www.scirp.org/(S(lz5mqp453edsnp55rrgjct55.))/reference/referencespapers.aspx?referenceid=1754325 (accessed on 16 September 2023).
36. Abbas, I.I.; Chaaban, J.K.; Al-Rabaa, A.-R.; Shaar, A.A. Solid Waste Management in Lebanon: Challenges and Recommendations. *J. Environ. Manag.* **2019**, *248*, 109302. [CrossRef]
37. MOA. The Agriculture Sector-Climate Change Lebanon. 2007. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwij1qm06cSCAxXblFYBHc11D9IQFnoECBkQAQ&url=https%3A%2F%2Fclimatechange.moe.gov.lb%2Fviewfile.aspx%3Fid%3D154&usg=AOvVaw3XCNRdMdWyG4R_nasBGR12&opi=89978449 (accessed on 16 September 2023).
38. Wancura, J.H.; Brondani, M.; Vezaro, F.D.; Martins-Vieira, J.C.; Moreira, B.P.; Dos Santos, M.S.; Abaide, E.R.; De Castilhos, F.; Mayer, F.D. Motivations to produce biofuels from rice bran: An overview involving a recent panorama. *Ind. Crops Prod.* **2023**, *203*, 117170. [CrossRef]
39. Martín, M.; Taifouris, M.; Galán, G. Lignocellulosic biorefineries: A multiscale approach for resource exploitation. *Bioresour. Technol.* **2023**, *385*, 129397. [CrossRef]
40. Vickram, A.; Saravanan, A.; Senthil Kumar, P.; Thamarai, P.; Yasodha, S.; Jamuna, G.; Rangasamy, G. An integrated approach to the sustainable development and production of biofuel from biopolymers and algal biomass derived from wastewater. *Fuel* **2023**, *349*, 128691. [CrossRef]
41. Adams, P.; Bridgwater, T.; Lea-Langton, A.; Ross, A.; Watson, I. Biomass Conversion Technologies. In *Greenhouse Gas Balances of Bioenergy Systems*; Elsevier: Amsterdam, The Netherlands, 2018; pp. 107–139. [CrossRef]
42. Velvizhi, G.; Jacqueline, P.J.; Shetti, N.P.K.L.; Mohanakrishna, G.; Aminabhavi, T.M. Emerging trends and advances in valorization of lignocellulosic biomass to biofuels. *J. Environ. Manag.* **2023**, *345*, 118527. [CrossRef]
43. Garba, A. Biomass conversion technologies for bioenergy generation: An introduction. In *Biotechnological Applications of Biomass*; Basso, T.P., Basso, T.O., Basso, L.C., Eds.; IntechOpen: London, UK, 2020; pp. 1–18. [CrossRef]
44. Rosendahl, L. Biomass resources, fuel preparation and utilization for improving the fuel flexibility of advanced power plants. In *Advanced Power Plant Materials, Design and Technology*; Elsevier: Amsterdam, The Netherlands, 2010; pp. 312–331. [CrossRef]

45. Williams, C.L.; Dahiya, A.; Porter, P. Introduction to bioenergy and waste to energy. In *Bioenergy*, 2nd ed.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2020; pp. 5–44. [CrossRef]
46. Chen, H.; Wang, L. *Technologies for Biochemical Conversion of Biomass*; Academic Press: London, UK, 2016.
47. Chen, H.; Qiu, W. Key technologies for bioethanol production from lignocellulose. *Biotechnol. Adv.* **2010**, *28*, 556–562. [CrossRef]
48. Kumar, S.; Ankaram, S. Waste-to-Energy Model/Tool Presentation. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 239–258. [CrossRef]
49. Sangeetha, T.; Rajneesh, C.P.; Yan, W. Integration of microbial electrolysis cells with anaerobic digestion to treat beer industry wastewater. In *Integrated Microbial Fuel Cells for Wastewater Treatment*; Butterworth-Heinemann: Oxford, UK; Cambridge, MA, USA, 2020; pp. 313–346. [CrossRef]
50. Ghosh, P.; Sengupta, S.; Singh, L.; Sahay, A. Life cycle assessment of waste-to-bioenergy processes: A review. *Bioreactors* **2020**, 105–122.
51. Wang, W.; Lee, D. Valorization of anaerobic digestion digestate: A prospect review. *Bioresour. Technol.* **2021**, *323*, 124626. [CrossRef]
52. Ge, X.; Yang, L.; Sheets, J.P.; Yu, Z.; Li, Y. Biological conversion of methane to liquid fuels: Status and opportunities. *Biotechnol. Adv.* **2014**, *32*, 1460–1475. [CrossRef]
53. Xu, F.; Khalaf, A.; Sheets, J.; Ge, X.; Keener, H.; Li, Y. Phosphorus Removal and Recovery From Anaerobic Digestion Residues. *Adv. Bioenergy* **2018**, *3*, 77–136.
54. Patra, D.; Patra, B.R.; Pattnaik, F.; Hans, N.; Kushwaha, A. Recent evolution in green technologies for effective valorization of food and agricultural wastes. In *Emerging Trends to Approaching Zero Waste*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 103–132. [CrossRef]
55. Galbe, M.; Wallberg, O.; Zacchi, G. Techno-economic aspects of ethanol production from lignocellulosic agricultural crops and residues. In *Comprehensive Biotechnology*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2011; pp. 519–531. [CrossRef]
56. Chandel, A.K.; Garlapati, V.K.; Singh, A.K.; Antunes, F.A.F.; da Silva, S.S. The path forward for lignocellulose biorefineries: Bottlenecks, solutions, and perspective on commercialization. *Bioresour. Technol.* **2018**, *264*, 370–381. [CrossRef]
57. Khan, Z.; Dwivedi, A.K. Fermentation of Biomass for Production of Ethanol: A Review. *Univers. J. Environ. Res. Technol.* **2013**, *3*, 1–13.
58. Rodionova, M.V.; Bozieva, A.M.; Zharmukhamedov, S.K.; Leong, Y.K.; Chi-Wei Lan, J.; Veziroglu, A.; Veziroglu, T.N.; Tomo, T.; Chang, J.; Allakhverdiev, S.I. A comprehensive review on lignocellulosic biomass biorefinery for sustainable biofuel production. *Int. J. Hydrogen Energy* **2022**, *47*, 1481–1498. [CrossRef]
59. Tse, T.J.; Wiens, D.J.; Reaney, M.J.T. Production of Bioethanol—A Review of Factors Affecting Ethanol Yield. *Fermentation* **2021**, *7*, 268. [CrossRef]
60. Wu, X.; Luo, N.; Xie, S.; Zhang, H.; Zhang, Q.; Wang, F.; Wang, Y. Photocatalytic transformations of lignocellulosic biomass into chemicals. *Chem. Soc. Rev.* **2020**, *49*, 6198–6223. [CrossRef]
61. Kumar, M.; Goyal, Y.; Sarkar, A.; Gayen, K. Comparative economic assessment of ABE fermentation based on cellulosic and non-cellulosic feedstocks. *Appl. Energy* **2012**, *93*, 193–204. [CrossRef]
62. Youngs, H.; Somerville, C. Development of feedstocks for cellulosic biofuels. *F1000 Biol. Rep.* **2012**, *4*, 10. [CrossRef]
63. Sindhu, R.; Binod, P.; Pandey, A. Biological pretreatment of lignocellulosic biomass–An overview. *Bioresour. Technol.* **2016**, *199*, 76–82. [CrossRef]
64. Broda, M.; Yelle, D.J.; Serwa'nska, K. Bioethanol production from lignocellulosic biomass—Challenges and solutions. *Molecules* **2022**, *27*, 8717. [CrossRef] [PubMed]
65. Sharma, S.; Tsai, M.-L.; Sharma, V.; Sun, P.-P.; Nargotra, P.; Bajaj, B.K.; Chen, C.-W.; Dong, C.-D. Environment Friendly Pretreatment Approaches for the Bioconversion of Lignocellulosic Biomass into Biofuels and Value-Added Products. *Environments* **2022**, *10*, 6. [CrossRef]
66. Gautam, P.; Kumar, S.; Lokhandwala, S. Energy-Aware Intelligence in Megacities. In *Current Developments in Biotechnology and Bioengineering*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 211–238. [CrossRef]
67. Ghisellini, P.; Santagata, R.; Zucaro, A.; Ulgiati, S. Circular patterns of waste prevention and recovery. *E3S Web Conf.* **2019**, *119*, 00003. [CrossRef]
68. Mazzà, G.; Malek, R.; Raguzzoni, K.; Ragazzi, M.; Ciolli, M. The Usage of Compost-Like Outputs in Lebanon: Regulatory Framework, Opportunities and Threats. A Survey. 2020. Available online: https://www.google.com.hk/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiIh9r26sSCAxV9glYBHeVNC8oQFnoECBYQAQ&url=https%3A%2F%2Fwww.microfinanzaesviluppo.it%2Fwp-content%2Fuploads%2F2021%2F02%2FCompost_Survey_Lebanon.pdf&usg=AOvVaw3wkZbrLlxfj0F38KB-xja2&opi=89978449 (accessed on 16 September 2023).
69. Keener, H.M. Challenges and Opportunities in Composting Organic Waste. In *Climate Change and Food Security in South Asia*; Lal, R., Sivakumar, M., Faiz, S., Mustafizur Rahman, A., Islam, K., Eds.; Springer: Dordrecht, The Netherlands, 2010. [CrossRef]
70. Mahinpey, N.; Gomez, A. Review of gasification fundamentals and new findings: Reactors, feedstock, and kinetic studies. *Chem. Eng. Sci.* **2016**, *148*, 14–31. [CrossRef]
71. Mussatto, S.I.; Motta, I.L.; Filho, R.M.; van der Wielen, L.; Capaz, R.; Seabra, J.; Osseweijer, P.; Posada, J.; de Freitas Gonçalves, M.; Scorza, P.R.; et al. Sustainable Aviation Fuels: Production, Use and Impact on Decarbonization. In *Comprehensive Renewable Energy*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2022; pp. 348–371. [CrossRef]

72. Zhang, J.; Zhang, X. The thermochemical conversion of biomass into biofuels. In *Biomass, Biopolymer-Based Materials, and Bioenergy*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 327–368.
73. Sadhwani, N.; Liu, Z.; Eden, M.R.; Adhikari, S. Simulation, Analysis, and Assessment of CO_2 Enhanced Biomass Gasification. *Comput. Aided Chem. Eng.* **2013**, *32*, 421–426.
74. Zhang, W.; Chen, Q.; Chen, J.; Xu, D.; Zhan, H.; Peng, H.; Pan, J.; Vlaskin, M.; Leng, L.; Li, H. Machine learning for hydrothermal treatment of biomass: A review. *Bioresour. Technol.* **2022**, *370*, 128547. [CrossRef]
75. Yang, W.; Pudasainee, D.; Gupta, R.; Li, W.; Wang, B.; Sun, L. An overview of inorganic particulate matter emission from coal/biomass/MSW combustion: Sampling and measurement, formation, distribution, inorganic composition and influencing factors. *Fuel Process. Technol.* **2021**, *213*, 106657. [CrossRef]
76. Hupa, M.; Karlström, O.; Vainio, E. Biomass combustion technology development–It is all about chemical details. *Proc. Combust. Inst.* **2017**, *36*, 113–134. [CrossRef]
77. Lam, M.K.; Loy AC, M.; Yusup, S.; Lee, K.T. Biohydrogen Production from Algae. In *Biohydrogen*, 2nd ed.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 219–245. [CrossRef]
78. Alnouss, A.; McKay, G.; Al-Ansari, T. Superstructure Optimization for the Production of Fuels, Fertilizers and Power using Biomass Gasification. In *Computer Aided Chemical Engineering*; Elsevier: Amsterdam, The Netherlands, 2019; Volume 46, pp. 301–306. [CrossRef]
79. Gao, Y.; Wang, M.; Raheem, A.; Wang, F.; Wei, J.; Xu, D.; Song, X.; Bao, W.; Huang, A.; Zhang, S.; et al. Syngas Production from Biomass Gasification: Influences of Feedstock Properties, Reactor Type, and Reaction Parameters. *ACS Omega* **2023**, *8*, 31620–31631. [CrossRef]
80. Sikarwar, V.S.; Zhao, M. Biomass Gasification. In *Encyclopedia of Sustainable Technologies*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 205–216. [CrossRef]
81. Tasaka, K.; Furusawa, T.; Ujimine, K.; Tsutsumi, A. Surface Analyses of Cobalt Catalysts for the Steam Reforming of Tar derived from Biomass Gasification. *Stud. Surf. Sci. Catal.* **2006**, *159*, 517–520. [CrossRef]
82. Walling, E.; Babin, A.; Vaneeckhaute, C. Nutrient and Carbon Recovery from Organic Wastes. In *Biorefinery*; Springer: Cham, Switzerland, 2019. [CrossRef]
83. Palmer, R. Identification and Comparison. In *Encyclopedia of Forensic Sciences*; Academic Press: San Diego, CA, USA, 2013; pp. 129–137. [CrossRef]
84. Rasul, M.G.; Jahirul, M.I. Recent developments in biomass pyrolysis for bio-fuel production: Its potential for commercial applications. In Proceedings of the Recent Research in Environmental and Geological Sciences, 7th WSEAS International Conference on Energy & Environment (EE'12), Kos Island, Greece, 14–17 July 2012; pp. 256–264, ISBN 978-1-61804-110-4.
85. Saravanan, A.; Senthil Kumar, P.; Khoo, K.S.; Show, P.; Femina Carolin, C.; Fetcia Jackulin, C.; Jeevanantham, S.; Karishma, S.; Show, K.; Lee, D.; et al. Biohydrogen from organic wastes as a clean and environment-friendly energy source: Production pathways, feedstock types, and future prospects. *Bioresour. Technol.* **2021**, *342*, 126021. [CrossRef]
86. Angin, D.; Şensöz, S. Effect of pyrolysis temperature on chemical and surface properties of biochar of rapeseed (*Brassica napus* L.). *Int. J. Phytoremediat.* **2014**, *16*, 684–693. [CrossRef]
87. Egbosiuba, T.C. Biochar and bio-oil fuel properties from nickel nanoparticles assisted pyrolysis of cassava peel. *Heliyon* **2022**, *8*, e10114. [CrossRef] [PubMed]
88. Hu, Z.; Zhou, T.; Tian, H.; Feng, L.; Yao, C.; Yin, Y.; Chen, D. Effects of pyrolysis parameters on the distribution of pyrolysis products of Miscanthus. *Prog. React. Kinet. Mech.* **2021**, *46*, 146867832110109. [CrossRef]
89. Lee, Y.; Eum, P.; Ryu, C.; Park, Y.; Jung, J.; Hyun, S. Characteristics of biochar produced from slow pyrolysis of Geodae-Uksae 1. *Bioresour. Technol.* **2013**, *130*, 345–350. [CrossRef]
90. Mašek, O. Biochar in thermal and thermochemical biorefineries—Production of biochar as a coproduct. In *Handbook of Biofuels Production*, 2nd ed.; Woodhead Publishing: Amsterdam, The Netherlands, 2016; pp. 655–671. [CrossRef]
91. Larina, O.M.; Markin, A.V.; Borshchevskaya, E.A.; Shrednik, V.N.; Shabalin, E.V. Study of the Electron-Density Distribution of Composite Films by the Method of High-Energy X-ray Diffraction. *J. Phys. Conf. Ser.* **2016**, *774*, 012137. [CrossRef]
92. Bertero, M.; Sedran, U. Coprocessing of Bio-oil in Fluid Catalytic Cracking. In *Recent Advances in Thermo-Chemical Conversion of Biomass*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 355–381. [CrossRef]
93. Charis, G.; Danha, G.; Muzenda, E. Optimizing Yield and Quality of Bio-Oil: A Comparative Study of Acacia tortilis and Pine Dust. *Processes* **2020**, *8*, 551. [CrossRef]
94. Jha, S.; Nanda, S.; Acharya, B.; Dalai, A.K. A Review of Thermochemical Conversion of Waste Biomass to Biofuels. *Energies* **2022**, *15*, 6352. [CrossRef]
95. Arellano, O.; Flores, M.; Guerra, J.; Hidalgo, A.; Rojas, D.; Strubinger, A. Hydrothermal carbonization of corncob and characterization of the obtained hydrochar. *Chem. Eng. Trans.* **2016**, *50*, 235–240. [CrossRef]
96. Nasrollahzadeh, M.; Nezafat, Z.; Shafiei, N. Lignin chemistry and valorization. In *Biopolymer-Based Metal Nanoparticle Chemistry for Sustainable Applications*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 145–183. [CrossRef]
97. Singh, R.; Prakash, A.; Balagurumurthy, B.; Bhaskar, T. Hydrothermal Liquefaction of Biomass. In *Recent Advances in Thermo-Chemical Conversion of Biomass*; Elsevier: Amsterdam, The Netherlands, 2015; pp. 269–291. [CrossRef]
98. Basu, P. Hydrothermal Conversion of Biomass. In *Biomass Gasification, Pyrolysis and Torrefaction*, 3rd ed.; Demirbas, A., Ed.; Academic Press: London, UK, 2018; pp. 331–371. [CrossRef]

99. Sharma, H.B.; Venna, S.; Dubey, B.K. Resource recovery and circular economy approach in organic waste management using hydrothermal carbonization. *Clean Energy Resour. Recovery* **2021**, *1*, 313–326. [CrossRef]
100. Wang, Y.; Wu, P.; Bolan, N.S.; Wang, H. The potential agronomic and environmental applications of biochar: Prospects and challenges. In *Reference Module in Earth Systems and Environmental Sciences*; Elsevier: Amsterdam, The Netherlands, 2022. [CrossRef]
101. Kumar, A.; Saini, K.; Bhaskar, T. Hydochar and biochar: Production, physicochemical properties and techno-economic analysis. *Bioresour. Technol.* **2020**, *310*, 123442. [CrossRef] [PubMed]
102. Zhang, J.; Liu, J.; Liu, R. Effects of pyrolysis temperature and heating time on biochar obtained from the pyrolysis of straw and lignosulfonate. *Bioresour. Technol.* **2015**, *176*, 288–291. [CrossRef]
103. Masoumi, S.; Borugadda, V.B.; Nanda, S.; Dalai, A.K. Hydrochar: A Review on Its Production Technologies and Applications. *Catalysts* **2021**, *11*, 939. [CrossRef]
104. Zhang, Z.; Zhu, Z.; Shen, B.; Liu, L. Insights into biochar and hydrochar production and applications: A review. *Energy* **2019**, *171*, 581–598. [CrossRef]
105. Armah, E.K.; Chetty, M.; Adedeji, J.A.; Estrice, D.E.; Mutsvene, B.; Singh, N.; Tshemese, Z. Biochar: Production, Application and the Future. In *Biochar—Productive Technologies, Properties and Applications*; IntechOpen: London, UK, 2022; pp. 1–22. [CrossRef]
106. Islam, M.; Halder, M.; Siddique, M.A.B.; Razir, S.A.A.; Sikder, S.; Joardar, J.C. Banana peel biochar as alternative source of potassium for plant productivity and sustainable agriculture. *Int. J. Recycl. Org. Waste Agricult.* **2019**, *8* (Suppl. S1), 407–413. [CrossRef]
107. Choudhary, P.; Prasad, M.; Choudhary, M.; Kumar, A.; Kumar, S.; Srinivasan, R.; Mahawer, S.K. Exploring invasive weed biochar as soil amendment: A study on fodder oats productivity and soil biological properties. *Environ. Res.* **2023**, *216*, 114527. [CrossRef]
108. Ye, L.; Camps-Arbestain, M.; Shen, Q.; Lehmann, J.; Singh, B.; Sabir, M. Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use Manag.* **2019**, *36*, 2–18. [CrossRef]
109. Frimpong, K.A.; Phares, C.A.; Boateng, I.; Abban-Baidoo, E.; Apuri, L. One-time application of biochar influenced crop yield across three cropping cycles on tropical sandy loam soil in Ghana. *Heliyon* **2021**, *7*, e06267. [CrossRef]
110. Knoblauch, C.; Renuka Priyadarshani, S.H.; Haefele, S.M.; Schröder, N.; Pfeiffer, M. Impact of biochar on nutrient supply, crop yield and microbial respiration on sandy soils of northern Germany. *Eur. J. Soil Sci.* **2021**, *72*, 1885–1901. [CrossRef]
111. Christou, A.; Stylianou, M.; Georgiadou, E.C.; Gedeon, S.; Ioannou, A.; Michael, C.; Papanastasiou, P.; Fotopoulos, V.; Fatta-Kassinos, D. Effects of biochar derived from the pyrolysis of either biosolids, manure or spent coffee grounds on the growth, physiology and quality attributes of field-grown lettuce plants. *Environ. Technol. Innov.* **2022**, *26*, 102263. [CrossRef]
112. Joseph, S. Biochar increases soil organic carbon, avocado yields and economic return over 4 years of cultivation. *Sci. Total Environ.* **2020**, *724*, 138153. [CrossRef]
113. Kalu, S.; Simojoki, A.; Karhu, K.; Tammeorg, P. Long-Term Effects of Softwood Biochar on Soil Physical Properties, Greenhouse Gas Emissions and Crop Nutrient Uptake in Two Contrasting Boreal Soils. *Agric. Ecosyst. Environ.* **2021**, *316*, 107454. [CrossRef]
114. Soinne, H.; Keskinen, R.; Heikkinen, J.; Hyväluoma, J.; Uusitalo, R.; Peltoniemi, K.; Velmala, S.; Pennanen, T.; Fritze, H.; Kaseva, J.; et al. Are There Environmental or Agricultural Benefits in Using Forest Residue Biochar in Boreal Agricultural Clay Soil? *Sci. Total Environ.* **2020**, *731*, 138955. [CrossRef] [PubMed]
115. Romero, C.M.; Hao, X.; Li, C.; Owens, J.; Schwinghamer, T.; McAllister, T.A.; Okine, E. Nutrient retention, availability and greenhouse gas emissions from biochar-fertilized Chernozems. *Catena* **2021**, *198*, 105046. [CrossRef]
116. Wu, W.; Yang, M.; Feng, Q.; McGrouther, K.; Wang, H.; Lu, H.; Chen, Y. Chemical characterization of rice straw-derived biochar for soil amendment. *Biomass Bioenergy* **2012**, *47*, 268–276. [CrossRef]
117. Zhang, M.; Liu, Y.; Wei, Q.; Gou, J. Biochar enhances the retention capacity of nitrogen fertilizer and affects the diversity of nitrifying functional microbial communities in karst soil of southwest China. *Ecotoxicol. Environ. Saf.* **2021**, *226*, 112819. [CrossRef]
118. Tangmankongworakoon, N. An approach to produce biochar from coffee residue for fuel and soil amendment purpose. *Int. J. Recycl. Org. Waste Agric.* **2019**, *8*, 37–44. [CrossRef]
119. Razzaghi, F.; BilsonObour, P.; Arthur, E. Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma* **2020**, *361*, 114055. [CrossRef]
120. Zhang, Q.; Xiao, J.; Xue, J.; Zhang, L. Quantifying the effects of biochar application on greenhouse gas emissions from agricultural soils: A global meta-analysis. *Sustainability* **2020**, *12*, 3436. [CrossRef]
121. Sial, T.A.; Lan, Z.; Khan, M.N.; Zhao, Y.; Kumbhar, F.; Liu, J.; Zhang, A.; Hill, R.L.; Lahori, A.H.; Memon, M. Evaluation of orange peel waste and its biochar on greenhouse gas emissions and soil biochemical properties within a loess soil. *Waste Manag.* **2019**, *87*, 125–134. [CrossRef] [PubMed]
122. Joseph, S.; Pan, G. Effects of biochar on availability and plant uptake of heavy metals–A meta-analysis. *J. Environ. Manag.* **2018**, *222*, 76–85. [CrossRef]
123. Ogura, A.P.; Lima, J.Z.; Marques, J.P.; Massaro Sousa, L.; Rodrigues, V.G.S.; Espíndola, E.L.G. A review of pesticides sorption in biochar from maize, rice, and wheat residues: Current status and challenges for soil application. *J. Environ. Manag.* **2021**, *300*, 113753. [CrossRef] [PubMed]
124. Yang, X.B.; Ying, G.G.; Peng, P.A.; Wang, L.; Zhao, J.L.; Zhang, L.J.; Yuan, P.; He, H.P. Influence of biochars on plant uptake and dissipation of two pesticides in an agricultural soil. *J. Agric. Food Chem.* **2010**, *58*, 7915–7921. [CrossRef]

125. Yang, S.; Chen, X.; Jiang, Z.; Ding, J.; Sun, X.; Xu, J. Effects of Biochar Application on Soil Organic Carbon Composition and Enzyme Activity in Paddy Soil under Water-Saving Irrigation. *Int. J. Environ. Res. Public Health* **2019**, *17*, 333. [CrossRef]
126. Fawzy, S.; Osman, A.I.; Mehta, N.; Moran, D.; Al-Muhtaseb, A.H.; Rooney, D.W. Atmospheric carbon removal via industrial biochar systems: A techno-economic-environmental study. *J. Clean. Prod.* **2022**, *371*, 133660. [CrossRef]
127. Chu, Q.; Xue, L.; Cheng, Y.; Liu, Y.; Feng, Y.; Yu, S.; Meng, L.; Pan, G.; Hou, P.; Duan, J.; et al. Microalgae-derived hydrochar application on rice paddy soil: Higher rice yield but increased gaseous nitrogen loss. *Sci. Total Environ.* **2020**, *717*, 137127. [CrossRef]
128. Zhang, A.; Cui, L.; Pan, G.; Li, L.; Hussain, Q.; Zhang, X.; Zheng, J.; Crowley, D. Effect of biochar amendment on yield and methane and nitrous oxide emissions from a rice paddy from Tai Lake plain, China. *Agric. Ecosyst. Environ.* **2010**, *139*, 469–475. [CrossRef]
129. Mau, V.; Arye, G.; Gross, A. Poultry litter hydrochar as an amendment for sandy soils. *J. Environ. Manag.* **2020**, *271*, 110959. [CrossRef]
130. Chan, K.Y.; Van Zwieten, L.; Meszaros, I.; Downie, A.; Joseph, S. Using poultry litter biochars as soil amendments. *Aust. J. Soil Res.* **2008**, *46*, 437–444. [CrossRef]
131. Ren, J.; Wang, F.; Zhai, Y.; Zhu, Y.; Peng, C.; Wang, T.; Li, C.; Zeng, G. Effect of sewage sludge hydrochar on soil properties and Cd immobilization in a contaminated soil. *Chemosphere* **2017**, *189*, 627–633. [CrossRef]
132. Al-Wabel, M.I.; Usman, A.R.; El-Naggar, A.H.; Aly, A.A.; Ibrahim, H.M.; Elmaghraby, S.; Al-Omran, A. Conocarpus biochar as a soil amendment for reducing heavy metal availability and uptake by maize plants. *Saudi J. Biol. Sci.* **2015**, *22*, 503–511. [CrossRef]
133. Patel, A.; Agrawal, B.; Rawal, B.R. Pyrolysis of biomass for efficient extraction of biofuel. *Energy Sources Part A Recovery Util. Environ. Eff.* **2020**, *42*, 1649–1661. [CrossRef]
134. Gupta, S.; Kua, H.W.; Low, C.Y. Use of biochar as carbon sequestering additive in cement mortar. *Cem. Concr. Compos.* **2018**, *87*, 110–129. [CrossRef]
135. De Jager, M.; Schröter, F.; Wark, M.; Giani, L. The stability of carbon from a maize-derived hydrochar as a function of fractionation and hydrothermal carbonization temperature in a Podzol. *Biochar* **2022**, *4*, 52. [CrossRef]
136. Glaser, B.; Parr, M.; Braun, C.; Kopolo, G. Biochar is carbon negative. *Nat. Geosci.* **2009**, *2*, 2. [CrossRef]
137. Gąsior, D.; Tic, W. Application of the biochar-based technologies as the way of realization of the sustainable development strategy. *Econ. Environ. Stud.* **2017**, *17*, 597–611. [CrossRef]
138. Garcia, B.; Alves, O.; Rijo, B.; Lourinho, G.; Nobre, C. Biochar: Production, applications, and market prospects in Portugal. *Environments* **2022**, *9*, 95. [CrossRef]