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Biochar: An Effective Solution for Sustainable Agriculture and Ecosystem Restoration

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environmental benefits

Abstract

This article discusses various aspects related to biochar, its production, and its environmental and agricultural benefits. Biochar is a carbon-rich material produced from biomass through pyrolysis in conditions of limited oxygen. It possesses a range of beneficial properties, such as improving soil quality, increasing its fertility, enhancing crop yield, and carbon sequestration. Biochar helps retain nutrients, improves soil water retention, and reduces greenhouse gas emissions. Its application contributes to better seed germination, seedling growth, as well as increasing plant resistance to environmental stressors and diseases. The use of biochar in different doses and pyrolysis conditions can significantly enhance its effectiveness in agriculture and ecological rehabilitation. The use of biochar for the reclamation of contaminated soils reduces the availability of toxic substances, such as heavy metals and pesticides, making this material a promising tool for ecosystem restoration. Thus, biochar represents a promising solution for improving soil and ecosystem health, reducing pollution, and mitigating the impacts of climate change, providing new opportunities for sustainable agriculture and environmental protection.

Cite

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1. INTRODUCTION

Demographic growth, rapid industrialization, and urbanization contribute to the formation of large volumes of organic waste, including agricultural waste, municipal solid waste (MSW), industrial and marine waste, as well as forestry waste. According to the United Nations Environment Programme, over 140 billion tons of biomass from agricultural crops are generated worldwide annually. This creates new opportunities for using biomass as a renewable energy source, which can significantly reduce the negative impact on the environment [1].

Biochar is a substance obtained from various materials through thermal conversion with limited oxygen access at temperatures below 700°C. It is a versatile renewable energy source that can be used for heat, electricity, and liquid biofuel production. Biochar, which is charcoal formed as a result of pyrolysis, has a durable porous structure containing a sufficient amount of functional groups, inorganic nutrients, and stable carbon components [2]. The term "biochar" is associated with carbon material used for ecosystem restoration, particularly for improving soil quality and cleaning water bodies. Moreover, biochar can play an important role in mitigating climate change, particularly in the process of capturing CO_2 from the atmosphere and industrial emissions [3]. Furthermore, the gases produced during pyrolysis can be used to integrate biochar production with other processes, such as bioenergy generation.

Biochar is a stable source of nutrients for the soil, surpassing other organic fertilizers, and plays a key role in the processes of adsorption and mineralization. It helps increase the availability of nutrients in the soil and improve environmental quality. This carbon-rich substance, used as a soil additive in agricultural lands, also helps reduce the risk of pollution and ecosystem degradation. In addition to its main components, such as carbon, hydrogen, and oxygen, biochar can contain macronutrients including nitrogen, phosphorus, and potassium. However, the composition and characteristics of biochar depend on the choice of feedstock and production technology (i.e., the type of thermal conversion and temperature regime) [4].

The addition of biochar leads to a number of positive changes, such as increased microbial activity in the soil, improved nutrient uptake by plants, enhanced availability of these nutrients in the soil, and reduced leaching. It also improves soil aeration, increases porosity, bulk density, infiltration rate, aggregate stability, water retention capacity, and hydraulic conductivity. Moreover, biochar stabilizes heavy metals, reducing their bioavailability to crops grown in adverse or nutrient-poor soils [5]. Biochar can be used to mitigate soil contamination, including through the immobilization of heavy metals and organic pollutants. Heavy metals in the soil are dangerous contaminants that degrade soil quality, making it difficult to successfully grow crops. These metals do not biologically decompose and can remain in contaminated soil and water for long periods. Soil contamination with heavy metals such as Cd, Cr, Hg, Pb, Cu, Zn, As, Co, Ni, and Se is a global issue that threatens human health. The process of removing heavy metals from contaminated soils is costly and labor-intensive for agriculture [6]. However, biochar is capable of stabilizing metals like Cd, Cu, Ni, Pb, and Zn in the soil, reducing their bioavailability through enhanced adsorption and chemical precipitation [7]. Thus, the physicochemical properties of biochar promote the adsorption of heavy metals and organic pollutants, which is crucial for reducing their impact on the environment. Additionally, biochar supports microbial abundance and mitigates the negative effects of heat, drought, and salinization on agricultural crops.

Assessing the potential benefits of biochar in the context of mitigating climate change is challenging due to its ability to sequester carbon in a stable form, reduce emissions of potent greenhouse gases such as nitrous oxide and methane, improve crop yields and fertilizer use efficiency, restore degraded lands, and mitigate water pollution by removing organic contaminants (e.g., pesticides, herbicides, personal care products, dyes, pharmaceuticals, humic substances, and N-nitrosodimethylamine) [8].

From a plant performance perspective, biochar can influence seed germination, growth, flowering, disease resistance, and adaptation to abiotic stresses. Several studies report that biochar contributes to an increase in yield by 10-42%, although some cases have shown negative results [9]. Typically, studies with positive effects used biochar application rates ranging from 5-20 Mg ha^{-1}, but the use of biochar and fertilizer mixtures in small doses (<1 Mg ha^{-1} of biochar) also led to increased yields, especially when applied as a band around the seeds.

The addition of biochar also has a positive effect on microbial communities due to its numerous small pores, labile carbon (C), and alkaline pH. The pores of biochar provide a safe environment for fungi and bacteria due to their size and ability to retain water, protecting them from predators that cannot access the micropores, as well as from desiccation [10]. Biochar, obtained from specific feedstocks at certain temperatures, includes labile carbon compounds that serve as a substrate for microbial growth and primers for the decomposition of soil organic matter [10]. pH changes induced by biochar application can affect microbial communities in soils, as bacteria typically prefer neutral pH, while fungi thrive in acidic or alkaline conditions, which in turn leads to changes in the food chain [10].

The process of producing and using biochar to improve soil fertility is an ancient tradition widely practiced by farmers in countries such as Europe, America, China, India, and Japan. Biochar is produced by pyrolyzing agricultural waste in pits or trenches [11]. According to farmers, the use of biochar helps improve nutrient retention in the soil, which in turn enhances soil quality and increases fertility. Several studies have noted that biochar application has a positive impact on soil fertility and crop yields, especially when mixed with fertilizers. Moreover, adding biochar to the soil promotes better nutrient uptake by plants, reducing dependence on chemical fertilizers, which is significant for developing countries such as India, where many farmers cannot afford chemical fertilizers. Therefore, further research should focus on studying the impact of biochar on improving nutrient availability, seed germination, vegetative growth, as well as increasing protein and chlorophyll content in plants.

2. FEEDSTOCK FOR BIOCHAR PRODUCTION

Biochar is part of a group of carbon materials that, when combined with other substances, form hybrid nanomaterials based on biochar. These materials are characterized by new physicochemical properties and demonstrate high efficiency in the process of decomposing water pollutants through adsorption, heterogeneous photocatalysis, and advanced oxidation methods.

Biomass is organic matter that is or was once living and can serve as a versatile renewable source of energy for ecological purposes (e.g., for electricity generation and heating), as well as for producing biofuels, compost, pharmaceuticals, chemicals, and biomaterials such as biochar. Almost all organic materials, including tree bark, nut shells, agricultural residues, and manure, can be used as feedstock for biochar production using appropriate technologies. Sources of biomass can include waste of animal, plant, or anthropogenic origin, such as industrial or municipal waste (sewage) [12]. The properties of biochar-based materials can vary depending on the type of biomass used, allowing them to be applied in various fields.

The type of feedstock has a significant impact on the production and quality of biochar. For biochar production, the feedstock should have low moisture content and high levels of cellulose, lignin, and hemicellulose. The lower the moisture content of the feedstock, the cheaper the drying and pretreatment processes will be. Feedstock with moisture content less than 30% is called dry, while feedstock with higher moisture content (more than 30%) is classified as wet [13]. Wet feedstock requires additional costs for pretreatment. Biomass can be divided into energy crops and waste, with energy crops being specially grown plants that play a key role in biorefining processes.

The availability and composition of feedstock are key factors that determine the efficiency and cost-effectiveness of biochar production. Despite the wide range of available feedstocks, their proper classification and characterization play an important role in their optimal utilization. This section focuses on the feedstock resources, their composition, and availability. A variety of feedstocks are used for biochar production, including agricultural, urban, and paper waste, wood and aquatic biomass, animal and human excrement, industrial waste, food and kitchen waste, dairy and paper mill waste, poultry waste, and other materials.

Agricultural biomass refers to biochar produced from agricultural waste rich in cellulose fibers. Such biochar has a significant impact on nitrogen and nutrient absorption by the soil and serves as a habitat for various soil organisms, which helps improve soil fertility. Coconut and palm nut shells are often used for biochar production through anaerobic combustion at a temperature of 400°C. Similarly, hazelnut shells, grape seeds, and chestnuts are also used for this purpose.

Urban waste includes both organic and inorganic components (Figure 1). The organic part is divided into biodegradable and non-biodegradable fractions. The biodegradable organic fraction consists of food scraps, kitchen waste, fruits, gardening waste, textiles, paper, leather products, and other materials [14]. The non-biodegradable organic fraction includes plastic bags, bottles, and electronic waste, while the inorganic fraction consists of glassware, metal products, sandstone, and others. Most non-degradable organic and inorganic waste can be recycled, while biodegradable fractions undergo biological decomposition. Urban waste is one of the most promising types of feedstock for biochar production and can be divided into municipal solid waste (MSW), industrial wastewater, sewage sludge, as well as livestock and poultry waste. MSW is used to produce biochar, which is then used as an adsorbent to remove dyes, minerals, pollutants, toxic substances, and other impurities.

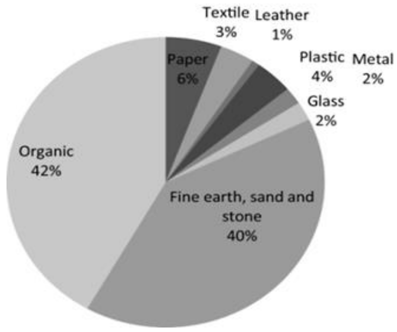

Figure 1. *Characteristics of Municipal Solid Waste [15]*

Forest/wood biomass – the largest regions of the world with high levels of forest biodiversity, which account for more than 67% of the total area of global forests, include the Russian Federation, Brazil, Canada, the United States, China, the Democratic Republic of the Congo, Australia, Indonesia, Sudan, and India [16]. Wood also plays an important role in biochar production due to its high-quality characteristics. Biochar produced from wood has a high calorific value due to the presence of lignin, resin, pectin, and volatile substances.

The main stream of biomass waste comes from agriculture, sewage sludge, as well as solid, animal, and food waste. Wet wastes containing more than 30% moisture are divided into two groups: lignocellulosic and non-lignocellulosic. Lignocellulosic biomass, which includes agricultural and forest waste, energy crops, and wood, has several advantages over non-lignocellulosic biomass, such as sewage sludge, algae, and animal waste, in biochar production. Figure 2 shows the biochar conversion process, illustrating various by-products. Value-added final products derived from biomass waste include biochar, syngas, ethane, methane, ethanol, and charcoal. Biochar serves a dual purpose, acting both as a soil fertilizer and an effective adsorbent.

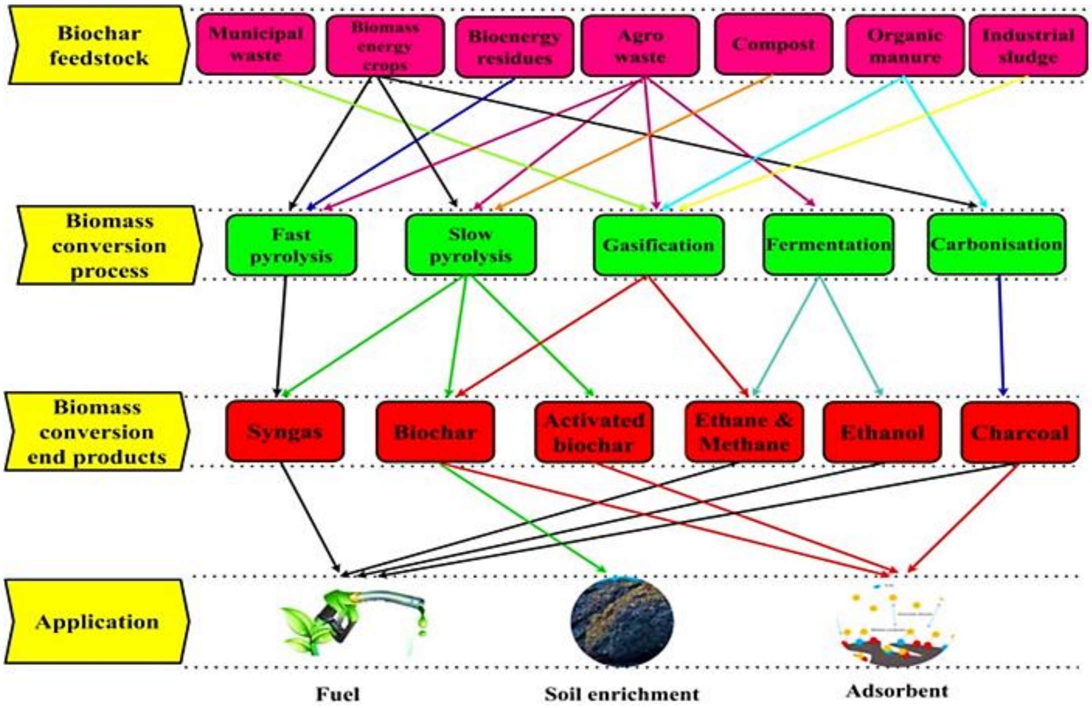

Figure 2. *The biomass conversion process into biochar and its further use [17]*

3. BIOCHAR PRODUCTION TECHNOLOGY

The biochar production process depends on three key factors: the type of production process (methods, temperature), types of biomass (e.g., rice husks, food waste, animal by-products, and other solid waste), and the technology used (pyrolysis, torrefaction, gasification).

Biomass can be converted through thermochemical processes such as pyrolysis to produce biogas, liquid fuels (e.g., bio-oils), and solid materials, including biochar. The biomass valorization process can be carried out using such main methods as pyrolysis, gasification, torrefaction, anaerobic digestion, or combustion, which allow organic materials to be converted into heat, electricity, or by-products such as biochar [18].

Thermochemical conversion involves the breakdown of the biomass structure in an oxygen-rich or oxygen-free environment at high temperatures. Biochar production starts with the primary conversion of biomass through thermochemical processes to obtain a carbonaceous material with the desired physicochemical characteristics. The operating principles, synthesis conditions, and the influence of these factors on biochar production within the most common thermochemical conversion processes are discussed in detail below:

Pyrolysis

During pyrolysis, the biomass mentioned earlier is subjected to thermal treatment to produce biochar and other by-products. Depending on the process conditions, products such as biogas, liquid bio-oils, and biochar can be obtained. It is important to note that to achieve high-quality carbonaceous material and maximize yield, the biomass must be pre-dried and ground. Heating is carried out at high temperatures (400-800°C) in the absence of oxygen, which allows the biomass to be transformed into various by-products used in energy production and environmental restoration. These by-products can be used as energy sources or for generating the heat necessary to maintain the pyrolysis process or the thermal treatment of feedstock. This process minimizes carbon emissions into the atmosphere [19]. According to the literature, pyrolysis can be slow or fast, depending on temperature and heating rate. Slow pyrolysis occurs at temperatures between 250 and 600°C with slow heating (1-10°C/min), while fast pyrolysis occurs at temperatures above 600°C with rapid heating (greater than 50°C/min) [20]. The concentration and physicochemical characteristics of products such as biogas, bio-oil, and biochar can vary depending on the type of pyrolysis. Slow pyrolysis of biomass produces a large amount of biochar, while low concentrations of gases and liquids are released, but with a high content of contaminating volatile organic compounds (VOCs).

Torrefaction

Torrefaction is a process in which biomass is exposed to moderate temperatures ranging from 300 to 550°C, with a heating rate of 50°C/min and a holding time of 20 to 40 minutes. This converts the biomass into biochar and other products such as bio-oil and syngas [21]. During torrefaction, moisture is removed from the biomass, and components such as lignin, cellulose, and hemicellulose partially decompose. Torrefaction also results in the formation of biochar as a solid product, in contrast to liquid or gaseous by-products. Biochar produced in this process has high quality, including high energy density, hydrophobicity, and a low oxygen-to-carbon ratio. High-quality biochar has an oxygen-to-carbon (O/C) ratio ranging from 0.2 to 0.6, preferably around 0.4. The carbon stability in biochar depends on this ratio: if it is high, the carbon oxidizes more quickly, increasing carbon dioxide losses. Conversely, a low O/C ratio increases the stability of biochar, and at an O/C ratio below 2, the half-life can be up to 1000 years. However, biochar produced by torrefaction may have an O/C ratio higher than 0.4, which lowers its quality. Therefore, torrefaction is considered a method of preliminary drying and accelerating the biomass heating process. The biochar yield in torrefaction ranges from 30% to 70% [22]. Before torrefaction begins, the agent is purged with nitrogen in a small stream for 10 minutes to remove any remaining oxygen (Figure 3).

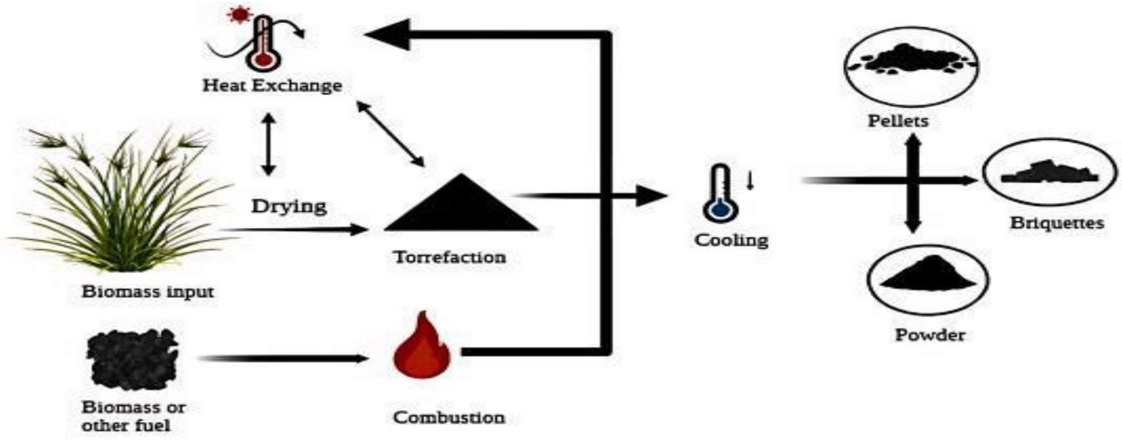

Figure 3. *Diagram of the biochar production process using the torrefaction method [23]*

Gasification

Gasification is a process in which carbonaceous material is converted into gaseous products, such as syngas, at temperatures below 700°C using oxidants such as air, oxygen, or steam [23]. The final yield is about 10% of the mass of the original biomass, which is lower compared to pyrolysis. Key factors influencing this process include the reagent-to-biomass ratio, temperature, reaction time, particle size, and pressure, with temperature having the most significant impact on the overall product yield [23]. Gasification is used to produce syngas ($CO+H_2$), which was previously used for various domestic purposes, including cooking, heating, and lighting. The gasification process consists of two stages: the first is the actual gasification of biomass, and the second is the purification and cooling of the syngas. A screw reactor is typically used for continuous biochar production.

4. PROPERTIES OF BIOCHAR

The properties of biochar largely depend on the feedstock and pyrolysis conditions, which influence its physicochemical characteristics. For example, biochar produced from wood with a high lignin content has a higher carbon content than biochar made from herbaceous materials, but it does not contain nitrogen (N) [24]. The carbonization process breaks down parts of the biomass, while retaining a significant portion of the carbon. This change in properties makes biochar more carbon-rich, which enhances its suitability for use in various technical processes.

The residence time, heating rate, and pyrolysis temperature are the key factors that determine the characteristics and properties of biochar. As mentioned in the torrefaction section, biomass with a high carbon content and low oxygen level produces a higher biochar yield compared to biomass with low carbon content and high oxygen levels. When biomass contains a lot of oxygen, oxidation occurs, and carbon is lost as carbon dioxide, which reduces the biochar yield. For example, biochar derived from organic fertilizer has a much lower yield compared to biochar produced from wood biomass or other agricultural residues. This is because organic fertilizer contains little carbon. Additionally, a slightly elevated pH in the biomass can promote the formation of ash. Organic fertilizer consists of various organic and inorganic compounds, which, during pyrolysis, lead to a higher ash production. Ash, which contains more minerals, can be used as compost in organic gardening.

The physicochemical characteristics of biochar can have both direct and indirect effects on soil properties. After biochar is added to the soil, its impact on the physical structure can be significant, as it affects aeration, water-holding capacity (WHC), bulk density (BD), as well as the distribution of pore sizes, porosity, and surface area of the soil. Moreover, the addition of biochar can alter various biological and chemical properties of the soil (Figure 4) [25].

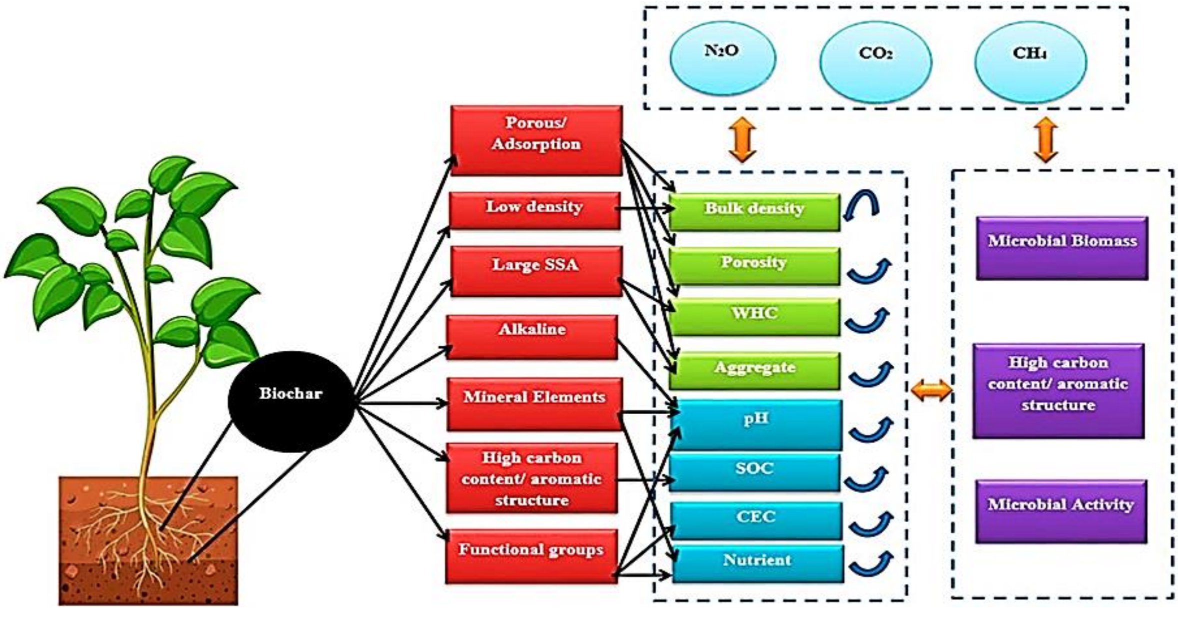

Figure 4. *The impact of biochar addition on the physicochemical and biological properties of soil; Carbon dioxide (CO_2), cation exchange capacity (CEC), nitrous oxide (N_2O), methane (CH_4), soil organic carbon (SOC), specific surface area (SSA), water-holding capacity (WHC) [25]*

Physical properties

The physical characteristics of biochar include specific surface area, particle size, pore size, pore volume, and density. During the pyrolysis process, the moisture and volatile organic compounds of the biomass contribute to the formation of pores on the surface of the biochar through displacement [26]. An increase in pyrolysis temperature leads to enhanced release of volatile organic compounds, an increase in the number of pores, and promotes greater production of syngas.

The physicochemical properties of biochar are shown in Figure 5.

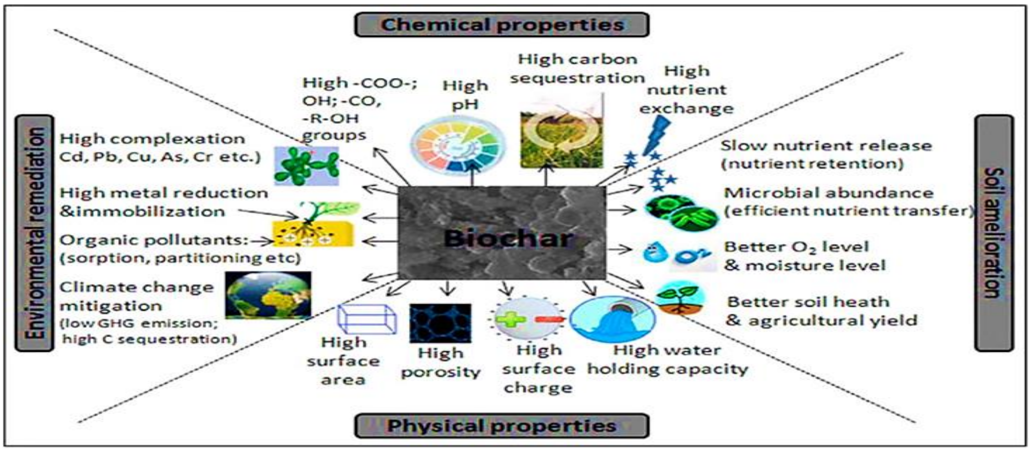

***Figure 5.** Characteristics of the physicochemical properties of biochar [27]*

The destruction of the fibrous structures of biomass leads to changes in the physical properties of biochar. These properties have both direct and indirect effects on soil systems. The main physical characteristics of biochar include specific surface area, density, porosity, pore volume and size, thermal conductivity, water-holding capacity, heat capacity, hydrophobicity, and grindability.

Chemical properties

Understanding the chemical properties of biochar is key to tailoring its characteristics to meet specific needs. For example, the raw material or pyrolysis conditions can be altered to enhance the adsorption properties of biochar, modify nutrient release mechanisms, or improve its compatibility with different types of soil. Chemical properties also play a significant role in assessing the environmental impact of biochar, especially when used for the reclamation of contaminated soils or water bodies. The chemical characteristics of biochar largely depend on the carbon, oxygen, nitrogen, and hydrogen content in the original biomass. During pyrolysis, chemical changes lead to the formation of various functional groups, improving the chemical properties of biochar.

The chemical characteristics of biochar are assessed based on its elemental composition, self-ignition, energy content, decomposition, pH value, and reactivity, which depend on the temperature and storage duration.

Impact on soil chemical properties

The addition of biochar to soil helps create favorable conditions for plant growth and nutrient uptake by improving both the physicochemical and biological characteristics of the soil, such as porosity, water permeability, aggregate stability, bulk density, hardness, pH, cation exchange capacity, and nutrient cycling [28].

The use of biochar can alter the chemical characteristics of the soil, including increasing organic carbon levels and pH. However, the degree of change in chemical properties depends on factors such as the type of biomass, pyrolysis temperature, soil types, and application rates. Alkaline types of biochar (with pH > 7) typically contribute to soil alkalization when added. The pH of biochar is largely determined by the raw material and can range from acidic to alkaline values. Biochar derived from various agricultural residues increased soil pH from 4.59 to 4.86, from 4.8 to 6.3, and from 4.3 to 4.6 [29].

Impact on soil biological properties

The use of biochar affects not only the physicochemical but also the biological properties of the soil. It influences the activity and structure of the soil microbial community, which is determined by the pore space of the biochar, its functional groups, volatile organic compounds on the surface, minerals, and porosity. These changes can impact soil structure, reduce nutrient leaching, improve nutrient cycling, create labile carbon compounds for microbial growth, enhance aggregation, increase nutrient immobilization and retention, and accelerate plant growth. The pores and particles of biochar create a favorable environment for the development of filamentous microbes and fungi. Biochar containing sugars and yeasts promotes the growth of Gram-negative bacteria and fungi. The alkaline nature of biochar can stimulate the growth of both Gram-negative and Gram-positive bacteria.

The effect of biochar on soil enzymatic activity depends on the interaction characteristics between the substrate and enzyme in the presence of biochar, which are related to its surface area and porosity. Biochar with greater porosity and surface area is more likely to reduce extracellular enzymatic activity, as the functional groups of biochar can bind enzymes and substrates, hindering substrate diffusion to the active sites of the enzyme. Soil treatment with biochar can have either positive or negative effects on enzymatic activity, and these effects depend on the biochar dose and soil type.

Physical structure of biochar

Biochar is a black, lightweight, and highly porous material with fine particles and a significant surface area. Its characteristics, such as microbial activity, ability to bind minerals and nutrients, and soil water-holding capacity (WHC), depend on the physical structure, pore size, and surface area of the raw material used for its production. Typically, the surface area of biochar ranges from 8 to 132 $m^2\ g^{-1}$, and the total pore volume varies from 0.016 to 0.083 $cm^3\ g^{-1}$. Among 12 types of biochar produced from different raw materials, sawdust with the lowest ash content (2.8 wt.%) demonstrated the highest surface area (203 $m^2\ g^{-1}$), while algae and cow manure, which contain more ash (around 38%), had a lower surface area (3-22 $m^2\ g^{-1}$). Figure 6 shows images of biomass and biochar obtained using scanning electron microscopy, where biochar was pyrolyzed at temperatures of 400-550 °C for 15-120 minutes, from poplar biomass, wastewater sludge, and corn [30].

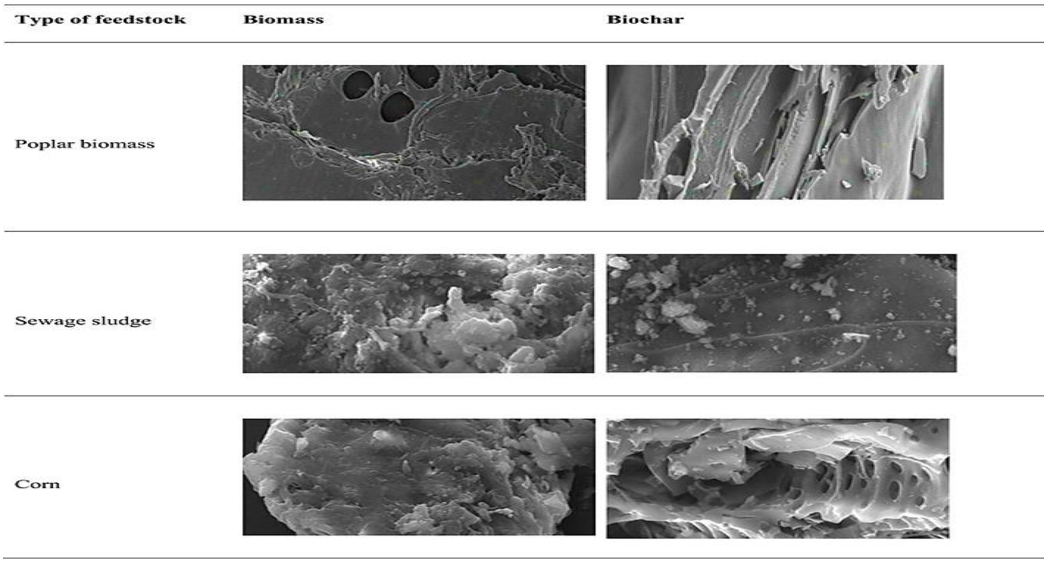

Figure 6. *Image obtained using scanning electron microscopy of different types of raw materials [30]*

5. APPLICATION OF BIOCHAR

Biochar is characterized by a high content of oxygen-containing carbon groups and inert carbon components, as well as a large surface area. Its porous structure enhances its potential for carbon sequestration, reduces greenhouse gas emissions, improves soil fertility, structure, and increases crop yields. The properties and structure of biochar determine its possible areas of application, including biofuel production.

The main methods of applying biochar to soil include incorporation into the upper layer, deep application, and fertilization. Biochar positively affects soil properties by increasing its water retention capacity, permeability, and fertility. Its high charge density also helps transport significant amounts of nutrients, altering soil characteristics and promoting increased crop yields [31].

Unlike commercially available activated carbon, biochar contains much more carbon. Therefore, it is widely used in the environmental field, where it serves as an effective tool for various pollution control methods. Biochar is used in biofuel production, soil improvement, the construction industry, carbon capture, and enhancing composting processes.

Biochar for Biogas Production

Anaerobic digestion (AD) is a widely used technology for the decomposition of organic matter and its conversion into bioenergy. The primary byproduct of this process is methane gas. During AD, certain amounts of CO_2 and H_2S are also released. An increase in CO_2 levels reduces the calorific value of methane. Additionally, there are other issues, such as low methane production efficiency, incomplete processing of volatile organic compounds, and operational failures due to a lack of microorganisms and difficulties in controlling pH. Therefore, there is a need to develop new technologies aimed at improving anaerobic digestion and increasing biogas yields.

Recent studies have shown that adding biochar to the anaerobic process can significantly increase biogas production. Biochar helps reduce the impact of toxins, shortens the lag time for methanogenic bacteria, and improves electron transfer between acetogenic and methanogenic microorganisms. As a result, the addition of biochar leads to a 22-40% increase in biogas production and a 28-64%

reduction in lag time. The number of methanogenic bacteria increased by 43.5%, while the number of other microorganisms increased by 24% [32].

Impact of Biochar on Soil Structure

The addition of biochar to soil can significantly improve its physical structure, particularly by increasing porosity, surface area, as well as the ability to absorb and retain moisture, while also enhancing oxygen uptake and other characteristics [33]. The increased surface area and porous structure create optimal conditions for the colonization of soil bacteria and fungi, which help absorb nutrients from the soil. Enhanced porosity improves the soil's ability to maintain moisture and aeration, which is critically important for microbial activity, thus stimulating the activity of nitrifiers. Some studies have shown that improved porosity supports the nitrification process by absorbing nitrifier inhibitors (such as phenols). However, this process develops slowly, and it takes several months to create an environment conducive to the colonization of nitrifiers.

The use of biochar in soil leads to changes in its properties, which help nitrogen-fixing bacteria create a suitable habitat inside the biochar pores. Both symbiotic and free-living bacteria positively affect the soil when biochar is applied. Free-living bacteria, such as *Azotobacter sp.* and *Azospirillum*, actively colonize and proliferate in biochar-treated soil due to the excess space and oxygen supply. Similarly, symbiotic bacteria, such as *Rhizobia*, are activated in biochar-treated soil, leading to an increase in nodule numbers and enhanced nitrogenase activity [34].

Biochar as a Plant Growth Regulator

The application of biochar can either reduce or stimulate plant growth, depending on the soil characteristics, type of biochar, and its production temperature (Figure 7). For example, adding 10% biochar derived from animal manure resulted in a decrease in the height of sunflowers, the number of leaves, seeds, and stem diameter. Meanwhile, biochar produced from corn and pyrolyzed at 400°C at a rate of 20 t ha^{-1} had no noticeable impact on the growth of Glycine max in clay loam soil [35]. Changes in soil properties generally led to improved plant growth after biochar application. In greenhouse conditions, the use of biochar derived from paper mill waste at a rate of 10 t ha^{-1} promoted the growth of radishes, soybeans, and wheat. Furthermore, the addition of biochar to sandy soil with unfavorable conditions enhanced corn growth by increasing the rate of photosynthesis, improving the plant-to-soil water ratio, reducing bulk density, and increasing the soil’s water retention capacity. Thus, biochar use can improve seedling emergence and plant growth, even in soils with unfavorable characteristics.

Biochar as a Source of Nutrients

Biochar can serve as a source of micronutrients such as boron, molybdenum, potassium (K), phosphorus (P), calcium (Ca), and others that are necessary for the formation of rhizobial nodules. When biochar is used in combination with compost, it significantly increases nutrient availability, which promotes higher crop yields. Chemical fertilizers added to the soil quickly lose their effectiveness due to leaching or conversion into other forms. Similarly, manure and compost can deplete the soil, leading to higher costs for farmers. Leaching of key nutrients such as phosphorus (P), potassium (K), and nitrate nitrogen (NO_3^-) can result in environmental pollution. In such conditions, the use of biochar along with fertilizers or compost may be more beneficial. This is supported by data from one study, which reports increased peanut yields, as well as a rise in soil pH and available forms of nitrogen and phosphorus. Additionally, several studies confirm the positive impact of biochar on soil fertility and the yields of various crops [37].

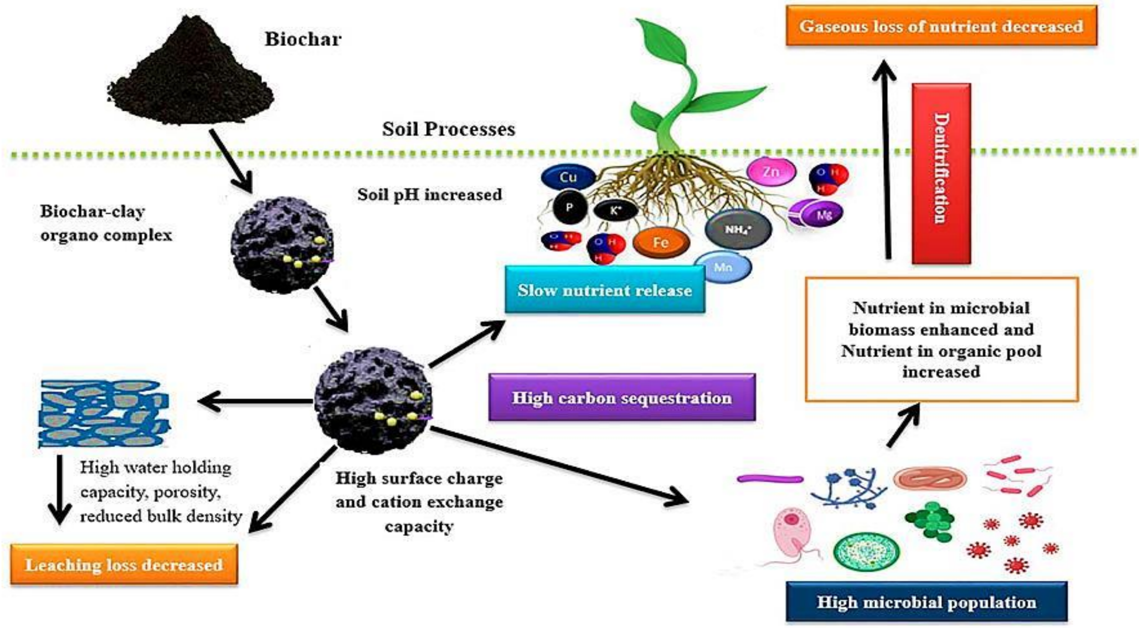

Figure 7. *The impact of biochar on changes in soil properties and plant growth: copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), phosphorus (P), potassium (K), ammonium (NH_4), zinc (Zn) [36]*

Microbial Interactions with Biochar

Biochar influences the soil microbiome in various ways. It provides a surface for microorganisms to attach, which can help improve nutrient availability while simultaneously inhibiting the development of harmful microorganisms. Biochar can also increase the diversity of soil microbiomes. A more diverse microbiome helps the soil remain resilient to environmental changes, facilitating nutrient cycling processes and stimulating plant growth. Research shows that the use of biochar can increase the population of beneficial bacteria, such as *Bacillus* and *Pseudomonas*, by up to 100% [38]. These microorganisms play a key role in supporting plant growth and improving nutrient cycling. The same study found that the application of biochar reduced the population of harmful fungi, such as *Fusarium* and *Phytophthora*, by 50%.

A report covering 964 observations from 72 studies published between 2007 and 2020 indicates that biochar significantly increased soil microbial biomass carbon by 21.7%, urease activity by 23.1%, alkaline phosphatase activity by 25.4%, and dehydrogenase activity by 19.8% [39]. No significant negative effects of biochar on enzymatic activity were observed.

Microorganisms also play an important role in cleaning the soil of contaminants, as biochar serves as a protective shelter for bacteria and fungi due to its porous structure. Studies have shown that adding biochar promotes the growth of specific bacterial communities characteristic of certain soil types. Biochar can also be loaded with microorganisms that aid in the removal of contaminants, making it one of the most promising methods of environmental remediation, combining bioremediation with enhanced efficiency through the use of biochar [40].

The Impact of Biochar on Crop Yields

Ensuring stable crop yields on limited arable land to meet the growing needs of the world's population remains one of the main challenges in agriculture. The effective use of biochar has become a promising solution to this problem by improving nutrient cycling in the soil, increasing the soil's ability to retain water and nutrients, which ultimately leads to higher crop yields. The positive impact of biochar on yield is explained by its influence on the physical-chemical and biological characteristics of the soil, such as bulk density, porosity, cation exchange capacity, as well as microbial and enzymatic activity in the soil.

An analysis of data on the impact of biochar on crop yields showed that the average increase in yield ranges from 4.9% to 48.4% globally. These positive results can be explained by several factors, such as the direct supply of nutrients to plants, increased soil pH and cation exchange capacity, improved nutrient uptake and fertilizer efficiency, as well as enhanced soil water retention capacity.

It is important to note that the effect of biochar on yield can vary significantly depending on various factors such as the type of feedstock used for biochar production, pyrolysis conditions, soil characteristics, farming practices, and the age of the biochar. Therefore, it is essential to consider these variables and adjust biochar application according to these factors to achieve optimal yields.

6. ENVIRONMENTAL BENEFITS OF BIOCHAR

Reduction of Greenhouse Gas Emissions

It is estimated that the global use of biochar could lead to a 12% reduction in greenhouse gas emissions. Recent studies show that using a composite of biochar and other materials in the soil, instead of pure biochar, can help combat climate change in two ways, although biochar itself can also reduce global greenhouse gas emissions. First, it is believed that combining biochar with compost will enhance the decomposition process by increasing the stable carbon content and producing a beneficial byproduct (a biochar-compost mix), which compensates for potential drawbacks of biochar pyrolysis, such as low macroelement content, issues with the composting system, and methane (CH_4) emissions [41]. Second, increasing organic matter in the soil and reducing greenhouse gas emissions, such as methane (CH_4) and nitrous oxide (N_2O), are also associated with the use of biochar [41].

In order for the use of biochar to result in a more favorable emissions balance compared to its use as a wood fuel, more active plant growth or reduced greenhouse gas emissions from the soil may be required. According to studies [42], biochar plays an important role in reducing methane emissions in rice paddies by stimulating methanotrophic bacteria (which absorb methane) and reducing the diversity of methanogenic bacteria (which produce methane).

The application of biochar in various soil types not only improves soil fertility but also contributes to effective carbon sequestration and the reduction of greenhouse gas emissions (Figure 8).

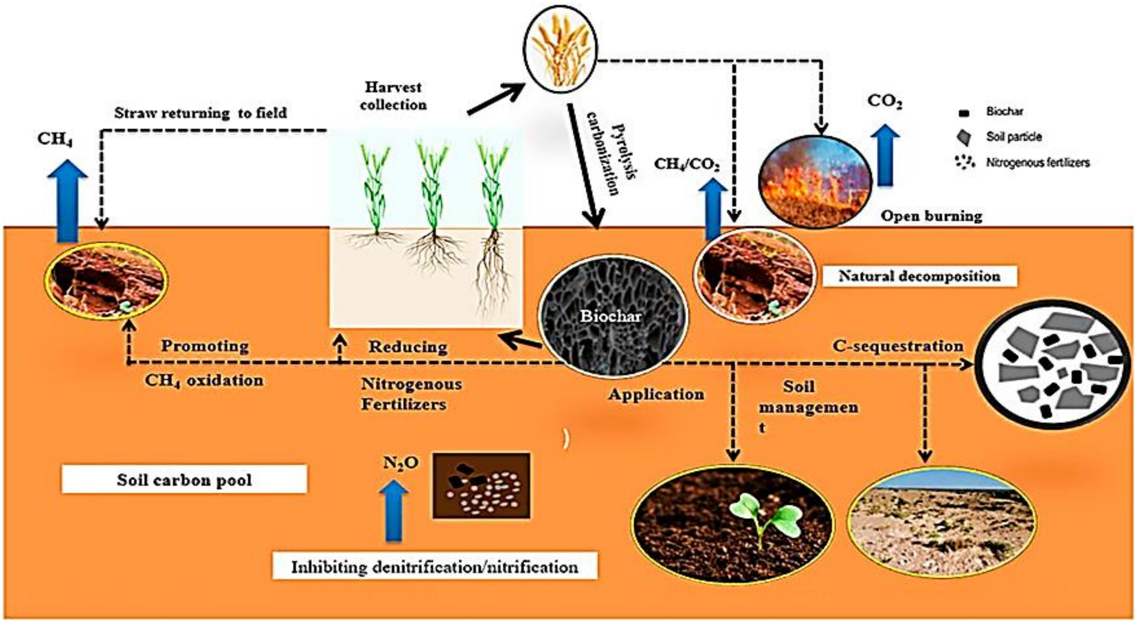

Figure 8. Mechanism of greenhouse gas (GHG) emission reduction and carbon sequestration (C) in soil with the use of biochar; carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) [43]

Impact of Biochar on N_2O Emissions from Soil

The processes of soil N_2O formation vary both spatially and temporally, complicating efforts to reduce its emissions. According to recent meta-analyses, the use of biochar reduces N_2O emissions from soil by between 49% and 8.1%. However, the mechanisms explaining this reduction are still poorly understood and are actively debated. Several hypotheses explain the involved mechanisms, including increased N_2O reductase activity and the reduction of N_2O to N_2 due to increased soil pH [44], improved soil moisture conditions and aeration, which inhibit the denitrification process, adsorption of carbon and nitrogen compounds in the soil, which reduces the sources of carbon and nitrogen necessary for N_2O formation, as well as the impact of toxic substances such as polycyclic aromatic hydrocarbons (PAHs), heavy metals, polychlorinated dibenzodioxins, and furans, present on the biochar surface, which may alter the microbial composition and functions of the soil community. The conceptual diagram of the main mechanisms by which biochar impacts N_2O emissions is shown in Figure 9.

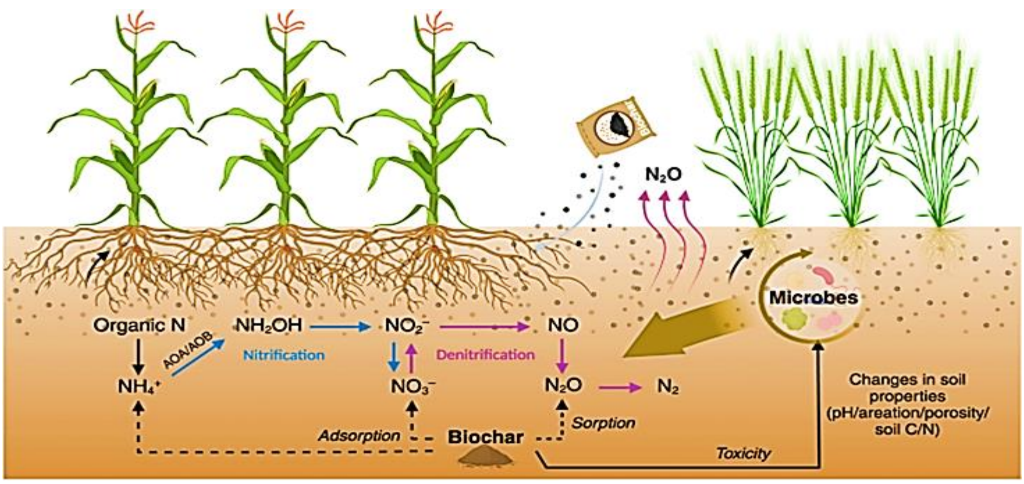

Figure 9. Diagram of the main mechanisms of biochar's impact on N_2O emissions [45]

Key mechanisms through which biochar influences N_2O emissions from soil include the following: biochar regulates gas emissions related to nitrification and denitrification processes through adsorption, which directly affects the efficiency of substrate use, such as NH_4^+ and NO_3^-; biochar influences the activity of microorganisms involved in the nitrogen cycle, as well as the structure and composition of their communities through changes in the soil environment (e.g., pH, aeration) and the introduction of toxic substances. This allows for the control of the intensity of nitrogen transformation processes in the soil and the proportion of gaseous products; in addition, the use of biochar can indirectly affect N_2O emissions by influencing crop growth and their ability to absorb nutrients.

Methane Emissions

In recent years, the use of biochar to reduce methane (CH_4) emissions has attracted particular attention. Studies have shown that biochar effectively reduces CH_4 emissions from various sources, such as livestock manure, rice paddies, and landfills. It is assumed that this effect is associated with the adsorption of CH_4 on the surface of biochar, which is then subject to microbial oxidation. One study showed that biochar made from spruce wood, applied at 10 t ha^{-1} over 7 years, significantly reduced CH_4 emissions by 43% [46]. A meta-analysis covering 43 articles confirmed that the use of biochar led to a significant reduction in CH_4 emissions, averaging 37.9% on rice paddies in East Asia. Biochar is also capable of reducing CH_4 emissions from landfills by up to 60%. Applying biochar to landfill cover soil significantly reduced emissions – by up to 80% [47]. This reduction is likely related to an increase in the population of methanotrophic bacteria that efficiently consume CH_4. Additionally, biochar improves soil aeration and drainage, further contributing to the reduction of CH_4 emissions. Thus, the hydrophobic cover soil of a landfill modified with biochar can more effectively reduce CH_4 emissions compared to soil treated with conventional material.

Impact on Heavy Metal Uptake

Many studies confirm that biochar can reduce the uptake of heavy metals (metalloids) by plants. A meta-analysis showed that the addition of biochar to soil resulted in an average reduction of Cd, Pb, Cu, and Zn concentrations in plant tissues by 38%, 39%, 25%, and 17%, respectively [48]. In studies where significant reductions in the bioavailability of heavy metals were observed, high doses of biochar, exceeding 10 Mg ha^{-1}, were often used [49]. Particles on the surface of biochar containing carbonaceous minerals have a particularly strong influence on reducing the bioavailability of heavy metals. The integration of these particles into organo-mineral microagglomerates can reduce Cr (VI) to Cr (III) through interaction with reduced iron, organic matter, and free radicals, including electron transfer, which decreases the availability of these metals to plants.

Additionally, biochar may increase the mobility of anionic metalloids, such as As, by reducing the number of positively charged sites and decreasing the binding of As as soil pH increases [50].

7. CONCLUSION

Biochar is a promising material with great potential for improving soil quality, increasing agricultural crop yields, and carbon sequestration. Its use in various areas, such as improving soil structure, enhancing its water retention capacity, and removing toxic pollutants from soil and water, demonstrates its potential as an environmentally sustainable resource. The positive effects of biochar include improving nutrient availability for plants, increasing their resistance to diseases and stress, as well as reducing greenhouse gas emissions.

Despite the clear environmental benefits of biochar, its cost and modification processes require additional efforts to reduce production costs and improve its accessibility for widespread use, especially among farmers. To achieve large-scale application, strategies must be developed to ensure its economic efficiency and availability.

Future research should focus on a more detailed analysis of the long-term impacts of biochar on ecosystems, as well as the development of clear guidelines for its application in different ecological conditions. Field trials are particularly important to understand the real effects of biochar use in the long term. Comprehensive life-cycle assessments, including the environmental and economic consequences of implementing biochar on a large scale in agriculture and industry, are also important directions for future scientific investigations.

AUTHOR CONTRIBUTIONS

Writing-review & editing, methodology, supervision: Davlat Yuldashbek; conceptualization, writing-review & editing, data curation: Nurlan Akhmetov.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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