

Review

Technology–Economy–Policy: Biochar in the Low-Carbon Energy Transition—A Review

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Abstract: Biochar can be regarded as a high-energy type of solid fuel produced via pyrolysis, which is the thermal modification of biomass of plant or animal origins. The biggest advantage of biomass relative to classic fossil fuels is the significant reduction in carbon dioxide emissions in the combustion process. Biochar is also considered a natural soil additive for improving soil parameters, increasing crop yields, remediating pollutants, and reducing emissions of methane, among other things. Over the past few years, the range of biochar applications has expanded significantly, as reflected in the number of scientific articles on the topic. Pyrolysates are used in the production of cosmetics, pharmaceuticals, building materials, animal feed, sorbents, and water filters, as well as in the field of modern energy storage and conversion, such as supercapacitors. The key importance of this material is attributed to its ability to sequester carbon and reduce greenhouse gas emissions. The relentless growth of the global economy and the high demand for energy generate large amounts of CO₂ in the atmosphere. Solving the carbon balance problem and the low-carbon energy transition toward carbon neutrality is very challenging. Biochar therefore appears to be an excellent tool for creating systems that can play an important role in mitigating climate change. The purpose of this review is to consolidate the existing knowledge and assess the potential of biochar in carbon neutrality based on the application sector.



Academic Editor: Davide Astiaso Garcia

Received: 19 March 2025

Revised: 8 May 2025

Accepted: 22 May 2025

Published: 23 May 2025

Citation: Saletnik, A.; Saletnik, B. Technology–Economy–Policy: Biochar in the Low-Carbon Energy Transition—A Review. *Appl. Sci.* **2025**, *15*, 5882. <https://doi.org/10.3390/app15115882>

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Keywords: biochar; carbon neutrality; carbon balance; energy transition; pyrolysates; sustainable development

1. Introduction

Today, one of the most important challenges to overcome for humanity is global warming and its impact on climate and environmental change. Scientific research indicates that alterations induced by global warming adversely affect human health and the integrity of ecosystems, potentially jeopardizing the sustainability of life on Earth [1]. Due to the increase in the average temperature of the Earth's surface, global warming leads to adverse effects such as rising sea levels, storms and floods, the spread of infectious diseases, and changes in ecosystems, etc. [2]. It is well known that global warming is rooted in the accumulation of greenhouse gases (GHGs) in the atmosphere, which are mainly released as a result of human activities, particularly the burning of fossil fuels [3]. These changes have intensified considerably in recent decades, and they were accelerated by the Industrial Revolution [4]. Scientific studies point to coal mining as a major source of pollution and environmental degradation [5–7]. Scientists are intensively searching for solutions that will lead to halting growing climate change [8,9]. Climate change is

a complex intergovernmental global challenge affecting various elements of the ecological, environmental, socio-political, and socio-economic disciplines [10–13]. The scale and complexity of environmental deterioration and climate change, especially with a growing global human population and unsustainable consumption patterns, requires disciplined and coordinated efforts to raise public awareness as well as to develop and implement effective responses. Due to industrialization, population growth, and rising living standards, it is virtually impossible to eliminate human activity; however, the consequences of inaction in the face of the above situation could prove disastrous. On 12 December 2015 in Paris, the United Nations Framework Convention on Climate Change (UNFCCC) reached an agreement to combat climate changes as well as to intensify and accelerate the measures and investment required for a sustainable low-carbon future. The main goal is to improve the global response to the threat of climate change by keeping the global temperature increase this century well below 2 °C, like pre-industrial levels, and to continue efforts to limit the temperature increase to 1.5 °C. In addition, the agreement aims to strengthen the capacity of nations to cope with the effects of climate change and align financial flows with low greenhouse gas emissions and climate-resilient pathways [14–17]. Scientists report that immediate steps can increase the likelihood of offsetting climate change’s destructive effects, but that its specific consequences are impossible to predict [18,19]. According to scientists, the only currently available path against climate change and environmental degradation is the production and use of products based on renewable resources, which can minimize the concerns caused by carbon emissions. Indeed, the consumption of renewable resources, especially biomass, releases carbon dioxide, which is offset by the carbon absorbed by biomass as it grows, which is why it is considered “carbon neutral” [20]. As a result, today the transition to zero- and low-carbon products is crucial to mitigate the negative impact of carbon emissions and address the challenges caused by climate change [21]. Biochar appears to be a concrete tool for creating systems that can play an important role in mitigating climate change. The purpose of this review is to consolidate knowledge and assess the potential of biochar in carbon neutrality by application sector. In this study, we have highlighted the promising role of biochar in various fields, which can help achieve sustainability goals for carbon neutrality and a sustainable environment. With the policy of transitioning to low-carbon energy in mind, the paper attempts to juxtapose the opportunities and threats of biochar in the energy sector.

This paper synthesizes diverse biochar applications across sectors and examines them within the broader policy and socio-political contexts. By comparing the opportunities and challenges biochar faces in the renewable energy sector, the review provides fresh insights into its potential role in achieving carbon neutrality. This holistic approach, integrating scientific, environmental, and policy perspectives, offers new insights into biochar’s place in global sustainability efforts.

To ensure the relevance and quality of the studies included in this review, a systematic literature screening process was applied. Only publications from recent years were considered to focus on the most current advancements in biochar research. Articles directly related to biochar policy implications, particularly in the context of low-carbon energy transitions and sustainability, were prioritized. Additionally, studies published in high-impact journals were given preference to guarantee the reliability and influence of the findings.

2. Biomass

Biomass is a renewable resource that has been utilized by humans since prehistoric times [22]. It encompasses all organic matter of plant or animal origin found in the biosphere, including materials derived from their natural or artificial processing [23–27]. Mankind has been using biomass since ancient times and the first reports of the intentional

human use of biomass date back about a million years. Researchers have discovered that the earliest consciously utilized by-products of biomass combustion were ash and charcoal, which were employed in prehistoric paintings located in caves that are over 40,000 years old [28]. Since early historic times, ashes have also been used in agriculture as a fertilizer to fertilize soils [29,30]. There is a current growing interest in biomass. It is mainly caused by the threats of climate change due to increased greenhouse gas emissions into the atmosphere and the search for alternative energy sources [23]. In addition, biomass is a readily available resource worldwide [31]. We consider biomass to be wood, its residues and by-products, i.e., wood chips and sawdust, agricultural residues such as quinoa, rice husks, and manure, as well as waste from the paper industry and the biogenic fraction of household waste and wastewater [29,32].

Rising living standards and economic development have resulted in a sharp increase in the production of bio-waste (organic, agricultural, and wood waste). Donner et al. (2021) report that the number of crops wasted by European residents in a year is 700 million tons [33,34]. In 2017, the European Union generated biological waste of various origins equivalent to 144 kilotons of oil [33], of which 70% was incinerated directly or after mechanical crushing (compression), nearly 12% was used for biogas production, and the remaining 6% of bio-waste was landfilled or composted [35]. Commonly used technologies for agricultural waste disposal, i.e., composting or open burning, result in the release of greenhouse gases such as CH_4 , N_2O , and min. pollutants into the atmosphere such as H_2S , SO_2 , and NH_3 . Consequently, the potential for the reutilization of agricultural waste diminishes as a result of such incineration [36]. One option for utilizing the biomass from agricultural waste is to produce biochar from it via pyrolysis. Producing biochar from biomass is an efficient and environmentally friendly method of processing it. The main raw materials for biochar production are animal excreta, agricultural and forestry residues, industrial bio-waste, and marine and aquatic organisms, etc. Biomass pyrolysis produces a range of solids, liquids, and gases [37]. Biomass is an indispensable part of sustainable energy development [5]. The use of biomass to generate thermal energy does not contribute to the accumulation of CO_2 in the atmosphere. During conversion, biomass emits approximately the same amount of carbon as is taken up during plant growth, thus helping to reduce greenhouse gas emissions. In addition, numerous studies and technical advances involving crop production and biomass conversion have resulted in higher biomass utilization efficiency at a lower cost compared to earlier years [23]. In the 19th century, the massive biomass transformation technology was direct combustion, mainly to produce energy in the form of heat. Advances in science and research and development and innovation by many researchers and scientists have led to the emergence of new concepts and technologies for converting biomass into a variety of products such as chemicals, commodities, heat, and most importantly, electricity [22].

3. Biochar

Bioproducts are environmentally friendly innovative products that can be obtained from biomass resources, offering sustainable solutions in various industries [7]. Currently, there is a wide range of bioproducts, such as bioplastics, biocomposites, and biofuels, etc., that have reached the commercialization phase and have shown successful results. An important branch of biomass products is biochar [38]. Biochar is a carbon-rich bioproduct formed by heating organic matter in a low-oxygen environment [39] or under anaerobic conditions [40]. Biochar is a technical term. The literature of the subject reports its various definitions. Lehmann and Joseph [41,42] define biochar as “a product rich in carbon (C)”. According to Shackley et al. [43], biochar is a “porous solid carbon product”. Verheijen et al. [44] described biochar as “biomass that has been pyrolyzed in a zero- or low-oxygen

environment applied to soil at a specific location". The definitions of biochar in the scientific literature are directly or indirectly related to its production process and potential application. Biochar is a carbon-rich product derived from the pyrolysis of solid biomass waste [41]. Biochar is a unique material with enormous potential. It is considered a very important tool for environmental management [42–49]. For thousands of years, charcoal has been one of the basic materials in the development of civilization [50]. Over the past few years, there has been tremendous progress in the field of biochar, both in science and industry, and its potential for use has increased interest in its beneficial applications in carbon sequestration, soil fertility improvement, pollution remediation, wastewater treatment, thermal and metallurgical purposes, and the metallurgical industry, etc. [51]. Recent studies suggest that biochar can be successfully used in both soil and non-soil applications, as it has the potential to combat climate change and maintain environmental sustainability [45]. The possibilities of using different origins of biochar to achieve carbon neutrality are presented in the diagram below (Figure 1).

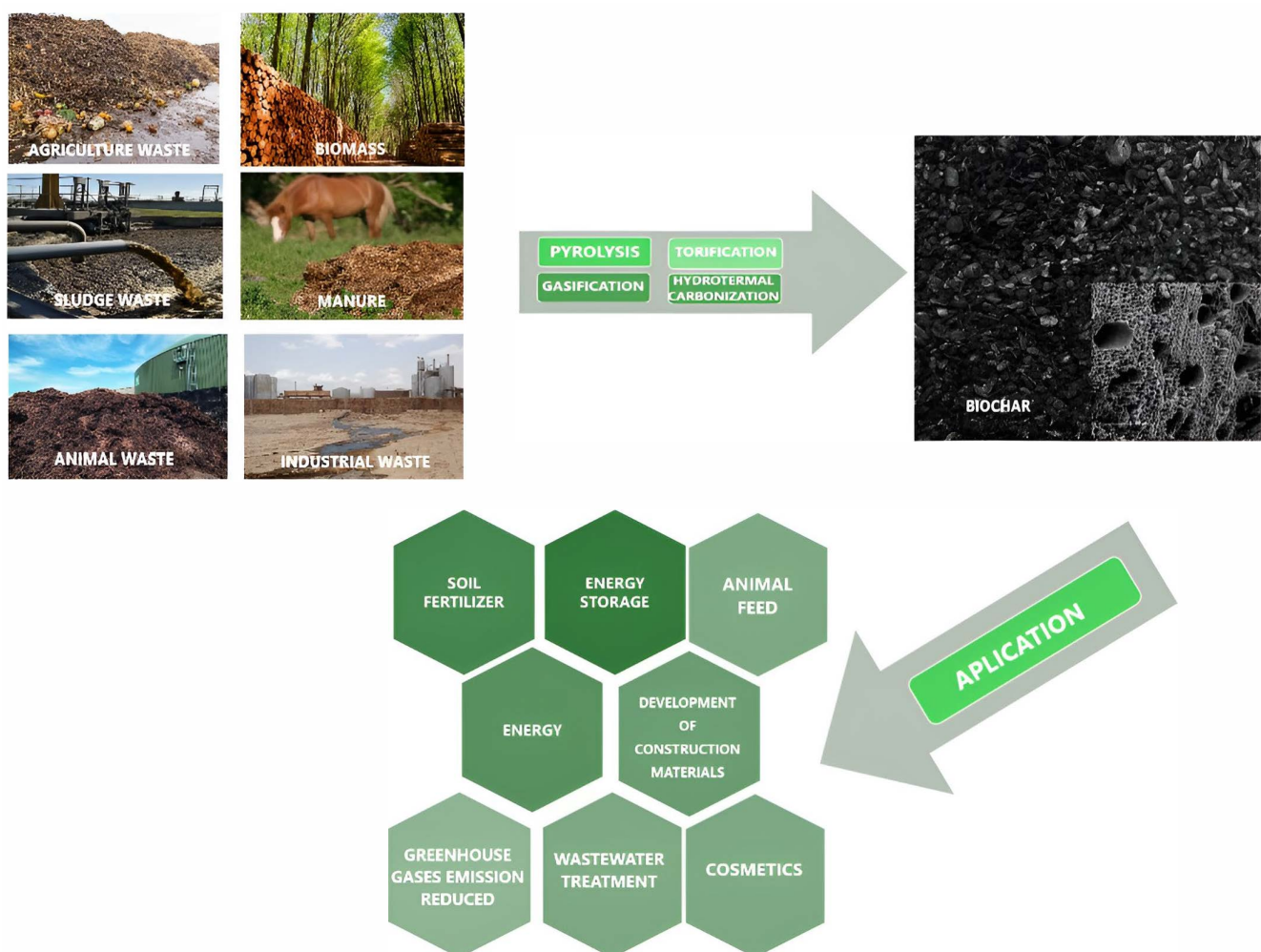


Figure 1. Different applications of biochar for carbon neutrality. Own elaboration.

The structure of biochar is characterized by a porous and complex composition [52]. Biochar is known for its significant porosity, characterized by a diverse range of sizes and distribution of pores [53]. It consists of a network of carbon-rich particles formed during the carbonization of biomass. This porosity increases the ability of biochar to retain water, nutrients, and other substances [54]. Indeed, when biomass undergoes pyrolysis, the dehydration process leads to the loss of water and the release of volatile components

from the carbon matrix, which contributes to the formation of the pore structure of the biochar. These pores are divided into three groups: micropores (<2 nm), mesopores (2–50 nm), and macropores (>50 nm) [55]. Porosity is a key factor when biochar is used for applications other than energy production. For example, as sorbents or fertilizers, the porosity of biochars significantly affects their effect on the biological, chemical, and physical properties of the soil [56]. In addition, biochar has a significant surface area due to its porous nature [55]. This property is a key attribute of biochar in chemical reactions, adsorption, and interactions with other substances. At the microscopic level, biochar consists of a mixture of amorphous carbon, microcrystalline structures, and residual organic matter [57]. These structures contribute to the physical properties and reactivity of biochar. Yaashikaa et al. show that [58] the surface of biochar can contain functional groups such as hydroxyl, carboxyl, and phenolic groups, which are responsible for various chemical behaviors and interactions, such as increasing their sorption properties. It should be noted that factors such as the type of raw material, pyrolysis conditions, and post processing play a key role in the specific structure of biochar. This diversity increases the versatility of biochar, leading to a wide range of applications, including soil improvement and environmental reclamation. The biochar sector is projected to grow at an impressive rate of about 13.9% per year between 2024 and 2030, revolutionizing sustainable practices and contributing significantly to environmental protection [59].

The process of producing biocarbon from biomass through energy generation occurs with virtually no sulfur and very little nitrogen [60]. The resulting biocarbon has high energy and is comparable to the coal used in industry as a raw material for fuel production [61,62]. Currently adopted low-carbon policies reducing the negative environmental impact of fossil fuels and the rapid depletion of fossil coal resources require the use of renewable and alternative sources of clean energy. The subject's literature and numerous studies report that biocarbon obtained via thermal processes from biomass is the only energy source capable of replacing conventional fossil fuels [41].

4. Technologies: Biochar Production

The properties and performance of biochar largely depend on the production techniques used. Each technique affects the properties of the biochar, including the yield, pore structure, surface area, carbon content, and nutrient retention capacity [50]. Among the new concepts and technologies for biomass conversion, thermochemical processes play an important role [21]. Biomass during biochemical or thermochemical conversion exhibits the characteristics of both a feedstock for direct energy production and a source of valuable chemicals [8]. Many methods of biochar production from biomass have been described, such as pyrolysis, gasification, and hydrothermal carbonization, etc. [63].

4.1. Pyrolysis

Pyrolysis is a process in which biomass undergoes thermal decomposition in the absence of oxygen. The process of biomass pyrolysis is used on an industrial scale [64–67]. The products of the process are carbonizate, which is a highly carbonized solid, bio-oil, also known as pyrolytic oil, and gas [64,68]. There are two stages in the process, i.e., the primary and secondary reactions. The primary stage includes the processes of dehydration, dehydrogenation, and decarboxylation [69]. Once the primary reaction is complete, a secondary reaction begins, which includes the breaking of large molecules and the transformation of solids into biochar and gases [63]. Based on the process parameters used, a distinction can be made between slow (biocarbonization), moderate, fast, and flash pyrolysis [8]. Slow pyrolysis involves heating at a lower rate (0.1 to $1\text{ }^{\circ}\text{C s}^{-1}$) for a long time (hours to days) at a temperature of 300 – $900\text{ }^{\circ}\text{C}$. The slow pyrolysis process provides a

favorable environment for secondary processes and results in the increased production of biochar. In fast pyrolysis, biomass is heated at a higher temperature (300–1000 °C) and a high heating rate (10–1000 °C s^{−1}) for a short time (0.5–2 s) [70]. The main products produced during the pyrolysis process include a solid (biochar), a liquid (bio-oil), and a gas (syngas). Fast pyrolysis (temperature of 500 °C, residence time at final temperature of 1 s) yields about 12% of biochar [50]. It should be noted that fast pyrolysis generally focuses on the production of bio-oil, while slow pyrolysis seeks to generate more biochar [71]. Moderate pyrolysis (temperature 400 °C, residence time at final temperature 10–20s) yields about 20 to 25% of biochar. The highest percentage of biochar obtained at about 35% can be achieved using slow pyrolysis (temperature 400–500 °C, residence time at final temperature of 5–30 min) [72,73]. Flash pyrolysis is a rapid thermal decomposition process typically occurring at temperatures between 400 °C and 700 °C, with heating rates exceeding 1000 °C/min and very short residence times of 0.5 to 10 s, aimed at maximizing the production of bio-oil and gases while minimizing biochar yield. Biochar is a solid carbon material that can be used as a catalyst, adsorbent, and fuel. Syngas consists of CH₄, CO₂, H₂, CO, and other low-molecular-weight gases, which can be used in gas engines after processing. Bio-oil consists of water, alcohol, phenolic compounds, aliphatic and aromatic hydrocarbons, and nitrogenous compounds (pyrazines, pyridines, and amines, etc.), which can be used in boilers to generate heat [63,74].

The pyrolysis temperature affects the properties of the biochar, such as the surface area, functional groups, and porosity. The increase in temperature causes an increase in the surface area and porosity due to the breakdown of the aliphatic alkyl and ester groups present in organic compounds, leading to the removal of pore-blocking substances. Biochar produced at a lower temperature is hydrophilic and simulates the structure of graphene, with fewer functional groups on its surface. In contrast, biochar produced at higher temperatures is hydrophobic; the functional groups are reshuffled and new groups are introduced, such as carboxyl, lactone, phenol, and pyridine, etc., which can act as electron donors and acceptors [75,76]. The temperature of pyrolysis and the types of raw materials are the most important factors in determining the properties of carbonates and thus their application [77]. The types of biomass feedstock affect the yield and quality of biochar. Pyrolysis of forest plants yields 30% of biochar compared to 45.69% of biochar produced from lignin, indicating that biochar yields depend on the lignin content [78,79].

4.2. Gasification

Gasification is the process of decomposing biomass into gaseous fuel (H₂, CO, and CH₄, etc.) at higher temperatures (500–1400 °C) under oxygen-deficient conditions. The production of the gas product can be increased by passing various gasification agents, such as steam, CO₂, and some mixtures of gases. While gasification, like pyrolysis, can produce biochar by heating biomass at high temperatures in a controlled environment with a limited supply of oxygen, it targets the production of syngas for energy purposes, with less emphasis on biochar production [80]. During this process, more than 50% of the biomass is converted into gaseous fuel, and the biochar produced via this process is smaller in size and resistant to chemical oxidation [81]. Temperature is an important factor in the gasification process and results in the increased production of carbon monoxide and hydrogen, with a decrease in carbon dioxide, methane, and hydrocarbons at higher temperatures [82]. The surface area of the biochar produced via gasification is usually smaller and has fewer functional groups, such as hydroxyl, carbonyl, and carboxyl groups, than biochar produced via pyrolysis [83]. The quality and performance of biochar is also affected by the equivalency ratio (ER). A higher ER means that more oxygen is supplied to the gasifier, which can have a positive or negative effect on the properties of the biochar. In

a study by Yao et al. in 2018, the biochar yield and carbon content decreased from 0.22 to 0.14 kg g⁻¹ of biomass and 88.17% to 71.6%, respectively, along with an increase in ER from 0.1 to 0.6 [84]. The high presence of oxygen molecules results in increased ash content with reduced mechanical strength and performance of biochar. James et al. conducted research on the effect of air flow on the properties of biochar made from pine chips. They noted that an air flow of 8 to 20 L min⁻¹ produces alkaline biochar (pH > 7.0), and that no acidic functional groups are present at a high air flow [85]. Biochar produced via gasification has a high content of alkali and alkaline earth metals, which depends mainly on the type of biomass [86].

4.3. Torrefaction

Torrefaction is another method used for the thermal decomposition of biomass. Torrefaction yields products such as biochar, bio-oil, and biogas, among which biochar has a significant share [87]. Two types of torrefaction can be distinguished: dry and wet. Dry torrefaction occurs at about 300 °C in an inert atmosphere [87,88]. Nitrogen is usually used as an inert gas. However, in recent years, it has been observed that the use of non-inert gas reduces energy consumption and lowers costs, and also reduces the formation of carbon monoxide and carbon dioxide as by-products [89]. Temperature is a key parameter in determining the final product of dry torrefaction [90]. Observations indicate that biomass pretreatment, which involves drying before dry torrefaction, is another key element. Adding a pretreatment step increases energy consumption and the costs of the process, but can improve the efficiency of the setup [91]. Wet torrefaction occurs when the pretreatment step is omitted and the temperature is much lower in comparison to in dry torrefaction [92]. Wet torrefaction also uses under-critical water as a reaction medium, which increases the solubility of the biomass [93]. Wet torrefaction is more efficient than dry torrefaction due to its lower temperature and shorter holding period [89]. It has been noted that torrefaction usually occurs at low temperatures [94]. The result of torrefaction is biochar, which can be used as a solid fuel [87].

4.4. Hydrothermal Technology

The process involves the thermochemical conversion of wet biomass into hydrochar. Hydrochar is similar to the biochar obtained through use of the various processes discussed above. This process is similar to the natural process of coal formation [87]. Hydrothermal treatment is carried out at moderate temperatures (150–350 °C) under a pressure of 10–15 bars [75]. At higher temperatures and pressure, water undergoes a dramatic change in properties, acting more like an organic solvent and favoring reactions that are typically catalyzed by acids and alkali and that promote the decomposition of biomass [95]. Although the exact mechanism of hydrothermal treatment is not understood, it is expected to involve hydrolysis, dehydration, decarboxylation, aromatization, and recondensation. During the hydrolysis process, the biomass breaks down into saccharides and lignin, and in the dehydration process, water is removed from the biomass by eliminating the hydroxyl group. CO₂ is removed during the decarboxylation process, leading to aromatization. The various compounds that are formed during all these processes, i.e., furfural, are hydrolyzed and decompose into phenols, aldehydes, and acids. All of these compounds recondense with aromatic polymers, resulting in the formation of hydrochar [10]. The main advantage of the hydrothermal process is its ability to convert wet biomass into carbonaceous solids with high efficiency without the need for energy-intensive drying. Other advantages include its conductive properties, controllable surface functions, the existence of a natural binder, and high calorific value, etc. [96]. At higher temperatures (~350 °C), the process shows a decrease in the yield of hydrochar (29%) and bio-oil (31%) and a significant increase

in the gas fraction (67%) [97]. An increase in temperature also causes a decrease in the O/C and H/C ratio. Wang et al. produced hydrochar from sunflower stalks using hydrothermal carbonization combined with the activation method, and the produced hydrochar had a high surface area of $1505 \text{ m}^2 \text{ g}^{-1}$ and energy density of 35.7 Wh kg^{-1} [98,99].

5. Policy: Support for Biochar

In order to realize the large-scale environmental and economic potential of biochar, both through ecosystem services and the many possible applications in innovative value chains, the international policies of countries and environmental and sectoral regulations should be well integrated. Government support and a favorable policy framework are key factors driving the European biochar market. European governments are increasingly recognizing the environmental and agricultural benefits of biochar and are implementing policies to promote its production and use. These policies include grants, subsidies, and funding for research and development projects focused on biochar. In addition, a regulatory framework is being created to ensure the quality and safety of biochar products, increasing consumer confidence and market acceptance. To fully realize biochar's potential in reducing greenhouse gases and supporting innovative value chains, its carbon sequestration capabilities must be better integrated into national and international carbon accounting frameworks. Biochar's effectiveness in CO_2 removal and its recognition in climate policies need further clarification, particularly regarding how its benefits are measured and incorporated into carbon accounting systems. The European Union has made significant progress by including biochar in its regulatory frameworks, such as the European Green Deal and the 2021–2027 Common Agricultural Policy (CAP) reform. These efforts are key to recognizing biochar as a tool for carbon sequestration. The EU has introduced regulations on biochar and established a CO_2 absorption certification system, ensuring that its carbon sequestration potential is properly monitored. Biochar is also gaining recognition as a Negative Emission Technology (NET), which supports its role in climate mitigation. To fully leverage this potential, political and financial support is essential. Policies incentivizing large-scale biochar production, particularly through carbon removal compensation, will make biochar a more economically viable solution. The integration of biochar into carbon accounting systems is vital for achieving climate neutrality goals, such as the EU's target of net zero emissions by 2050. Establishing systems for carbon credits and rewards for biochar-based sequestration will boost market growth and its adoption in tackling climate change. Government initiatives aiming to promote sustainable agriculture, soil health, and climate change mitigation further support the growth of the biochar market. Collaboration between governments, research institutions, and industry stakeholders fosters innovation and drives advances in biochar production technologies. Strong government support and policy incentives create a favorable environment for the growth and development of the biochar market in Europe. Until recently, the EU did not have clear regulations on the use of biochar. Net greenhouse gas emissions from the land use, land use change, and forestry (LULUCF) have not been counted as EU emission reduction targets for a long time [100]. In recent years, the increased awareness of EU rulers has contributed to concrete actions in the Community of States to mitigate climate change. Significant changes in the use of biochar were introduced after the establishment of the European Green Deal [101]. The EU has established new regulations regarding fertilizing products, thanks to which biochar has appeared for the first time in European Union legislation [102]. A reform of the Common Agricultural Policy (CAP) for the period 2021–2027 has been introduced, which includes the use of biochar for soil carbon sequestration. Also, a new action plan for a closed economy has been adopted by the European Commission [103], and the EU carbon dioxide absorption certification system by 2023 was announced [103–105]. In addition,

net greenhouse gas emissions from the LULUCF sector have been included in the EU's provisions to achieve the 2030 emissions reduction target [106,107]. The EU has pledged to obtain climate neutrality ("net" emissions) by 2050 and "at least 55%" emission reductions by 2030 [105].

To better illustrate the policy landscape, a comparison of the policies currently supporting biochar in key regions is provided (Table 1).

Table 1. Overview of global biochar support programs.

Continent	Program/Initiative	Description	References
North America	Bloomberg Cities Idea Exchange (USA)	Initiative supporting cities in solving issues like climate change, including the biochar project in Lincoln, Nebraska.	[108]
North America	Biochar Policy Project (USA)	Project advancing the biochar industry in the USA, supporting farmers and removing investment barriers.	[109]
North America	Great Plains Biochar Initiative (USA)	Initiative supporting the biochar market in the USA, offering workshops and grants.	[110]
North America	CARBONITY Biochar Plant (Canada)	The largest biochar facility in North America, supported by the Canadian government.	[111]
Asia	Biochar Policy Project (Vietnam)	UNIDO project developing policy and action plans for biochar in Vietnam.	[112]
Africa	BIO4Africa	Project supporting agriculture in Africa using biochar technology.	[113]
Africa	Biochar Plus Project	EU project advancing biochar technology in Africa, the Caribbean, and the Pacific.	[114]
South America	Biochar for Sustainable Soils (B4SS) (Peru)	Project developing biochar from green waste in Lima, Peru, reducing emissions.	[115]

5.1. Biochar in Negative Emission Technologies (NETs) and Carbon Dioxide (CO₂) Greenhouse Gases (GHGs)

In order for the international community to achieve the goal of the Paris Agreement, namely, to keep the increase in the global average temperature well below 2 °C like pre-industrial levels, it will become necessary to implement Negative Emissions Technologies (NETs) on a large scale [100]. Greenhouse gas (GHG) removal serves to offset residual GHG emissions that are technically impossible or too costly to eliminate [116,117].

Biochar is counted as a NET tool in the ecosystem management sector. The sector is concerned with afforestation and reforestation, practicing soil carbon sequestration, blue carbon, increased weathering, and ocean fertilization [100]. Over the past decade, the biochar system has gained increasing attention. This is reflected in the growing scientific literature [118] and in references and considerations in the reports of the International Panel on Climate Change [119–121]. The biochar system (BS) is considered a NET because of the cycle results in the long-term removal of carbon dioxide (CO₂) from the atmosphere. BS refers to a production and use cycle, in which biochar is first derived from biomass through pyrolysis and then used for any purpose that does not produce greenhouse gas emissions. Scientists report various data of negative BS emission potential [122–124]. For example, Lima et al. found that using 1 m³ of *Dillenia excelsa* wood waste is equivalent to reducing CO₂ emissions by 1687 kg [125]. Chen et al. [126], cited by the Intergovernmental Panel on Climate Change (IPCC), argued that the use of biochar is a safe and promising approach to promoting carbon neutrality, as 2.0–2.6 tons of carbon dioxide are captured per ton of biochar. This is in line with Neogi et al. [127], who considered biochar a promising negative emission technology (NET). In line with this, it has been reported that biochar systems can

provide emission reductions of 3.4–6.3 Pg of CO₂ equivalent per year, half of which is carbon dioxide removal worldwide [128]. The biochar system is characterized by characteristics such as the amount of biochar co-products produced in the production process, the potential for biochar applications, and the benefits important to sustainability. Syngas, bio-oil, and process heat are three co-products of biochar that can be used as renewable energy sources. These products reduce CO₂ emissions by replacing fossil fuels in energy generation, and there are positives to the biochar itself. In the NET field, the BS excels in many ways. The relatively low costs associated with mitigating climate change warrant attention, as they may vary based on location-specific conditions, the type of feedstock employed, and the production processes utilized for biochar. Biochar can be used as an intermediate for the production of a variety of goods beyond climate change mitigation, and potentially many valuable private goods for biochar users. In addition, the biochar system has fairly high accuracy in measuring permanently sequestered carbon compared to other terrestrial NETs, particularly soil carbon sequestration practices such as minimum tillage and permanent soil cover [129]. Overall, the land application of biochar leads to soil carbon sequestration, which can reduce net greenhouse gas emissions [68]. In addition, the use of biochar on farms by improving nutrient availability and the physical, chemical, and biological properties of the soil can increase crop production [64]. Therefore, it can reduce the loss of nutrients, sediment, and pollutants; in other words, the use of biochar not only sequesters carbon in soil, but also restores the organic matter lost with the removal of biomass from agro-forestry systems. Due to its specific surface area, surface functional groups, porous structure, and high content of elements such as carbon, oxygen, hydrogen, ash, sulfur, and nitrogen, biochar can contribute to many applications [8]. In the current context of intensifying climate change, the depletion of soil organic carbon, the desertification of the land, and depleting water resources, the benefits of the BS are unquestionable. Biochar has the potential to become an important social and economic branch, on which governments should focus their attention. Biochar as a soil additive can increase yields, although the variability of biochar properties is quite high depending on the specific crop, soil, and raw material used for biochar production and process conditions [130]. What is more, there are many possible uses for biochar that precede or do not include its ultimate application to soil, but that still result in long-term carbon sequestration. For example, biochar can be used as an additive in animal feed, paints, and textile fabrics, as an insulating material and a building material, and it can be used in the production of high-technology materials, as a material for batteries, etc. [131]. Currently, apart from the market for organic soil additives, the demand for biochar is generally insufficient to trigger an increase in its production. The BS as a NET can only be interesting if it is implemented on a large scale. Political support is essential for the economic viability of large-scale biochar production used for climate change mitigation and soil carbon restoration. From the perspective of economic policy, it seems essential to derive financial profits from the removal of greenhouse gases. The introduction by the EU of regulations concerning the safe production and use of biochar, as well as the certification of greenhouse gas removal and appropriate compensation for greenhouse gas removal, would significantly increase interest in the production and use of biochar [132]. The use of the BS offers opportunities for the cost-effective removal of greenhouse gases and many other social benefits that should be promptly utilized in the reduction in emissions and the absorption of greenhouse gases to achieve the EU's net zero emissions target by 2050 [133]. The diagram below shows the possible use of biochar in neutralizing carbon dioxide (Figure 2).

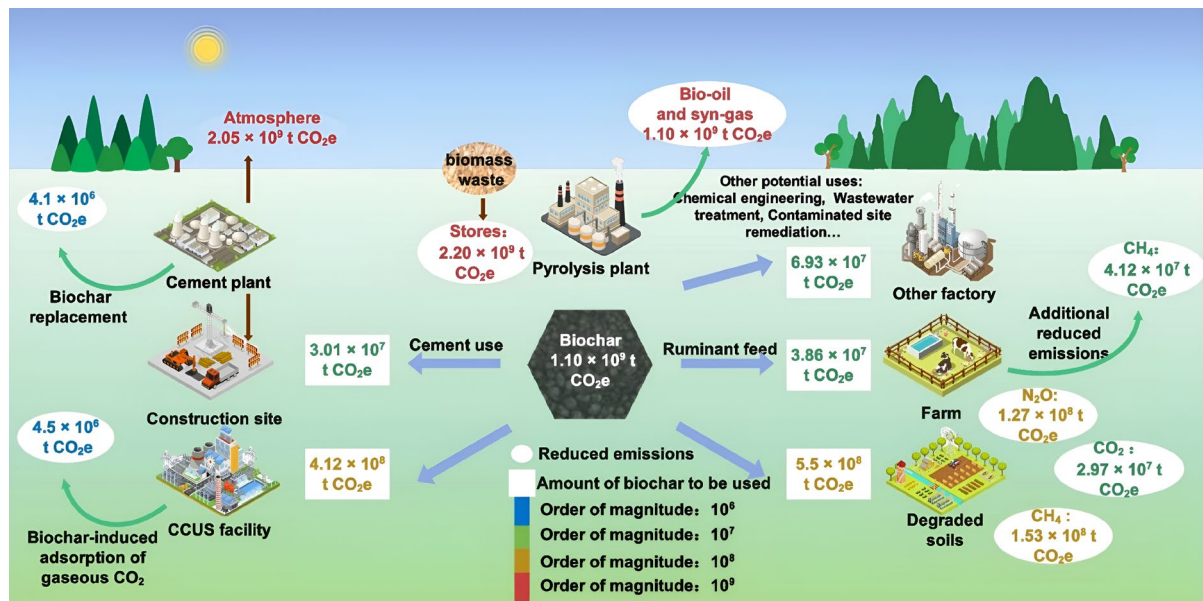


Figure 2. Possible use of biochar to achieve carbon neutrality [134].

5.2. The European Biochar Industry

Biochar is gaining importance in the energy sector, becoming an attractive alternative to traditional coal. It is also increasingly being used in industry, as it seeks to decarbonize and effectively manage biodegradable waste. The European Biochar Industry Consortium (EBI) has released its latest report on the European market. According to it, the production of biochar in 2023 increased to 75,000 tons, which represents a 41% increase compared to 2022. Projections indicate that biochar production will reach 115,000 tons by the end of 2024. In 2023, 48 new biochar plants were put into operation in Europe, bringing the total number of plants to 171. It is estimated that by the end of 2024, this number will exceed 220 installations. In addition, nearly 40 new projects are at an advanced stage of planning or obtaining permissions and are scheduled to come into effect in 2025, which will allow an additional 35,000 tons of biochar to be produced per year. By the end of 2023, the Nordic countries had the largest share of biochar production, with a market share of 28%. Denmark, Finland, and Sweden dominate the field. Germany ranks second place with 26%, and Switzerland is third with 16%. Significant increases in biochar production have also been recorded in Spain, France, and the UK. One of the main benefits of using biochar is the revenue generated from CO₂ removal certificates on voluntary emission reduction credits. Even so, not every biochar producer is seeking certification for the organic production of this raw material. Currently, 75% of the biochar produced has such certification.

There are more than 30 suppliers of biochar production technology in the European market. Woody biomass remains the dominant raw material, but agricultural residues and municipal waste, including sewage sludge, are growing in importance [135].

6. Economy: Application of Biochar

Traditionally, biochar has been used for soil improvement, maintaining the oxygen and moisture contents in the soil, releasing nutrients, enriching microorganisms, and bioremediation purposes [136].

Biochar is considered an innovative tool that shows many benefits, i.e., improved water holding capacity and soil fertility, greenhouse gas removal, carbon sequestration, acidity and salinity leveling, and pathogen removal [45]. Biochar is very durable and can remain in the soil for up to hundreds of thousands of years, contributing to carbon neutrality due to its negative carbon nature and CO₂ sorption [45]. Thanks to its ability to

immobilize heavy metals and organic pollutants, biochar is used in various fields: it acts as a biocatalyst in biorefineries; in construction materials it can replace Portland cement (a material with a high carbon footprint) [48]; and it can act as energy storage in batteries and supercapacitors [49].

Recent studies by scientists report that biochar can be successfully used in the renewable energy sector. The use of biochar depends on its properties, while the properties of biochar depend directly on the composition of biomass and the technology and conditions used to convert biomass to biochar [136]. The presence of various trace elements in biochar can supplement microbial nutrients and replace the requirement for additional mineral addition during fermentation. Biochar used in microbial fuel cells (MFCs) provides support for microbial growth and biofilm production. The properties, i.e., high surface area, porosity, and functional groups, provide a suitable environment for the production of the microbial biofilms required for electrical production in MFCs. Biochar is also widely used for biodiesel production and is receiving increasing attention due to its heterogeneous nature. Advances in science and the development of technology have opened up new opportunities for biochar in areas such as renewable energy (microbial fuel cells, catalysts in transesterification in biodiesel, and hydrogen production) carbon sequestration, water and air purification, and feed and cosmetic additives, etc. Most studies suggest that the use of biochar improves the efficiency and productivity of various processes. The table below (Table 2) shows the possibilities of using biochar obtained from different biomass at a specific pyrolysis temperature. To fully realize the potential of biochar, there is a need to make biochar production technology more economical and efficient [63].

Table 2. Biochar application.

Biomass Feedstock	Pyrolysis Temperature (°C)	Applications	Ref.
Red cedar wood	750	Energy storage	[137]
Cotton stalk	600	CO ₂ capture	[138]
Almond shells and olive stones	400–650	CO ₂ capture	[139]
Palm kernel shell	700	CO ₂ capture	[140]
Pomelo pericarp inner spongy layer	400	Energy	[141]
Rice husk	600	CO ₂ capture	[142]
Chicken manure	450	CO ₂ capture	[143]
Spruce whitewood	600	Energy storage	[144]
Chicken manure		Mitigation of greenhouse gas emissions reduced N ₂ O, CH ₄ , and NH ₃ production	[145]
Bamboo		Mitigation of greenhouse gas emissions reduced NH ₃	[146]
Rice straw		CH ₄ and N ₂ O	[147]
Wheat straw		CH ₄	[148]
Hardwood tree		N ₂ O	[149]

Table 2. Cont.

Biomass Feedstock	Pyrolysis Temperature (°C)	Applications	Ref.
Wood	300	Development of construction materials	[150]
	400		[151]
	500		[152]
	700		[153,154]
Maize straw	400	Development of construction materials	[155]
Sewage sludge	700	Development of construction materials	[156]
Wheat straw	650	Development of construction materials	[157]
Basket willow	500	Soil fertilizer	[50]
Giant miscanthus	500	Soil fertilizer	[50]
Wood bark	500	Soil fertilizer	[158]
Pinewood	500–600	Soil fertilizer	[159]
Oak wood	400–500	Soil fertilizer	[160]
Coconut shell	800	Cosmetics and personal care products	[161]
Canda straw Rice straw Soybean straw Peanut straw	400	Wastewater treatment	[162]
Pine fruit shells	900–600	Wastewater treatment	[163]
chicken manure	200–600	Wastewater treatment	[164]
Rice straw Chicken manure Sewage sludge	550	Wastewater treatment	[165]

Although biochar is often considered a valuable tool for carbon sequestration due to its stability and long-term ability to store carbon, it is crucial to assess the overall carbon balance by considering the energy consumption and carbon emissions associated with pyrolysis processes. While pyrolysis itself is an energy-intensive process, the energy required for its operation can come from both renewable and non-renewable sources, and this choice can significantly impact the overall carbon footprint of biochar production. In particular, the net carbon sequestration benefits of biochar can be influenced by several factors, such as the type of feedstock, pyrolysis temperature, and heating rate. High-temperature pyrolysis, while producing biochar with a higher carbon content, requires more energy and can potentially lead to higher carbon emissions, thus potentially offsetting some of the sequestration benefits. On the other hand, lower-temperature processes may be more energy-efficient, but could result in lower biochar yields. Furthermore, lignocellulosic materials such as wood generally require more energy to pyrolyze than agricultural residues, which can impact the net carbon balance [33,42].

6.1. Application of Biochar in the Renewable Energy Sector

6.1.1. Renewable Energy

Traditional biomass—the burning of charcoal, organic waste, and crop residues—has been an important source of energy for a long period of human history. It also remains an important source of energy in lower-income communities. In 2023, the use of biomass as an energy source among all renewable energy sources accounted for about 3.9% worldwide (149 GW) and 14.0% in Europe [166]. Today, modern biofuels, i.e., bioethanol and biodiesel,

made from crops such as corn, sugar cane, hemp, and cassava, are key transportation fuels in many countries. The interactive chart shows the production of modern biofuels around the world [167].

6.1.2. Biomaterials in MFCs for Bioelectricity Production

A microbial fuel cell (MFC) can be an effective solution to energy shortages and environmental pollution. The MFC is a device that consists of anode and cathode chambers separated by a proton exchange membrane, and that uses microorganisms as catalysts to convert chemical energy into electricity. In their life cycle (growth, reproduction, and production of intermediates), microorganisms metabolize organic material, which undergoes oxidation and reduction, and produce electrons and protons [168]. Under anaerobic conditions, the electrons generated in the anode chamber pass to the electrode through a membrane-bound electron transporter, electron mediator, or nanowires [169]. From the anode electrode, electrons move to the cathode through the outer circuit, while at the same time, a proton moves to the cathode through the proton exchange membrane [170]. The reduction process takes place in the cathode chamber between the electron, proton, and electron acceptor, and direct current is produced. Different types of electrode materials have been studied, and their performance depends on their physical and chemical properties, which affect microbial adhesion, electrode resistance, and the electron transfer rate. Despite advances in MFC technology, a lower current output and higher costs remain major constraints to using the technology on a larger scale. Many studies indicate that 20–50% of the cost of operating an MFC is due to the electrode material (gold, stainless steel, nickel, titanium, or copper, etc.), as they are non-renewable and require additional surface modification [63]. Biochar is considered an alternative, renewable material for electrode production [171]. It is usually produced from locally available raw materials and results in a reduction in the costs associated with purchasing, transporting, and storing raw materials [172]. Biochar-based electrodes are inexpensive compared to other commercial solutions. A team of researchers (Cao et al.) prepared an N/Fe-doped carbon electrode (N/Fe-C) by directly carbonizing waste adsorbent, and showed that the incurred cost of the N/Fe-C material was about a thousand times lower (depending on the raw material's cost and energy consumption) than that of a commercial Pt electrode [173].

6.1.3. Application of Biochar in Biorefinery

Biomass pyrolysis produces biochar, bio-oil, and syngas. These products—bio-oil and syngas—are considered sustainable energy sources contributing to carbon neutrality. However, the economic feasibility of using biochar in these processes depends on a variety of factors, including the feedstock, energy market conditions, and the specific goals of the facility. Gasification may provide higher syngas yields, beneficial for energy generation, while pyrolysis produces a higher yield of biochar, ideal for long-term carbon sequestration. The economic outcomes of each process can vary based on the feedstock type, local energy markets, and technological approaches. An analysis of these trade-offs in real-world conditions would give clarity on the economic returns from both the gasification and pyrolysis pathways. For instance, facilities focusing on syngas production may find gasification to be more economically viable if energy prices are high. Conversely, pyrolysis may be favored in markets prioritizing sustainability and carbon sequestration, despite potentially lower short-term economic returns. To strengthen the economic feasibility claims regarding biochar utilization in energy production, it is advisable to include case studies from operational European facilities. For example, the Pyreg GmbH plant in Germany integrates pyrolysis technology to produce both biochar and syngas from organic residues, with the syngas being used for heat and electricity generation, enhancing the overall profitability

of the system. Similarly, the Nettenergy company in the Netherlands operates mobile pyrolysis units that produce syngas on site for immediate energy use, while also generating marketable biochar. These examples demonstrate that pyrolysis systems can offer dual economic returns—through biochar as a soil amendment and syngas as a renewable energy source. Compared to gasification systems, which prioritize the syngas yield at the cost of solid residues, pyrolysis provides an additional revenue stream through biochar, particularly valuable for carbon sequestration schemes [174–176].

Bio-oil and syngas are considered sustainable energy sources that can contribute to carbon neutrality [177]. Bio-oil is a dark brown liquid that consists of alcohol, phenol, hydroxy ketones, esters, and carboxylic acids, etc. [178]. Bio-oil can be used for combustion in engines and boilers. Gupta et al. [179] reported methods to improve the quality of bio-oil so that it can meet the criteria for hydrocarbon fuels. Researchers report that these criteria can be achieved through physical enrichment using density difference or chemical enrichment through catalytic cracking and hydrotreating. Syngas consists of hydrogen, methane, carbon monoxide, and ethene, etc., and can be used as a clean energy source [180]. Roy and Dias [181] found that the global warming potential with bio-oil is 55% lower compared to fossil fuels. Biochar acts as activated carbon and provides support for the metal catalyst. Lee et al. [182] reported that a new Ru-ReO_x catalyst was loaded onto rice straw biochar, and can generate value-added chemicals such as tetrahydrofuran and 1,4-butanediol. Catalysts on biochar were three times more active compared to on conventional activated carbon. Metal catalysts on biochar can be used in biorefining, transesterification, hydrogenation, and in hydrodeoxygenation gasification reactions [183].

6.1.4. Biochar as a Material for Batteries and Supercapacitors

Biochar in lithium-ion batteries has the same function as graphite. Researchers have shown that biochar, due to its porous structure that enhances Li⁺ ion transfer, can be used as an anode material for lithium-ion batteries [184]. The addition of certain elements to biochar, i.e., nickel and tin, can increase its reusability and discharge capacity [185]. Lei et al. [186] developed a composite of iron carbide and biochar as a cathode for a lithium–sulfur battery, which reflected a discharge capacity of 555 mAh/g after 250 cycles. Qiao et al. [187] produced biochar with potassium chloride, which was used as a cathode in a zinc–air battery and showed high specific capacitance and peak power density compared to a Pt/C-based zinc–air battery. Gonzalez-Canche et al. [188] developed the use of biochar as a pigment in solar absorber coatings, in which it reduces the reflectance of the material. Tihihonen et al. [189] successfully investigated the use of biochar in solar cells with dye instead of a platinum catalyst. Rawat et al. proved that the production of biochar via high-temperature pyrolysis yields biochar with a graphite-like structure with high electrical conductivity, so biochar can be used in electrochemical double-layer capacitors [190]. The diagram below (Figure 3) shows the process of obtaining and using biochar in supercondensers. Oxides of transition metals such as manganese dioxide, nickel oxide, and polyaniline have been used to modify biochar to produce electrochemical double-layer capacitors or composite supercapacitors [191].

The key quantitative parameters for the application of biochar in energy storage devices are summarized in Table 3. The data highlight biochar's potential as an electrode material with good capacity, conductivity, and stability, especially after chemical or structural modifications.

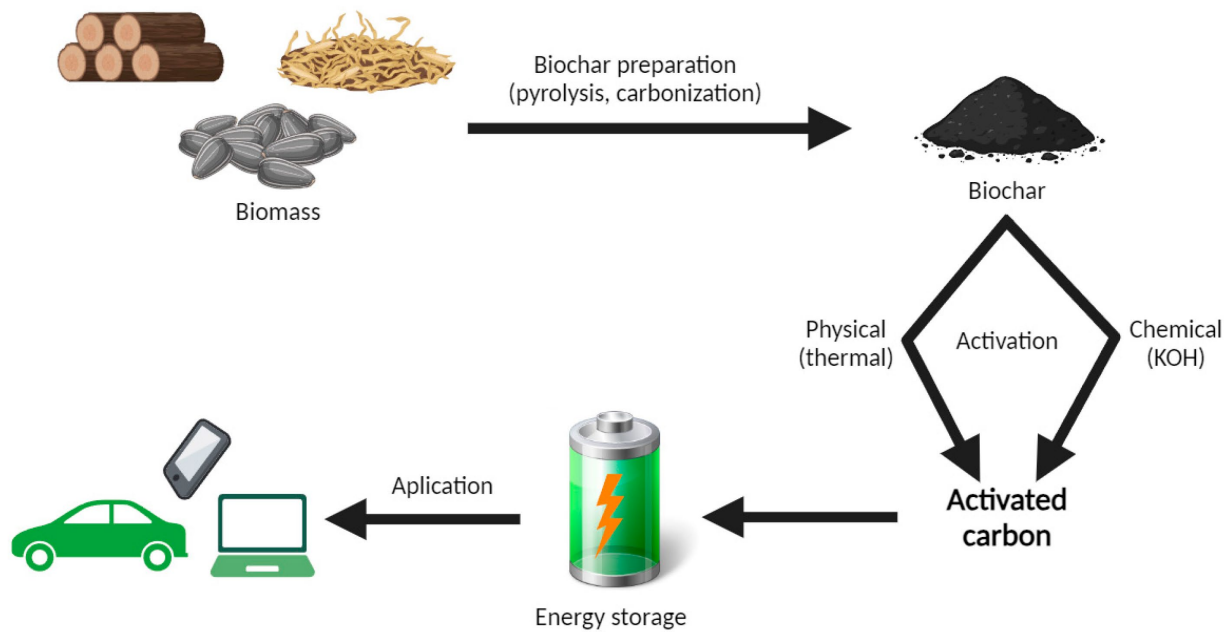


Figure 3. An example of the process of making and using biochar in supercapacitors [188].

Table 3. Applications of biochar in energy storage devices along with corresponding performance parameters.

Application/Device	Biochar Function	Modification	Performance/Parameters	Ref.
Lithium-ion battery	Anode	Pure biochar	Enhanced Li ⁺ transfer	[184]
		Biochar with Ni and Sn	Higher reusability and discharge capacity	[185]
	Cathode	Fe ₃ C–biochar composite	555 mAh/g after 250 cycles	[186]
Zinc–air battery		KCl-activated biochar	Higher capacitance and peak power density vs. Pt/C	[187]
Solar absorber coatings	Pigment material	Pure biochar	Reduced reflectance	[188]
Dye-sensitized solar cell (DSSC)	Catalyst (counter electrode)	Biochar replacing Pt	Effective Pt replacement	[189]
Electrochemical double-layer capacitor (EDLC)	Electrode	High-temperature pyrolyzed biochar	High conductivity and graphite-like structure	[190]
Composite supercapacitor	Electrode	Biochar with MnO ₂ , NiO, and polyaniline	Increased capacitance and cycling stability	[191]

6.1.5. Biochar as a Building Material to Achieve Carbon Neutrality

The demand for construction materials continues to grow due to global population growth and infrastructure development. Scientific sources report that about 40% of total CO₂ emissions come from construction work. Cement production generates 36% of total CO₂ emissions [45]. During the construction of buildings, 70% of CO₂ emissions come from the use of cement, and the remainder from the transportation of raw materials and aggregate production [45].

Therefore, to achieve carbon neutrality, it is necessary to develop building materials with a smaller or negligible carbon footprint. Biochar, as a material with a negative carbon footprint, has demonstrated its use as a carbon-neutral/negative substitute for cement or aggregate [192]. Fine-grained biochar can be used as a cement material, while coarse-

grained biochar can replace aggregate in concrete. Biochar has an affinity with cement, asphalt, and polymeric materials due to its porous nature and functional surface, which is where chemical reactions take place. The use of biochar as an additive to building materials offers a number of benefits, such as hygrothermal regulation, improved indoor air quality, self-repairing ability, sound insulation, electromagnetic shielding, and the immobilization of pollutants. Adding 1% of biochar to a cement matrix can increase its compressive strength by up to 9% [193]. The large surface area, porosity, and surface features of biochar increase water retention and CO₂ storage capacity and can promote the use of biochar as a building material through internal hardening and carbonation [194–196]. Adding 4% of biochar to cement stores 0.12 kg of CO₂, and supplementing cement with 8% of biochar reduces CO₂ emissions by up to 15% compared to Portland cement. The use of biochar as a filler material with a negative carbon footprint can improve the properties of cement-based composites and promote environmental sustainability. Adding biochar to construction materials retains water, which promotes internal curing, facilitates the hydration of biochar–cement composites, and ensures long-term durability [197] (Figure 4). Dixit et al. reported that fine biochar can replace cement due to its lightness and high strength and can be used in the production of ultra-high-performance concrete [198]. Supplementing with 2 and 5% of biochar reduced the shrinkage of the calcined marine clay-based concrete to 21 and 32%, respectively. The use of 5% of biochar in ultra-high-performance concrete contributed to the carbon sequestration of about 115 kg of CO₂ per m³ [199].

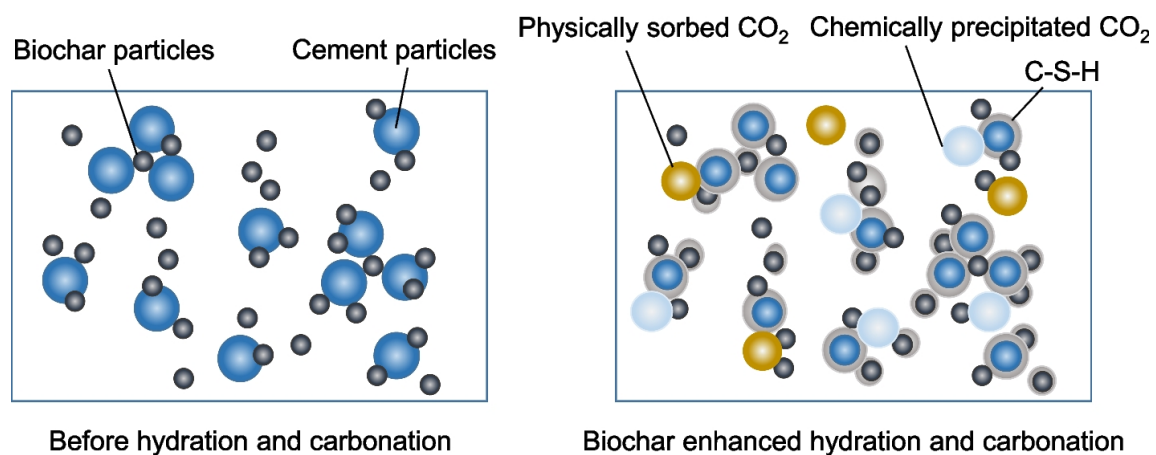


Figure 4. Diagram of the effect of biochar as an additive to cement [134].

6.1.6. Biochar-Based Composites

Replacing cement with biochar supports both waste management and carbon sequestration. However, optimizing the dosage of biochar in the mix can increase the compressive strength, toughness, and durability of biochar–cement composites. Biochar at a concentration of 0.5–2% can be used as a filler in biochar–cement composites to increase mechanical performance [200]. Praneeth et al. observed that replacing sand with 20% of biochar increased flexural strength by 26% and reduced bulk density to 10% [194]. The addition of biochar improved mechanical properties such as tensile strength, flexural strength, and functional performance, such as the electrical conductivity and rolling resistance of biochar–polymer composites. The addition of biochar in epoxy resin increases its use for surface coating, laminating electronic circuit boards, and further use in the automotive and aerospace industries [201]. Carbon black is a filler used in rubber composites, which can be replaced by biochar prepared from waste biomass [202]. Biochar from coconut shells showed five times the tensile modulus of rubber composites compared to natural rubber [203]. Biochar has a stable porous honeycomb structure, contains no flammable

volatiles, exhibits high thermal resistance, and can be used as a fireproof material [45]. Concrete and asphalt mixtures are present in pavement materials that can adsorb and retain solar energy and reflect the urban heat island effect, releasing stored energy. Asphalt pavement generates volatile organic compounds that pose a health risk to construction workers. Adding biochar into concrete can increase the water sorption capacity by mitigating the heat island effect [204]. Tan et al. showed that a temperature of about 6 °C can be lowered for 18 h by using biochar in pavement production [205]. Biochar can reduce the emissions of volatile organic compounds by 50% [206]. Cement composites with biochar reduced thermal conductivity by 25% [207]. The addition of 2% of biochar showed lower thermal conductivity and significantly increased the acoustic performance of biochar–cement composites. Biochar can be used in chip boards to adsorb VOCs, and can improve indoor air quality and interior finishes. The use of 3D printing in the development of construction materials can reduce waste by up to 30–60%, labor input by up to 50–80%, and production time by up to 50–70% [208]. The addition of biochar with a negative carbon footprint in 3D-printed concrete reduces the density of the concrete and increases its durability [45].

Despite the promising potential of biochar in the low-carbon energy transition, several challenges hinder its widespread implementation. A key limitation is the technological maturity of biochar production, which remains inconsistent and costs on a large scale. One of the primary issues is the lack of standardized processes, leading to variability in biochar quality depending on the feedstock and pyrolysis conditions. Additionally, although biochar production is often considered carbon neutral, the energy-intensive nature of the pyrolysis process can offset some of its environmental benefits, especially in smaller-scale operations. The scalability of biochar production systems remains another challenge, with many existing technologies being too small scale or inefficient for industrial adoption. To overcome these obstacles, further research is needed to improve the efficiency of production processes, reduce costs, and enhance the overall quality and functionality of biochar [209].

6.2. LCA as a Tool for Calculating the Actual Production Efficiency and Environmental Impact of a Product

The scientific literature has reported abundantly on the environmental benefits of biocarbon in many industries [210–213]. The essence in the production and use of biocarbon is that its production and applications have clear environmental and economic benefits before commercialization and large-scale industrial adoption [65,214]. To this end, researchers are using LCA analysis to assess a product's environmental impact, including its contribution to accelerating or halting climate change and ozone layer degradation [210–213].

LCA analysis is now considered one of the safest and most validating analyses of a product's broad environmental impact. The life cycle assessment (LCA) methodology is a technical tool that provides a systematic analysis and assessment of environmental aspects and the potential impacts associated with products or services throughout their life cycle. Life cycle assessment (LCA) can be characterized as the compilation and evaluation of inputs, outputs, and potential environmental impacts of a product or system throughout its life cycle. It is the most widely used type of assessment, with wide international acceptance for measuring environmental impacts. Life cycle assessment (LCA) is defined in ISO 14040 [210]. Many authors have used the LCA method to assess the environmental impact of biocarbon projects. In addition, scientists are still working to discover a general trend or pattern [211]. The use of the LCA method allows for quantifying the environmental impact of biocarbon production systems, providing a standardized tool for comparing different types of biocarbon feedstocks and production technologies [215]. In addition, LCA can serve as a decision-making tool and can be used to optimize biocarbon production systems. As reported by Yang et al. (2021), LCA of biocarbon production systems has been studied to understand the environmental impact in terms of biomass cultivation, har-

vesting and collection, transportation, pretreatment, pyrolysis technology, and biocarbon utilization [36]. Therefore, LCA of biocarbon production systems is important to minimize harmful environmental impacts and provide more visible economic benefits. According to a review of the scientific literature, the use of biocarbon provides significant benefits, through the neutralization of greenhouse gas emissions from both agricultural production and sequestration [210].

7. Economic Assessment

The economic feasibility of biochar as a versatile material in agriculture, energy production, and environmental protection has been widely discussed in the recent literature. In agricultural contexts, biochar has shown promise for improving soil health, increasing crop yields, and reducing dependency on chemical fertilizers. Research conducted on Mediterranean crops has indicated that biochar significantly boosts plant growth and grape production, with the cost–benefit ratio yielding returns within 1 to 4 years, depending on the biochar cost and the type of crops used. Similarly, studies on maize cultivation suggest that biochar can lower the costs associated with fertilizers and irrigation, with a payback period ranging from 2.8 to 5.5 years, contingent upon the price of biochar and the reductions in CO₂ emissions. However, not all studies confirm the economic advantages of biochar. For instance, in soybean production in Poland, its application was found to be less cost-effective than traditional fertilization methods unless carbon credit incentives were factored in. These results highlight the need for localized economic assessments that consider specific agricultural practices and regional market conditions when evaluating biochar’s profitability. Additionally, the production costs of biochar vary widely based on the type of biomass used and the methods of production, with estimates in a wide range. This underscores the importance of developing cost-efficient production techniques to make biochar economically viable. Ultimately, while biochar has the potential to offer significant economic benefits, its widespread implementation requires the careful consideration of both local economic circumstances and environmental factors [209,216–219].

8. Conclusions and Future Prospects

In the body of this paper, the authors focused on a broad discussion of biomass-to-biochar transformation as a strategy with multiple environmental benefits, which appears to be key to combating accelerating climate change by reducing pollution and maintaining environmental sustainability. In this paper, the authors highlighted the promising role of biochar in the energy industry, which can help achieve sustainability goals for carbon neutrality and build a circular economy. The subject’s scientific literature reports that waste biomass material with a negative carbon footprint, which is biochar, is showing applications both in and out of soil in the fight against climate change to achieve carbon neutrality. Biochar as a soil additive can positively increase water retention and nutrient use efficiency, accelerate plant growth, increase waste recycling and microbial diversity, inhibit pathogen activity, reduce fertilizer requirements and irrigation frequency, and minimize greenhouse gas emissions. Biochar can bind CO₂ in the long term and prevent the release of carbon back into the atmosphere, thus promoting net zero emissions under the UN Sustainable Development Goals. Biochar can significantly sequester carbon dioxide in the soil. In addition, biochar can be used as a green catalyst in biorefinery, remove organic and inorganic pollutants in the construction industry, and aid in carbon capture and energy storage, etc. Achieving net zero carbon emissions is a difficult but necessary task. Using waste to produce biochar appears to be a good investment to promote a circular economy. However, more research and analysis are still needed to assess the economic and environmental benefits of a circular economy. More field and local studies

are needed to assess the environmental impact of biochar before large-scale use. It is essential to continuously make the public, especially farmers and entrepreneurs, aware of the topics of carbon dioxide sequestration, sustainability, and carbon dioxide pricing so that they understand and appreciate the potential of biochar in solving the global problems of the energy industry, agriculture, and climate change. Achieving carbon neutrality is an arduous task that requires long-term strategies. The various uses of biochar do not reflect it as a solution to all climate change problems. However, the development of value-added products through the valorization of biochar has commercial applications in various sectors, which minimizes the environmental burden and enhances environmental protection, bringing local economic and global environmental benefits. The European market for biochar is largely driven by the increasing use of sustainable agricultural practices. Farmers and agricultural stakeholders are increasingly recognizing the benefits of biochar in improving soil health, increasing yields, and reducing the need for chemical fertilizers. Biomass is expected to be a major energy source in the coming decades. Biomass has the potential to become the best alternative to fossil fuels due to its easy availability, renewability, carbon neutrality, and relatively low sulfur content. Using biomass as an energy source instead of fossil fuels can reduce pollution and global warming, alleviate energy shortages, and promote sustainable development.

In addition to improving production efficiency, future research should focus on expanding biochar's applications across multiple sectors. Its multifunctional role makes it a crucial component in circular economies, especially in regions with limited resources or high pollution. Biochar's ability to mitigate environmental contamination positions it as a key solution for waste management and land reclamation. Additionally, its use in carbon-negative construction materials could play an important role in the building industry. To maximize biochar's potential, it is essential to establish policies that incentivize its development.

Author Contributions: Conceptualization, A.S. and B.S.; methodology, B.S. and A.S.; formal analysis, B.S. and A.S.; data curation, B.S. and A.S.; writing—original draft preparation, A.S.; writing—review and editing, B.S.; supervision, B.S.; project administration, A.S. and B.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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