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Review

Biochar as Soil Amendment: The Effect of Biochar on Soil Properties Using VIS-NIR Diffuse Reflectance Spectroscopy, Biochar Aging and Soil Microbiology—A Review

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Abstract: This literature review explores the assessment of biochar quality and its impact on soil properties using diffuse reflectance spectroscopy. Biochar, a product of biomass pyrolysis, is recognized for its positive effects on soil fertility and carbon sequestration. This review emphasizes the need for systematic research on biochar stability and highlights the potential of diffuse reflectance spectroscopy for analyzing soil–biochar interactions. Biochar acts as a soil conditioner, improving physical, chemical, and biological properties and enhancing soil fertility and crop yield. Furthermore, it aids in mitigating climate change by sequestering carbon dioxide. However, the long-term behavior of biochar and its interactions with various factors require further field research for optimal utilization, as the aging process of biochar in soil is complex, involving physical, chemical, and biological interactions that influence its impact on the agroecosystem. This review also emphasizes the importance of studying the interaction between biochar and soil microbes, as it plays a crucial role in enhancing soil fertility and plant resistance to pathogens. However, research on this interaction is limited. VIS-NIR spectroscopy is a valuable tool for monitoring biochar application to soil. Nevertheless, controversial results highlight the intricate interactions between biochar, soil, and environmental conditions.

Keywords: biochar; soil organic carbon; diffuse reflectance spectroscopy

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1. Introduction

Soil can be characterized as a natural, non-renewable, vital, multivariable, complex, regulatory resource, a significant driver of agriculture, a complex organic material [1], an environmental filter of nutrients [2], and a large pool of soil carbon [3] since its contribution to the ecosystem is necessary both for the dynamics and for the complex processes that take place in it [4]. Organic matter is one of the essential components that make up the soil [5,6] and contributes significantly to the assessment of soil conservation and quality [7].

The soil carbon pool is the largest terrestrial pool of organic carbon and plays a vital role in the global carbon cycle and in maintaining ecological balance [8]. Recently, soil management and the great biochar development scale have faced several new challenges [9,10] related to climate change due to increasing temperatures and anthropogenic factors. On the one hand, the continuous degradation of soils because of environmental degradation due to anthropogenic factors and the phenomenon of climate chains are presented as significant issues of environmental concern and are the primary concern of the global community, determining to a considerable extent the performance of productivity and, by extension, the quality, health, and properties of the soil.

On the other hand, increasing population trends, limitations of agricultural land for food production, water scarcity, loss of biodiversity, and maintaining food security in polluted soils [11–13] are some components that make the earth unsustainable and make it challenging to function [14]. It is imperative to maintain sustainable management and continuous monitoring of the change in soil properties to increase productivity and minimize or mitigate all those components that negatively affect it. According to the literature review, various types of research demonstrate the positive contribution of biochar in terms of its ability to maintain soil fertility and carbon sequestration for several years [15].

Its properties contribute to the soil's physical, chemical, and biological properties and plant growth [16]. A sustainable soil resource management strategy is to incorporate biochar into the soil [17], whose use has been known for 2000 years [18], creating an agronomic regime with a positive impact on the environment [19–21]. Studies prove its primordial roots and its impressive utilization by the farmers of modern societies [22]. As a soil improver, it is increasingly gaining the trust of its users, which is reflected in many publications [23], and there is an increase in searches of the scientific literature with the word "biochar" [24,25]. Biochar is a porous material whose production is carried out through pyrolysis or hydrothermal treatment of raw biomass [13].

The thermal depolymerization of biomass at high temperatures without the participation of oxygen is called pyrolysis [26,27]. The conceptual approach to the term includes the diverse uses and applications of biochar in various sciences [28]. The use of biochar is an emerging practice for soil amendment that yields promising results [29], attracting worldwide interest, both in research and practical applications [30]. The type of raw material and the production conditions are largely inextricably linked to its physical and chemical properties [31]. These properties determine its physicochemical behavior when applied to the soil and in combination with the properties of the soil [22]. The longevity of the material and its persistence in the environment for a long time are often pointed out in the literature [23]. When it is incorporated into the soil, it is subject to a natural aging process. The natural aging of biochar in the soil is slow and lasts for many years; therefore, accelerated aging techniques are applied as alternative ways of approaching its assessment [32].

For this reason, we need systematic research that will investigate the stability of biochar [33], but also detailed experiments and analyses that lend precision to soil analysis [34]. It is worth noting that the biochar–soil system shows strong multi-variability due to various factors that affect it. It is known that the yield of biochar in the soil varies significantly concerning its spatial location and the effect of aging [4]. Research has mainly focused on laboratory experiments, and very little has been reported on field experiments on biochar incorporation into the soil [35].

These experimental procedures show discrepancies due to many components, such as different methods of mixing biochar with soil, the effect of biochar aging, different climatic conditions, the slope of the field of application, and seasonal and spatial variation of the area [4]. The hardest part of biochar study research is gathering data from different soil types, changing weather conditions, and other land uses. This can be performed with fast, reliable, and non-destructive methods such as diffuse reflectance spectroscopy (VIS-NIR). The need for accurate information and monitoring of biochar's spatial and temporal variability becomes imperative and necessary.

According to some views, some biochar acts constructively in the soil, but not in the sense that soil and plant responses to biochar addition can be negative, positive, or neutral [16]. It is necessary to study the ways of optimizing the processing conditions to improve their properties with simple, cheap, and fast evaluation techniques. Selecting suitable conditions to produce biochar with desired characteristics requires knowledge of distinct additional factors that affect its qualitative and quantitative characteristics [22]. The effort to find fast and cheap solutions such as diffuse reflectance spectroscopy (VIS-NIR) combined with machine learning can be exploited to predict the long-term performance of biochar-amended soil and simplify the analysis routine [4]. In particular, biochar production has been proposed to incorporate it into the soil; the prevailing territorial and environmental regime should be taken seriously. This way, we can draw safe conclusions for the biochar characterization, its effect on the soil, and its aging process.

Consequently, diffuse reflectance spectroscopy has multiple benefits, and research should be directed toward using this technique to determine the properties of the soil–biochar system. In the present literature review, an attempt is made to investigate the assessment of the quality and longevity of biochar and how it affects the physical, chemical, and biological properties of soil using diffuse reflectance spectroscopy (VIS-NIR), with an emphasis on biochar aging and soil microbiome.

2. Materials and Methods

The main objectives of this study are to determine if reflectance spectroscopy can accurately predict organic carbon levels in soil that has been amended with biochar and if it can also track biochar's spatial and temporal integration and retention. Additionally, this study aims to investigate how various soil and climate conditions, different soil types, and future land use can influence the impact of biochar on soil properties and how non-destructive methods, such as reflectance spectroscopy, can effectively capture this information. It is worth noting that this research is original, as there has been limited investigation into using VIS-NIR diffuse reflectance spectroscopy in biochar studies.

To conduct this review, a procedure was developed using the method proposed by Thurer et al. [36] to search for and define the relevant literature. The conduct of this review should be described in detail so that its quality can be assessed. Limiting references is performed by including articles with a narrow time frame or excluding articles. In addition, the reduction in articles should be made according to the purpose and research questions of the specific review [37]. ScienceDirect and Google Scholar were chosen as search platforms due to their extensive publication databases. The search spanned from 2000 to 2023, except for a few articles and books arbitrarily selected or published before 2000. Keywords such as "biochar AND soil amendment", "biochar AND soil properties", "biochar AND soil microbiology", "biochar AND biochar aging", "biochar AND carbon sequestration", "biochar AND soil spectroscopy", and "biochar AND diffuse reflectance spectroscopy VIS-NIR" were used to retrieve a total of 208,124 references. To manage the high volume of citations, only the title, abstract, and keywords were considered to yield a manageable number of sources that could support this study's research questions. Articles and reviews were mainly included, while papers that did not meet the specified criteria were rejected to ensure the quality of the reports. Initially, duplicates and articles unrelated to this study were removed from the sample. The table presented in this study outlines the selection process for the final sample. Ultimately, 471 relevant citations were selected for this review. The present methodology is summarized in the table below (Table 1).

Table 1. Summary of Bibliographic Reference Screening Process.

Keywords	Science Direct	Google Scholar	Original Sample	Duplicates and Unrelated Articles Removed	Final Sample
biochar AND soil amendment	9.705	19.600	29.305	1.465	101
biochar AND soil properties	19.242	58.100	77.342	1.093	113
biochar AND soil microbiology	2.430	17.700	20.130	343	47
biochar AND biochar aging	6.296	18.200	24.496	456	45
biochar AND carbon sequestration	7.210	21.100	28.310	763	88
biochar AND soil spectroscopy	7.850	19.700	27.550	212	44
biochar AND diffuse reflectance spectroscopy VIS-NIR	129	862	991	154	33
	The final set of references				471

3. From the Raw Material (Biomass) to the Production of Biochar via the Pyrolysis Process

The feedstock undergoes decomposition through pyrolysis, the dominant technology for converting solid biomass into bio-oil, gaseous products, and biochar [38]. As a concept, biochar has been interpreted in many ways due to both the heterogeneity of the raw materials and the biochar production technology. Biochar research is being carried out in more and more countries, with widespread dissemination and different purposes depending on the raw materials, production, modification methods, local economy, and environment [39].

Biochar is considered a material of global application for the restoration and sustainability of soils due to its physicochemical characteristics and the extensive availability of raw materials [40].

Its production lies in a wide range of low-cost biomass materials. Various organic materials based on biological and agricultural wastes (barks, leaves, chips, peels, seeds, straw, and grass), industrial wastes (fibrous pulps and distillery wastes, sewage sludge), and municipal solids have been proposed as feedstocks for biochar production. Waste (animal waste) [41,42] and forest waste, such as conifer bark, sawdust pellets, paper, and moss [43]. Moreover, human sewage is used in biochar production and is a good carbon and nutrient source [44]. It is considered that the only eligible biomass for biochar production is that derived from fast-growing plants, plant-agricultural residues, and organic waste from urban areas [28]. The table below presents the raw materials for biochar production (Table 2).

Table 2. Biochar production raw material.

Biomass	References
Wood materials (pine sawdust), shavings	[45,46]
Crop residues and agricultural waste (rice husk, rice straw, cotton stalk, coconut shell, wheat straw)	[47–49]
Corn	[47,50]
Animal waste, animal manure	[51]
Mill waste, animal excreta, plant residues, forest waste, food waste, municipal solid waste, sewage, organic waste	[52]
Sewage sludge	[53]
Sugar beet waste	[54]

The process of producing biochar as black carbon [55] can be achieved with various types of biomass and undergo the pyrolysis process with various processes [56]. Nath et al. [57] state that during the pyrolysis process, the biomass is subject to a change in chemical composition with the production of volatile substances and a solid residue rich in carbon until the result is none other than the creation of biochar. Several biochar production methods have been proposed [58,59]. However, it can also be produced with waste buried in the ground; i.e., the burial of organic waste has been proposed [43].

These techniques involve heating the raw material used to produce biochar. The differences in these techniques are found in the amount of oxygen, the temperature range, the water content, and the pressure [60–62]. Pyrolysis refers to the thermal and chemical conversion of feedstock under conditions of limited or no oxygen [63] and is the most common and widespread method of biochar production [64]. It describes the thermal decomposition of organic compounds into three fractions or forms, solid, liquid (bio-oil), and gas [65–67].

Another definition that has been proposed includes the anaerobic digestion of biomass, usually between 260 °C and about 600 °C [43]. The present process generally occurs in oxygen-free conditions and at temperatures from 250 to 900 °C [68]. According to Lehmann [66], considering the pH, specific surface area, cation exchange capacity, and biochar yield, the optimum pyrolysis temperature could be 450–550 °C. Pyrolysis can be further classified into three categories depending on the heating rate and reaction time [69].

Slow pyrolysis is carried out through a slow rate of temperature increase over long biomass residence times [70–72] and is the most common process due to high-yield biochar production [73]. The pyrolysis temperature is >350 °C (generally 300–700 °C) [18], and the yield of this process is 35% biochar, 30% bio-oil, and 35% gas. However, bio-oil and gas production could be used to address the economic crisis [56]. Slow-cracking systems are called "charcoal furnaces" and are less controlled because the bio-oil and gas are not separated. Therefore, biochar yield in slow pyrolysis can range between 25% and 60% [74–77].

Generally, the solid product yields higher when the production feedstock is heated at a slow heating rate of 10–20 °C/min to a temperature of 300–750 °C [78]. Typically, solid production is favored at a temperature of 400–500 °C, while at higher temperatures, more liquid and gas are produced [22]. By extension, a slow heating rate produces more solids [79]. Biochar formed at a higher temperature leads to more aromatic structures and the simultaneous loss of functional groups, reducing its cation exchange capacity (CEC).

As a result of its higher carbon content, the energy content of biochar increases with increasing temperature [22]. In contrast, in rapid pyrolysis, a rapid rate of temperature increase is observed at short biomass residence times and is used for bio-oil production [69,80]. Yields are typically 60% bio-oil and 40% biochar and gas. In a fast-cracking system, temperatures rise to 700 °C within minutes, produce more gases, and yield less carbon. According to Oni et al. [81], at a temperature between 500 and 700 °C, the biochar yield is 75% bio-oil, 12% solid, and 13% gas.

Intermediate pyrolysis uses a slow rate of temperature increase with moderate feedstock retention. Generally, it yields a better balance between solid and liquid but is rarely adopted as a method [56]. A consequence of the above is that the change in temperature and duration of pyrolysis brings about significant changes in the properties of biochar [82]. Its physicochemical properties depend on components such as raw material, heating rate, reaction temperature, reaction condition (environment), and reaction time [57,83,84]. For example, the ash content of biochar is generally related to the feedstock content. The higher the biochar yield, the more lignin and less cellulose are in the raw biomass [85]. On the other hand, production at temperatures above 700 °C produces smaller amounts of biochar and is less recommended. High pyrolysis leads to a decrease in reflectance, which is demonstrated by the fact that the pyrolysis process leads to removing moisture and alcohol from the raw material.

In addition, it increases the carbon content of biochar and decreases H and O levels [86]. A slow heating rate has been shown to reduce the rate at which volatiles from production materials escape into the atmosphere, causing more secondary reactions. While a rapid heating rate increases the volatility of volatile compounds, fewer secondary reactions occur [43]. Major organic compounds such as cellulose, hemicellulose, and lignin are expected to be broken down during pyrolysis. Following cellulose (315–400 °C) and lignin (>400 °C), hemicellulose (220–315 °C) is the first material to break down [68]. These compounds are composed of different amounts of basic elements; i.e., C-H-O-N and their content could significantly affect the yield and biochar content during the pyrolysis process [38]. Throughout this pyrolysis process, hemicellulose decomposes at a temperature of about 200 and 260 °C, and cellulose and lignin decomposition take place in a temperature range from 240 to 350 °C and from 280 to 500 °C, respectively [87,88]. However, during the decomposition of organic compounds by pyrolysis, there are deviations within the range of temperatures [68].

Biochar produced at high temperatures (600–700 °C) exhibits a profound hydrophobic nature with effective carbon layers [89]. During the pyrolysis process, the carbon crystal structure of the raw material selected for production is transformed into structured polyaromatic hydrocarbon sheets and acquires an amorphous and graphitic-type structure (graphene) [27,90]. About 50% of the carbon content remains in the final product. However, this ratio depends on the pyrolysis conditions. In addition, during the pyrolysis process, aliphatic bonds are converted to aromatic bonds [91]. Another critical parameter of biochar is its pH, which varies from neutral to alkaline [39]. Typically, it has been added to acidic soil to increase pH due to the formation of metal oxides [92].

The stability of biochar depends on the temperature at which it is formed and the type of raw material used to produce it. Various studies have shown that increased pyrolysis temperatures increase biochar stability [39]. The mechanical stability of biochar is inversely related to its porosity. Biochar with higher compressive strength is produced from biomass with higher density and lignin content [93]. Olive husk with high lignin content had a higher biochar yield than corn with less lignin under the same pyrolysis conditions [94], while biochar yield decreased with increasing cellulose content.

4. Properties and Characteristics of Biochar and Factors Affecting Its Performance

Biochar has a high percentage of carbon content and can act as a long-term carbon storage reservoir [35,95], with high stability and large-scale production potential [63,96]. It generally possesses a large surface area, a porous structure, and abundant surface functional groups [39,97]. It contains unstable, stable, volatile, and aromatic compounds due to the presence of carbon.

Rechberger et al. [98] report that biochar is rich in carbon content, and most of it is aromatic in structure and difficult to degrade [99,100]. Hydrogen H, oxygen O, nitrogen N, sulfur S, and ash are present in smaller amounts [18,39,52]. Its structure is highly porous due to carboxyl esterification and aromaticity, with a large specific surface area and low solubility [34]. Biochar properties affected by pyrolysis temperature are surface form and structure [101] and adsorption capacity [102]. Initially, biochar consists of various functional groups, such as hydroxyl (-OH), carboxylate (-COOH), and aldehyde (-CHO), which are located on its surface [18,54,66].

Functional groups vary depending on the type of biochar, the temperature at which it was formed, and the interacting compounds in the soil [103]. During the pyrolysis process, due to increased water loss and dehydration of the biomass, the development of the porous surface of the biochar takes place. Thus, based on pore categorization, biochar is produced with tiny pores (2 nm), medium pores (2–50 nm), and large pores (>50 nm).

Furthermore, the surface area of the biochar plays an essential role because the properties of adsorption and ion exchange are directly related to this property. In essence, it has an internal and an external surface. The first is the walls of the most profound and least open cracks and cavities (micropores). In contrast, the second includes all protrusions, larger cracks, and pores (mesopores and macropores). Macropores contribute less than micropores to the adsorption capacity [68]. Biochar ash is alkaline in nature, and therefore the pH of biochar reflects the ash content [104]. At the same time, its cation exchange capacity is related to its surface, the presence of carboxyl functional groups, the first matter of the biomass used, and the preparation temperature. The stability of the aromatic rings resulting from the increase in temperature turns the biochar into a solid material with high strength for centuries or millennia. Increasing production temperature leads to a decrease in aliphatic structures and the soluble fraction and an increase in the aromatic and insoluble fraction [105].

Therefore, biochar produced at a higher temperature may be more stable than that produced at a lower temperature. Many investigations agree that biochar can be preserved for many years in the soil, even for more than 1000 years [106]. This preservation is attributed to the durability of the biochar carbon and, in particular, to the aromatic carbon, which is more resistant to mineralization under abiotic and biotic stresses.

In essence, C stabilization occurs in aromatic compounds, which certifies the fact of carbon inflow and sequestration in the soil when subjected to a pyrolysis process [107]. In addition, oxygen (O/C) and hydrogen (H/C) content is low, directly related to their durability in the soil. If the pyrolysis temperature is lower than 400 °C ($T < 400$ °C), the structure of the biochar resembles amorphous carbon. In comparison, if the temperature is higher than 500 °C ($T > 500$ °C), the structure refers to thermally reduced graphene oxides [108,109]. Research shows that biochar's pore volume and surface area increase with increasing pyrolysis temperature [93,110].

At the same time, at a temperature >500 °C, the biochar is more resistant to the soil and contains a higher concentration of ash and pH. However, temperatures >700 °C are not acceptable for biochar yield but produce biochar with high stability [10]. Considering the pyrolysis process, which is an exothermic reaction [111], and the thermal behavior of the raw material [112], the control of the pyrolysis temperature can be considered a difficult task. Therefore, the reported temperature may be inaccurate and should be verified. The temperature has a significant impact on the adsorption capacity of biochar [113]. Regarding the effect of pyrolysis on the chemical characteristics of biochar, an increase in pyrolysis temperature also implies an increase in carbon concentration.

However, increasing temperatures gradually decrease H and O concentrations [86]. Generally, at high pyrolysis temperatures (T = 400–700 °C), the feedstock is transformed into stable polycondensed aromatic structures containing high carbon [114]. On the other hand, when the pyrolytic process occurs at a low temperature (400 °C), a biochar product rich in C=O and C-H functional groups is produced. Consequently, the dominant organic compounds are aliphatic or less stable cellulose-like structures at low pyrolysis temperatures, which microbes can quickly degrade. In addition, high pyrolysis temperatures (T > 500 °C) create more hydrophobic biochar, have a larger surface area and pores, have a higher pH due to ash, and are more suitable for organic pollutants.

Low temperatures (500 °C) lead to biochar having a smaller surface area and pores but more oxygen functional groups, making it more suitable for inorganic pollutants [68]. Generally, a higher pyrolysis temperature reduces the amount of solid product that can be made. Still, it improves its quality by giving it a more porous surface, a larger specific surface, more N and K, more C and aromatic substances, and fewer active O groups on its surface [115].

The residence time of biochar during the pyrolysis process significantly affects its porosity and specific surface area [116]. Biochar has a predominantly condensed aromatic structure highly resistant to microbial degradation [43]. The pH is either neutral or alkaline. Alkaline pH sometimes results from high-temperature biomass pyrolysis. However, at lower temperatures, high ionic-strength biochar is produced [43]. According to the literature review, biochar presents multifunctionality that lies in the fact of certain characteristics such as: alkalinity, stability, specific surface area, carbon content, mechanical strength, cation exchange capacity and nutrient retention [117–125].

5. The Positive Effect of Biochar on the Ecosystem, with Emphasis on Soil

Aiming at sustainable development, biochar can play an essential role in the long term [18]. Therefore, it is a product gaining more and more research interest, as its use is intended to improve crop yield and soil properties [126]. However, using biochar in soil is not only important for carbon sequestration but also acts as a soil management practice by affecting its physical and chemical properties [17,127]. Soil degradation results in reduced organic matter due to continuous loss, so biochar is a solution for this constant loss of organic matter [35].

In particular, biochar contributes to the assurance and quality of the soil as an environmentally friendly material with a renewable nature without producing pollutants. In addition, its incorporation into the soil could lead to achieving sustainable agriculture [128]. There are three functions of biochar for which its use has been mainly promoted in recent years, which include mitigating climate change [37] by sequestering carbon [129], enhancing the yield of crops, and improving soil structure and functions through multiple beneficial actions. It, thus, plays a vital and active role in agricultural economic development and is an economical solution as an adsorbent material with many environmental applications [56].

One of the significant benefits of biochar is that it helps fight climate change by sequestering carbon dioxide from the atmosphere. It can also be used to rehabilitate problem soils. Biochar has many benefits for agriculture and environmental economics in the long term, so its incorporation into agricultural practices is highly recommended [130]. Biochar is considered a material of global application for the restoration and sustainability of soils due to its physicochemical characteristics and the extensive availability of raw materials [40]. It can promote soil fertility improvement and contribute to climate change mitigation [129]. Biochar as a soil conditioner is gaining more and more interest in research [17]. Three main functions have been discussed in recent years: its contribution to mitigating climate change, its contribution to carbon sequestration in the soil, improving crop yield, and improving soil structure [35,95]. Soil improvement with biochar mainly refers to the improvement of soil nutrient availability (e.g., nitrogen, potassium, and other macronutrients or micronutrients), moisture content, cation exchange capacity (CEC), organic content C, and reducing soil erosion due to improved structure [57]. The effect of biochar on plant growth depends mainly on factors such as the type of biochar, the degree of its incorporation into the soil, the depth of mixing with the soil, the availability of nutrients, the texture of the soil, and the species of cultivated plants [131].

In the last two decades, there has been substantial research interest in studying and further investigating the potential of biochar in terms of increasing productivity, improving soil characteristics, and mitigating climate change. In general, researchers report the beneficial properties of biochar on soil physical, chemical, and biological properties, as well as plant growth [37]. In particular, as a soil conditioner, it can improve long-term physical (bulk density, water holding capacity, permeability, etc.), chemical (nutrient retention, nutrient availability, etc.), and biological properties (microbial population, earthworms, enzyme activity, etc.) for the benefit of plant growth [26]. Consequently, its ability to adsorb pollutants is known. It has already been shown to be widely applicable in wastewater treatment applications, but to date, the mechanisms of pollutant adsorption still need to be fully understood [18]. Additionally, there are many studies on its use as a compound fertilizer due to its high porosity and large surface area [132]. The application of biochar to the environment is not harmful because it has been found to contain several polycyclic aromatic hydrocarbons that are environmentally friendly. However, the commercial use of biochar has not been widely accepted, even though biochar is only a waste [43].

6. Effect of Biochar on Soil's Physical, Chemical, and Biological Properties

Biochar works in many ways when applied as a technique to improve soil quality. According to the literature review, many reports demonstrate the importance of biochar utilization in the agricultural ecosystem. The positive impact and beneficial effects of biochar incorporation on soil functions have now been demonstrated, as has its effect on soil physical, chemical, and biological properties. However, the factors influencing the long-term behavior of biochar in the environment still need to be better understood. A large body of literature supports the idea that soil amended with biochar has excellent potential to increase crop productivity due to the consequent improvement in soil structure, high nutrient use efficiency (NUE), aeration, porosity, and water holding capacity (WHC) [95]. Biochar exhibits a variety of functions when applied as a technique to improve soil quality. According to the literature review, various reports demonstrate the importance of biochar utilization in the agricultural ecosystem.

The positive impact and beneficial effects of biochar incorporation on soil functions have now been demonstrated, as has its effect on soil's physical, chemical, and biological properties. However, the factors influencing the long-term fate of biochar in the environment are still poorly understood. An abundant body of literature supports the idea that soil amended with biochar has great potential to increase crop productivity due to the consequent improvement in soil structure, high nutrient use efficiency (NUE), aeration, porosity, and water holding capacity (WHC) [95].

Regarding its effect on soil's physical properties, biochar contributes to soil texture, grain size, bulk density, aeration, and moisture retention [27]. In addition, an increase in porosity, a decrease in bulk density, and an enhancement of soil aggregation are observed [133,134]. Many studies have shown that biochar affects soil's water retention and hydrological functions. The results of these studies are variable due to different experimental conditions, including biochar and soil types. Few studies, however, have examined its effect on plant-available water (PAW) and water use efficiency (WUE) [86,135–140]. There is an improvement in the movement of water in the soil and an increase in available moisture, mainly in sandy soils with a low content of organic matter, a moderate improvement effect in soils of medium texture, and possibly a reduction in moisture retention for clayey soils. High cation exchange capacity (CEC), high specific surface area, pore volume, and porosity can increase water-holding capacity and improve the effects created by saline soils. Biochar increases soil's water-holding capacity, especially in arid soils considering climate change.

According to studies, straw biochar formed at 300 °C had a water-holding capacity of 13×10^{-4} mL m^{-2}, but this decreased to 4.1×10^{-4} mL m^{-2} when the carbonization temperature increased to 700 °C [76,95,141–154].

As a multifactorial carbonaceous and porous material, it improves soil properties and fertility by enhancing the availability of nutrients [155–160]. A stoichiometric change in the soil is observed with the simultaneous retention of nutrients [125,161,162]. The enhancement of soil nutrient bioavailability is explained by reducing nutrient leaching and immobilizing toxic elements in contaminated soils [163,164]. In particular, the effect on the potential of nitrogen in the soil is variable since a decrease, an increase, and no change are observed. However, the production feedstock is vital in soil nutrient availability [165–168].

Biochar is an essential means of long-term increase in organic C [63,148,169,170]. Its incorporation into the soil increases the cation exchange capacity (CEC) and the degree of base saturation, thereby increasing the retention of nutrients [146,171]. According to research, the improvement of CEC reached up to 20% and electrical conductivity (EC) up to 124.6% [95,146,172–176], increasing soil pH and reducing soil acidity by 31.9%. Significant crop production and nutritional value increases are observed when its application is in acidic and poor soils. Conversely, it can have controversial results in alkaline and fertile soils, causing a neutral or negative effect on plant tissue production [119,136,173,177–180]. In terms of its contribution to soil's biological properties shows growth in microbial activity and diversity [181–184]. It immobilizes the microbial nitrogen (N) of the biomass and stabilizes the microbial nitrogen (N) of the soil [174,185,186].

Its positive effects appear in the reduction in fertilizer leaching and improvement of soil aeration [146,187], in the improvement of stream flow resistance [188], in the decontamination of air and water soil [189–192], and in the general improvement of soil aeration and hydrological soil functions [193–195]. The effect of biochar on plant growth and crop yield depends on the crop type, soil type, biochar properties, rate, method, and frequency of its application. Crop yield responses are generally reported as positive. Biochar application has been reported to increase plant productivity by approximately 10% and up to 25% for aboveground biomass. Other research investigates biochar's effect on increasing corn's biomass due to increased soil pH and CEC. Increase grain and maize yields by 150% and 98% with 15 and 20 t/ha biochar, respectively, to improve soil's physical and chemical properties.

The effectiveness of biochar in improving plant productivity is variable, considering climate change, soil properties, crops, and experimental conditions. These differences could also be explained by the different pyrolysis processes and soil interactions with biotic and abiotic factors [119,196–200]. A general increase in crop productivity and yield is observed. Biochar showed an increase in available plant water content of 33–45% in coarse-grained soils and 9–14% in clay soils. A tremendous increase was achieved by adding 30–70 Mg/ha. At the same time, there was an average increase of 27% in the rate of photosynthesis in C3 plants but no effect in C4 plants.

Increased stomatal conductance, transpiration rate, and chlorophyll content were attributed to the combined effects of biochar, water availability, and nitrogen fertilization, sequestering soil carbon as a long-term carbon pool and reducing emissions of greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). However, the accuracy of its application remains controversial. Biochar application to paddy fields caused a 12% increase in CO_2 emissions but a decrease in NO_2 emissions. In a pasture ecosystem, biochar application showed no change in CO_2 or NO_2 emissions. Other research showed a CH_4 reduction in soybean crops after biochar addition due to increased soil pH and strong adsorption capacity and a 50% N_2O reduction in soybean plots on acidic soils. With the addition of biochar, there is a spatial reorganization of C within soil particles, but the mechanisms remain unclear [147,171,194,201–208].

Mitigating Climate Change by Removing CO_2 from the Atmosphere

Biochar's proposed climate change mitigation mechanisms are its molecular structure, dominated by aromatic carbons that make it more resistant to microbial decomposition, allowing it to remain in the soil for thousands of years and potentially limiting greenhouse gas emissions. The change in CO_2 emission rate can be related to soil temperature, soil type, pyrolysis temperature, and biochar application rate [63,95,96,186,209–220].

Biochar provides a large capacity to adsorb heavy metals from the soil due to its large surface area, multi-layered porous structure, abundant surface functional groups, increased soil redox potential, pH, organic matter content, and cation exchange capacity [143,221,222]. At the same time, it shows a reduction in the leaching of nutrients into the soil due to the high CEC of biochar [77]. The modern literature references the involvement of biochar in other areas as well. The use of biochar in the horticulture industry for fruit and vegetable production is considered [205,223]. In addition, it contributes to the restoration of forest ecosystems and urban soils due to its ability to adsorb and immobilize organic substances [224]. However, it exhibits combinatorial and synergistic action with other materials such as compost, manure, paper mill sludge, and biosolids [225–227].

7. Soil Organic Carbon Sequestration

Soil carbon is one of the critical indicators of soil health, contributing positively to three main components: increasing crop productivity, soil water management, and climate regulation [228]. Safe storage of atmospheric carbon in soil is considered a potentially effective and sustainable climate change mitigation strategy [229]. The goal of an ambitious program called "Four per Mile Soils for Food Security and Climate" was to increase the stock of soil organic matter (SOM) by 0.4% per year to offset the emission of greenhouse gases into the atmosphere from anthropogenic sources [230,231]. Consequently, increased soil carbon storage through soil carbon management in terrestrial ecosystems has more comprehensive benefits through biodiversity protection, enhanced food security, and climate change mitigation [232].

Soil carbon (C) plays an essential role in diverse soil functions, such as water retention and infiltration, nutrient storage and recycling, biomass production, habitat for biological activity, and carbon storage. Soil C is also considered one of the key indicators of soil function in terms of agricultural productivity, water security, and climate regulation [228]. The estimated size of the soil organic carbon (SOC) pool at a depth of 1 m is twice that of atmospheric stocks [233]. Therefore, even small changes in SOC stocks would affect the atmospheric stock [234]. Soil organic carbon can contribute to reducing atmospheric CO_2 concentrations. Numerous variables, such as soil characteristics, climate, and land use (agricultural activities), can affect the rate of decomposition of soil organic carbon (SOC) [235]. Unsustainable agricultural practices have led to significant depletion of SOC stocks [236]. By choosing crops with deep roots and higher acceptable root density, it is possible to ensure the conservation of SOC stocks by reducing tillage and increasing below-ground carbon inputs. Moreover, adding organic matter degradation agents works beneficially in maintaining and increasing SOC stocks [237–239].

The variability present in each soil is a factor that makes complex both the qualitative and quantitative analysis of those soil properties related to fertility, soil quality, and, by extension, productivity. Different studies have demonstrated the potential to store even more carbon in soils by applying certain management practices such as afforestation, conservation tillage practices, or soil conditioners, with the latter showing high potential [96]. Another SOC sequestration option is to use carbon-rich soil amendments with long mean residence times and low decomposition rates.

As a solid product of the pyrolysis process, biochar can be used as a soil conditioner that contributes positively to crop management. Yang et al. [105] state that biochar is a friendly option as an excellent soil conditioner, and its application is a good carbon sequestration strategy involving transporting and storing carbon from atmospheric CO_2 in long-lived carbon pools to reduce the net rate of increase in atmospheric CO_2. Carbon sequestration by biochar is determined by its stability in soil and its effects on soil's organic carbon (SOC) mineralization [240,241], which must be clarified before application on a large scale in agricultural lands. Carbon sequestration and the reduction in carbon dioxide from the atmosphere have been gradually achieved in recent years with biochar, which consists of organic carbon with a low degradation rate. The presence of organic matter and its nutrients is crucial because nutrients provide essential mineral supplements for the soil [43]. Incorporation of biochar into the soil has not only been promoted as a direct carbon sequestration strategy due to its high carbon content and high strength and durability [66,242] but also as an agricultural management practice with beneficial effects on soil physical and chemical properties [17,127].

Direct measurement of SOC stocks is based on appropriate sampling and processing of soil samples, followed by laboratory analysis to determine SOC concentration [243,244]. However, detecting any measurable changes can be difficult due to the slow rate of SOC changes and the large spatial variability in soil organic carbon content [245]. SOC stocks for a given depth are estimated from bulk density, SOC concentration, and soil depth (FAO, 2019) [246]. Correct sampling depth, accurate bulk density, and SOC content measurements are crucial. In a review including 41 studies by Davis et al. (2017) [247], the sampling depth for soil organic carbon (SOC) assessment was found to range from 10 cm to 100 cm. However, IPCC (2006) [248] states that SOC measurement should be performed at the upper 30 cm depth, while FAO (2019) [246] suggests deeper soil sampling, although a shallower depth may be considered depending on the objectives of this study. The "equivalent soil mass" approach is recommended when calculating SOC stocks [246,249,250].

The mineralization of soil organic carbon, one of the important processes driving carbon exchange between the soil and the atmosphere, inevitably changes after adding biochar. However, biochar addition affects the mineralization rate of native SOC [182,240], referred to as "priming", where "positive priming" is increased mineralization of native SOC while "negative priming" is reduced SOC mineralization [21]. In the literature, the rate of mineralization due to the presence of biochar has also been reported as a "positive priming effect" [251], a "negative priming effect", and a "no effect" [252], possibly due to differences in biochar characteristics and different soil types [105]. Under certain conditions, the so-called "priming" effect may be due to a combination of several mechanisms and is related to biochar properties and soil properties (e.g., organic carbon composition and structure, pH, presence of microorganisms, etc.) [253].

Several mechanisms have been proposed to explain the positive and negative impacts of adding soil biochar on the rate of SOC mineralization (Table 3). Several studies report that the positive priming effect appeared after one and a half years after biochar addition and later shifted toward negative priming [254]. Other studies found that after biochar addition, the priming effect was negative for half a year, and there was no significant priming effect later [240,255]. Positive and negative priming effects on natural organic carbon mineralization in biochar-amended soils have been reported [256].

Table 3. Factors influencing the positive (+) and negative (−) priming SOC after biochar addition to soil.

Positive Priming (+)	References	Negative Priming (-)	References
Enhancement of microbial activity.	[21,251]	Physical protection of SOC from increased soil accumulation	[218,255]
Enhancing soil fertility with a positive impact on microbial population growth.	[257]	Limitation of its carbon availability to the microbial population due to absorption of organic matter by the biochar.	[248,254]
Application of biochar to sandy soil affected the priming SOC positively due to better soil aeration.	[182]	Inhibition of microbial activity due to toxic substances in biochar.	[258]
Application of biochar amount $\leq$15% (w/w) to the soil had better results.	[259,260]	Negative priming SOC after biochar application due to plant incorporation and root exudation.	[261]
Biochar produced at low pyrolysis temperatures using manure and crop residues as feedstock contributes most constructively to priming SOC.	[251]	Biochar application rate from 0.4% to 1.9% (w/w) to the soil.	[262]
The addition of biochar caused an insignificant effect in the first three months and then a significant positive effect after aging for six months. Accordingly, the direction and magnitude of the priming effect may vary with incubation time.	[260]		
They observed that biochar produced at 300 °C induced a positive–negative–positive initiation effect in natural priming SOC, while the biochar produced at 500 °C had a negative–positive–negative priming effect.	[263]		

Therefore, soil organic matter mineralization, one of the most important processes driving soil–atmosphere carbon exchange, inevitably changes after biochar addition [105]. Changes in soil organic carbon stocks after biochar addition are significantly influenced by actual conditions (laboratory, greenhouse, field), the presence or absence of plants, the rate of biochar application, as well as various soil properties, and the amount of biochar incorporated into the soil [239,254]. Comparing field experiments and laboratory experiments (with controlled conditions) has been found that the latter category was less representative than field investigations due to the lack of factors affecting the biochar–soil system, such as moisture, temperature, and interactions between carbon derived from biological activity, soil organic matter, and inputs due to the presence of plants [257,264]. For this reason, the overall effect of biochar addition on total soil organic carbon is difficult to estimate. In conclusion, we should take the meta-analysis of Gross et al. [96] seriously on the effect of biochar on carbon sequestration, as presented in the table below (Table 4). The current meta-analysis demonstrates that various factors are acting on the soil–biochar system.

Table 4. The meta-analysis of Gross et al. [96] on the effect of biochar on carbon sequestration.

Experiment Characteristics		Location Features	Soil Properties	Biochar Characteristics
Field study	Single or continuous application	Climatic zone	Soil texture	CEC
Laboratory study	Duration	Tillage intensity	pH	Raw material
Greenhouse	Application quantity	Crop type	SOC content	Carbon content
	Sampling depth	Additional fertilization		C:N ratio

8. Biochar Life Cycle Assessment in Soil—The Aging Process

Most research usually focuses on the technical aspects of pyrolysis rather than the type of feedstock, which plays a decisive role in the characteristics of biochar [101,265–267]. Downie et al. [268] and Kasozi et al. [269] report that the physicochemical and biological properties of incorporated biochar in soil change over time. Once biochar is incorporated into a soil system, it will inevitably undergo a series of physical and chemical processes that alter its properties and functions [13,270]. Therefore, when used as a soil conditioner, its incorporation into the soil is modified over time through physicochemical processes [108], and its properties change [271]. This process is called the "aging effect", and these changes in its properties over time have been shown to influence the impact of biochar on agroecosystem functions [162,272–274]. The process of biochar aging is a natural one. When applied to the soil, the biochar undergoes a series of biochemical interactions such as surface oxidation, mineral dissolution, and mechanical breakage [275,276]. The biochar aging process disrupts its role as a soil conditioner because various surface characteristics of biochar are altered through different biotic and abiotic factors. Biochar ages slowly, and some of the organic matter that comes from it, e.g., fulvic and humic acids and dissolved organic carbon, can move to deeper levels by leaching or deep infiltration [277].

The biochar aging process occurs in two stages, short-term and long-term. Short-term aging refers to the hydration and oxidation of its surfaces after exposure to air and soil moisture. Long-term aging occurs after applying biochar to the soil, as it is subject to effects that alter its properties. Long-term aging results from the physical and biochemical breakdown of biochar particles, salts, and organic compounds' solubilization, dissolved compounds' adsorption from the soil solution, and the neutralization of alkali over time [277]. Hammes and Schmidt [278] state that once biochar is incorporated into the soil, it undergoes a process of freeze–thaw cycles, receives the effects of rain and other microclimatic factors, the penetration of plant roots and fungal hyphae, the effects of microfauna and mesofauna (bio-irritation), and fragmentation of the particles. Biochar aging is a long-term interaction between biochar and soil lasting over six months [37]. Bandara et al. (2021) [279] refer to the aging process of biochar after its incorporation into the soil as a natural process subject to a series of biochemical interactions (surface oxidation, mineral dissolution, and mechanical fragmentation).

Natural aging can be achieved through a series of environmental processes and is a complex process with various mechanisms. The three main mechanisms are natural, chemical, and biological aging. Natural aging refers to the wet–dry cycle or freeze–thaw cycle for further natural breakdown of biochar, mainly in regions with ice and temperature variation [277,280–282]. Chemical aging involves the abiotic oxidation and degradation of biochar using H_2O_2 [283]. The effect of chemical oxidation is to increase the hydrophilicity of the biochar [278]. Biological aging occurs through biotic degradation by microbes and other organisms [280,281]. However, other aging processes exist, such as photochemical degradation through solar radiation, mild oxidation due to atmospheric oxygen, aging under the influence of radical exudates, and oxidation due to microbial activity [13]. The above aging processes result from mechanical fragmentation, surface oxidation, the release of dissolved organic matter (DOM), and the dissolution of minerals (reduced ash content).

The aging process that biochar undergoes with soil minerals and microbial activity leads to the appearance of aggregates of minerals and organic groups, which enhance the retention of nutrients [37]. Microaggregates of organic matter can be detached, and colloidal particles can move through the soil profile. Consequently, accumulation can protect the biochar and enhance the stabilization of organic matter over extended periods in the soil. Such changes could improve or decrease biochar performance for field applications and long-term carbon storage.

These natural processes cause changes in the physical and chemical properties of the biochar and, by extension, in its specific surface area, surface morphology, acidity, element composition, cation exchange capacity, and the presence of aromatic chemical compounds. Due to degradation processes, the ratio between aliphatic compounds and more stable aromatic compounds can change over time [284]. Therefore, environmental factors (microbial interactions, temperature, humidity, and mechanical breakdown) are key to its decomposition. During the aging process, the specific surface area, surface morphology, pH, and other properties will change significantly under various processes, such as freeze–thaw cycles, photochemical degradation, dry–liquid cycles, and oxidation [54,285,286].

During the aging process, changes in oxygen-containing functional groups (O), ash content, and specific surface area (SSA) are observed, which consequently affect its adsorption capacity [287,288]. The adsorption capacity is directly linked to the dissolution of the organic fractions (Dissolved Organic Matter). Biochar pores can adsorb volatile organic matter dissolved in fractions (DOM) and lead to their clogging, reducing its surface area and enhancing its polarity. Likewise, DOM can increase oxidized functional groups, with a consequent increase in CEC [289]. Guo et al. [290] observed that the Cu (II) adsorption capacity of aged biochar was lower than that of fresh biochar, possibly due to changes in the number and characteristics of functional groups and a decrease in the specific surface area of biochar.

Gronwald et al. [291] reported that seven months of aging in the field reduced the adsorption capacity of biochar by 60 to 80%. Studying the long-term effects of biochar from the soil is time-consuming since the natural aging process of biochar is prolonged. With the process of biochar aging, dissolution and leaching of soluble salts and organic compounds occur, with the result that the pH value of the soil can be gradually modified [286]. In addition, biochar aging exhibits variability in biochar functions. On the one hand, it causes a decrease in pH, a decrease in surface area, a decrease in carbon in aliphatic compounds [285,292], and a decrease in Ca and P content [279].

On the other hand, biochar aging leads to an increase in CEC and the number of oxygenated surface functional groups (carboxylic acids) through oxidation processes, an increase in monosaccharides, and an increase in Al, O, K, and Si elements [279]. Thus, aging affects the elemental composition of biochar [293–298]. Tang et al. [299] concluded that more oxygen-containing functional groups ($-$OH and $-$COC$-$) may appear on the surface of biochar under the effects of high temperature and freeze–thaw aging so that biochar can have higher hydrophilicity and polarity. Finally, little is known about the influence of soil pH and other soil properties on aging processes [284].

According to a study by Dong et al. [300], the C, N, and H contents of naturally aged biochar were much higher than those of fresh biochar, while the O content was lower. After 90 days of aging in cropland soil, biochar's specific surface area and pore volume had also grown. Furthermore, changes in biochar properties during aging processes could affect its ability to immobilize and adsorb heavy metals [301]. Biochar aging with large-scale application affected Cd bioavailability and microbial activity in Cd-contaminated soils. Both poultry-litter biochar (PBC) and sugar-gum wood biochar (SBC) improved microbial activity, decreased the amount of Cd that plants could use, and raised the pH of the soil [279].

According to research by Xu et al. [282], aging biochar reduces cadmium immobilization. Nagodavithane et al. [302] observed an increase in Cd sorption in the presence of biochar aged for 12 months compared to fresh biochar. In another study, biochar aging increased solubility due to the release of dissolved organic carbon and As availability [303]. Aging biochar, derived from sewage sludge, for more than 30 days favors Pb (II) and As (III) adsorption due to the increased density of available oxygen-containing groups [304]. Lin et al. [305] observed that aged biochar derived from peanut shells had a negative effect on Al toxicity and improved soil pH, thereby inhibiting plant growth compared to fresh biochar.

Once biochar is incorporated into soils, the hydrophobic character of fresh biochar can negatively affect soil nutrient distribution [306]. The hydrophobic properties are due to the aliphatic compounds of the tar residues, which contain a higher concentration of tar that makes them hydrophobic during their production at a low temperature. Biochar becomes more hydrophilic as it ages, allowing for more significant interaction with the soil solution. In essence, it reduces the absorption of hydrophobic organic pollutants and anionic elements while increasing the adsorption capacity of cationic elements. The biochar type, heavy metals, and soil type play a decisive role in their absorption capacity during biochar aging [279]. Furthermore, the biochar aging process affects the long-term immobilization of heavy metals in soils [307]. Biochar is subject to aging rate retardation through oxidation, which leads to the formation of carboxyl, carbonyl, phenolic, and other oxygen-containing functional groups on the biochar surface.

The aging process is different in different soil types, and there is a general lack of knowledge about the effects of aging on biochar [307]. The cycling of soil organic carbon and biochar and their interaction in soils still need to be better understood [308]. Biochar aging in soil significantly affects organic carbon mineralization [105]. Biochar aging can interact with mineral-bound organic matter, cation retention, and anion bioavailability [277]. Findings show that the direction of the biochar-induced priming effect changes over time and that the priming effect induced by fresh biochar may be different from that induced by the corresponding biochar that has undergone aging and soil modification for a relatively long time.

Further research into the priming effect that fresh and aged biochar induces is necessary [105] to evaluate biochar's effects on soil's organic carbon mineralization more precisely. Spokas [33] reports an overall increase in carbon mineralization in biochar placed in soil aged three years due to surface chemical oxidation. Li et al. [309] reported low total carbon mineralization in wheat straw biochar-amended soil aged six years due to the loss of easily mineralizable carbon during aging. Biochar aging can deplete volatile C, VOC carbon, and nutrients [277].

Biochar in the soil is subject to various natural aging mechanisms. Among them is its complete mineralization into H_2O and CO_2, which is also considered the fastest mechanism. Slower mechanisms of natural aging include biotic and abiotic aging modes with half-lives of up to 1000 years. Indeed, the long-term behavior of biochar within the soil environment has yet to be documented in sufficient detail. It is time-consuming to monitor the long-term effects of biochar application, as part of the natural aging process can be very slow.

A key disadvantage of natural aging techniques is that this process must be ascertained in the field. It will take several years for the relevant observations to be made. For this purpose, there is the possibility of simulating natural aging or accelerated aging, which can offer a shorter observation time and obtain faster results. Therefore, various artificial aging methods, such as chemical oxidation, natural aging, and biological aging, have been proposed as substitutes for natural aging, reducing the aging duration from years or months to days or hours. Long-term soil monitoring with biochar incorporation can give us information about how the incorporation of this material changes over time. Artificial aging methodologies have been created and developed to minimize this phenomenon's study time and have immediate results [107].

Artificial aging can simulate the natural aging process through natural aging [310], chemical oxidation [54], photocatalytic aging [287], and biological aging [287,288,311]. Biological senescence is quite rare in the literature, especially under the influence of soil and root biomass [13]. Li et al. [309] report results on the quantitative comparison of results between physical aging in the field and chemical aging (chemical oxidation and freeze-thaw). The results showed that artificial biochar aging methods cannot yet simulate biochar aging in soil. Compared with natural aging in the field, chemical aging tends to have a higher degree of oxidation on the surface of the aged biochar.

In contrast, the issues of oxidation inside the biochar and the introduction of exogenous elements by the oxidizing agents have yet to be fully elucidated. In this study, freeze–thaw aging only changed the porous structure of the biochar without significant changes in elemental composition, in contrast to natural aging. The most common methods for evaluating the quality and longevity of biochar are summarized below (Table 5), as are the components that affect its aging (Table 6).

Table 5. Biochar quality and longevity assessment methods.

Methods for Evaluating the Quality and Longevity of Biochar	References
Analysis of carbon content (volatile matter content) and oxidation resistance evaluation	[312]
Carbon structure analysis (elemental composition and molecular proportions) by NMR, SEM, X-ray diffraction, or spectroscopy techniques	[313,314]
Biochar incubation and modeling	[121,313]

Table 6. Components affecting biochar aging.

Components Affecting Biochar Aging	References
Composting	[315]
Incubation	[316]
Field	[289,317]
Dry–wet and freeze–thaw cycles	[282]
Hot air application	[13]
Acid wash with HNO_3/H_2SO_4	[318]
Alkaline leaching with KOH, NaOH, H_2O_2	[277,283].

9. Diffuse Reflectance Spectroscopy (VIS-NIR) in Biochar-Amended Soil

Numerous studies have demonstrated the ability of VIS-NIR diffuse reflectance spectroscopy (VIS-NIR) in biochar-amended soil to provide reliable information on the soil's physical, chemical, and biological properties. Therefore, soil condition monitoring is in high demand in precision agriculture to determine proper management practices such as plowing, fertilization, and irrigation [16]. There is a substantial need for inexpensive and sustainable methods to map variable soil properties [9] periodically. The diffuse reflectance spectroscopy technique can be rapidly and non-destructively applied to investigate the composition of food, agriculture, and the environment [7]. By extension, diffuse reflectance spectroscopy in the visible and near-infrared (VIS-NIR) has replaced laborious traditional and conventional methods in the determination of the physical and chemical properties of the soil, according to the latest publications [319].

Diffuse reflectance spectroscopy has attracted the attention of researchers in recent years because it is an analysis technique with many benefits. First, it is a technique that is easy, fast, reliable, non-destructive, environmentally friendly, simple to use, economically viable, and efficient for large numbers of samples [320,321] with little preparation without chemicals [322]. Additionally, it offers field portability, laboratory use [323], and a repeatable analytical technique used for 30 years to predict qualitative and quantitative soil parameters [16,319,324,325]. Consequently, soil spectroscopy is essential for measuring and monitoring soil and obtaining large amounts of quantitative soil information in various soil and environmental science applications [326]. Visible and near-infrared diffuse reflectance (VIS-NIR) spectroscopy can measure the intensity of reflected energy for each wavelength after irradiating sample surfaces [7]. In essence, it works based on the interaction of radiation with the components of the sample and the covalent bonds of atoms such as O, C, H, and N with the organic matter. The signal reflected from the object (e.g., soil) is based on the vibration of tiny atoms such as C-H, O-H, and N-H bonds. It produces spectral signatures defined by their absorption or reflection as a function of wavelength in the electromagnetic spectrum. However, the general complexity of the soil composition makes it difficult to use VIS-NIR diffuse reflectance spectroscopy, resulting in difficulty distinguishing the absorption patterns of specific components.

Additionally, overlapping absorption and low concentrations are inhibiting factors in measuring soil properties by VIS-NIR diffuse reflectance spectroscopy [7]. Several soil properties are reported in the literature to be accurately predicted using VIS-NIR diffuse reflectance spectroscopy [218]. VIS-NIR spectroscopy has been used for more than 30 years to investigate soil properties, including organic carbon (SOC) content [327]. Thus, this technique is more established than other spectroscopic techniques [328]. Diffuse reflectance spectroscopy is suitable for soil organic C analysis since absorption bands of organic molecules are detected within these spectral regions (Vis: 350–700 nm, NIR: 780–2500 nm). Many studies report the value of VIS-NIR in determining organic carbon or, conversely, the effect of organic matter on the spectral characteristics of soil color [324]. Maurel and McBratney [327] characterize the VIS-NIR method as suitable for the determination of soil organic carbon, and it has been successfully used to measure its concentration [329] and estimate soil stocks [330]. Furthermore, water strongly affects soil VIS-NIR spectra in the absorption bands around 1400–1900 nm and other parts of the VIS-NIR region [331]. Soil bulk density and soil water content have been predicted to a satisfactory extent using the diffuse reflectance spectroscopy technique [332–334].

So far, several soil studies using VIS-NIR diffuse reflectance spectroscopy technique have clearly shown absorption characteristics for clay, total nitrogen (N) content, and total organic carbon. However, results for soil pH, extractable phosphorus (P), potassium (K), calcium (Ca), sodium (Na), magnesium (Mg), and cation exchange capacity (CEC) ranged from moderate to excellent [335]. By extension, VIS-NIR diffuse reflectance spectroscopy is a vital assessment technique in evaluating various soil properties. Soil components that cause active spectral absorptions in the VIS-NIR spectrum region are listed below (Table 7). This spectroscopic technique also includes the VIS-NIR regions (4000–28,600 cm^{-1}) [319]. In addition, it can detect specific spectra corresponding to various substances in a wavelength range (350–2500 nm) and perform qualitative and quantitative analysis of soil components combined with artificial intelligence and machine learning algorithms [336,337]. On the one hand, coupling spectroscopic techniques with multivariate data analysis creates powerful tools for developing both quantitative and qualitative calibration models in soil science [319,325].

On the other hand, selecting the most appropriate multivariate analysis model is difficult due to the high multicollinearity of the associated wavelengths [338]. According to the literature review, the most widespread computational intelligence model for land property estimation is the partial least squares regression (PLSR) method [16]. On the contrary, Heil and Schmidhalter [338] report the minimal application of techniques such as support vector machines (SVM) and random forests (RF), machine learning algorithms in the modeling of soil properties [339]. An interesting challenge is using neural networks

(AANs) to create a spectroscopic biochar imprinting model. In general, using pre-processing techniques to remove and minimize the noise of the ground spectral data is an essential tool that improves the performance of the calibration model. On the other hand, these techniques derive through a series of mathematical procedures that can eliminate variability in light scattering phenomena and improve spectral characteristics [7].

At the same time, beyond the calibration model, the choice of spectral data pre-processing methods arbitrarily takes place. How it affects the final soil property prediction has yet to be disclosed. For this reason, many investigations have used various combinations of methods for pre-processing the raw spectral signatures—new possibilities for estimating soil organic carbon using VIS-NIR spectroscopy with multivariate modeling techniques. In addition, combined VIS-NIR spectroscopy with partial least squares regression (PLSR) has been applied to the determination of total nitrogen (Total N), moisture content, and pH [334,340–343]. In some agricultural lands, the approach based on VIS-NIR spectroscopy has also been widely used to monitor agricultural pollution, especially heavy metal pollution [344].

Thus, diffuse reflectance spectroscopy is gaining ground in the quantitative and qualitative determination of soil characteristics while ensuring soil fertility and health extension. Of course, when this technique is adequately combined with chemometric methods and machine learning techniques to create a multivariate model, a powerful tool for determining the relationship between variables and the spectral signal is produced. However, soil spectral properties are affected by soil minerals, sample moisture content, organic matter, and texture [345,346]. The relationship between spectral data and soil characteristics is rarely linear. Although VIS-NIR spectroscopy is considered an established method for estimating soil properties, there currently needs to be an accepted universal model that is widely applied [7].

Consequently, PLSR was the most common regression method used, while MPLSR performed better mainly for determining total carbon and total nitrogen. More field experiments are needed to show the ability of VIS-NIR diffuse reflectance spectroscopy to predict soil properties rapidly and effectively in the field. According to the literature review, more background is necessary to systematically show the accuracy of field measurements for most soil properties [16]. According to the literature review, the determination of the soil carbon content in the NIR spectral region has been extensively developed in agriculture [327]. Biochar content can also be measured with NIR to obtain information about the biomass feedstock by comparing spectral bands [347].

However, biochar assessments with NIR are generally qualitative, and more research and fine-tuning in infrared band selection and spectral data analysis will be needed [313]. Several literature reports have shown the ability of the combined use of spectroscopic and chemometric methods with VIS-NIR to predict physical and chemical soil properties in the last 20 years [325,348,349].

Proper management strategies should be implemented to ensure the soil's quality and health. One such sustainable and promising practice is the incorporation of biochar into the soil. Biochar presents significant advantages for environmental sustainability. Currently, most studies on biochar have been conducted in laboratories. The effect of biochar on the environment needs to be better understood. In addition, the natural environment is more complex than that of the laboratory, which results in the uncertainty of the environmental effects of biochar [350]. The positive impact of biochar on soil properties may not always be noticeable, but the material's longevity and persistence in the environment are often highlighted in the literature. Biochar is resistant to biotic and abiotic decomposition processes, and this is because it has undergone thermal conversion. A rapid, low-cost, safe method of verifying soil amendments with biochar would be beneficial [351].

However, in recent decades, soil spectroscopy has become a powerful technical analysis tool over conventional methods [319]. It can be a fast, low-cost, safe method of verifying soil amendments with biochar [351]. Qualitative spectral analysis, which reflects the degree of aromaticity of the biochar, is also helpful in supporting conclusions about the expected lifetime of the coal. The inherent variability of biochar, combined with that of the soils in which they are applied, brings the need to determine its resistance to its degradation process and its use as a carbon sequestration strategy [352]. Consequently, assessing biochar stability can be difficult when choosing an analytical approach, leading to varying and possibly erroneous conclusions. Authors investigating biochar properties often focus more on the technical aspects of pyrolysis than on the type of feedstock for its characterization. Diffuse reflectance spectroscopy is a recent biochar characterization method.

Reflectance spectroscopy has been used to predict organic carbon C [329] and other soil properties; however, a study has yet to be performed to predict organic carbon in soil with biochar. Regarding biochar analysis by reflectance spectroscopy, it was only used to predict biochar stability indices [353] without studying biochar-amended soil. Characterization of biochar properties by VIS-NIR diffuse reflectance spectroscopy is described in the table below (Table 8) and other techniques (Table 9). This technique has the potential to be used to influence soil biochar and measure changes in carbon content over time [351,354]. In a review by England and Viscarra Rossel [320], VIS-NIR was considered the most suitable and cost-effective spectroscopic technique for estimating soil organic carbon, as it can measure its concentration in soil in situ or with minimal preparation. However, the use of VIS-NIR spectroscopy to measure SOC in biochar-amended soil is lacking. Indeed, until 2020, only some studies on using VIS-NIR spectroscopy in soils were amended with biochar [353,355].

The near-infrared (NIR) spectral region includes wavelengths between 700 and 2500 nm [325,356]. Generally, diffuse reflectance spectroscopy demonstrates the presence of aromatic carbon in biochar using the 780–2500 nm spectral band. Reeves et al. [357] report that biochar addition to soil can affect the spectral signature of soil carbon. At the same time, Allen and Laird [351] and Li et al. [358] showed that spectroscopy could predict the total C of biochar-amended soils. VIS-NIR spectroscopy is promising as an alternative to the traditional quantitative and qualitative analysis of biochar properties. It is suggested that more biochar samples be examined for a robust model to discriminate biochar types at different pyrolysis temperatures [354]. The surfaces of aged biochar are oxidized, while fresh biochar may have slight surface oxidation [359], so the NIR spectra of fresh and aged biochar may differ [351].

The study by Allen and Laird [351] demonstrated the ability of NIR to quantify the amount of biochar amended in soils by accurately predicting and validating C and biochar carbon concentrations using two independent sample sets. The power of NIR to model biochar C independently of total C was demonstrated by visually observing the different correlation spectra. The research by Darusman et al. [360] reports the determination of K and N elements by the short-wave near-infrared method in two different soil–biochar mixture samples with an R2 correlation coefficient of 0.86 and 0.77, respectively. Therefore, the approach can be applied to analyze the properties of mixed soil samples with biochar rapidly. MIR (mid-infrared) absorption spectra include characteristic vibrational signals of the aromatic structures of carbon and allow it to be distinguished from soil biological organic C [361–363].

Diffuse reflectance spectroscopy can predict the total C of soils with biochar [351,358]. Fikrat Feyziyev et al. [364], using VIS-NIR (350–2500 nm) on soils in Azerbaijan, showed good predictions in $CaCO_3$ and EC but not so good in total N and pH. Mohamed et al. [365] created soil property mapping with spectroscopy, while Viscarra Rossel et al. [366] created a spectral library for predicting C, Fe, CEC, pH, and soil texture. However, the spectral data are affected by humidity variations [345,346], as highlighted earlier. Biochar affects the spectral signature of soil C. Adding biochar to soil results in spectral distortions that mask or distort the spectral signature of original soil carbon using NIR-MIR spectroscopy [258]. Another study aimed to investigate the ability of NIR spectroscopy to predict N, K nutrient content in soil and biochar using SW-NIRS [360]. Ludwig et al. (2017) [367] looked into how VIS-NIR could be used to predict SOC, N, pH, and enzyme activities in two German forest sites. They used partial least squares regression (PLSR) for SOC and N content, but it had variable results for pH values that probably depended on the data range.

Liu et al. [368], in a large-scale approach to forests in a region of China, sampled from different depths, but horizons were not separated during analysis. It became possible to accurately predict SOC content, which confirmed the feasibility of estimating forest soil parameters based on VIS-NIR spectra. Thomas et al. [9] investigated the application of VIS-NIR to predict soil properties related to humus assessment for samples from the Oh and Ah horizons. For the Oh samples, useful predictions were found for N content, C/N ratio, pH value, and base saturation. In the Ah horizon, there was satisfactory precision for C and N content, pH value, and CEC. However, the results for the C/N ratio were poor. The Oh and Ah horizons showed distinct absorption features in wavelength ranges sensitive to organic matter. Thus, we hypothesize that the much higher percentage of organic matter in the organic layers leads to the observed differences. The most basic soil properties predicted by spectroscopies are presented in the table below (Table 10).

Biochar produced at high temperatures tended to absorb more than those made at lower temperatures in the range (780–2500 nm), and this was probably associated with an increasing fraction of aromatic C content as the cracking temperature increased. However, biochar produced at the same pyrolysis temperature but from different feedstocks showed differences in spectral shape and degree of absorption [353]. Other research focused on determining the energy quality of biochar, precisely measuring ash, volatile matter, fixed carbon content, and calorific value of biochar samples produced at different pyrolysis temperatures from three selected biomass feedstocks [369].

Table 7. Soil components cause active spectral absorptions in the VIS-NIR region.

Components	References
Clay minerals	[370]
Iron oxides	[366]
Carbon, Nitrogen	[64,366,371–373]
Soil moisture	[342,374]
Cation Exchange Capacity (CEC)	[375]
Soil texture (clay, silt, and sand)	[373,376,377]
pH	[378]
Microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN)	[379]
Root density	[380,381]

Table 8. Characterization of biochar properties by VIS-NIR diffuse reflectance spectroscopy.

Biomass	Identify Properties	References
Pinewood	Lactones, phenols, total and carboxylic acids	[382]
Pine, cedar, and cottonwood wood (different pyrolysis temperatures)	Ash content, volatile matter, carbon, and pyrolysis temperature	[354]
Eucalyptus wood (at different pyrolysis temperatures)	Carbon content and volatile matter	[383]
agricultural waste (bamboo chatter, firewood, coconut shell)	Ash, volatile matter, and carbon content	[384]
25 biochar samples from different feedstocks	Determination of production temperature and content of ash, volatile matter, carbon, aromatic carbon, and H/C_{org} ratio	[353]
Eucalyptus wood	Determination of final production temperature	[385]
Pine, cedar, cottonwood	Ash, volatile matter, and carbon content	[384]

Table 9. Biochar property determination techniques.

Biochar Characteristics	Analysis Technique	References
Resource size	Scanning Electron Microscopy (SEM)	[22]
Resource allocation	Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Spectroscopy (EDX)	[386]
Size and shape	Transmission Electron Spectroscopy (TEM)	[22]
Surface	Teller Brunauer Emmett (BET) Analysis	[387]
Crystalline nature	X-ray Diffraction (XRD)	[388] [389]
Moisture and ash content	Thermal analysis using thermogravimetric analysis (TGA)	[388] [389]
pH	pH meter	[390]
Biochar content in the soil	VIS-NIR diffuse reflectance spectroscopy	[355]

Table 10. Prediction of soil properties using VIS-NIR diffuse reflectance spectroscopy.

Soil Properties	References
Organic and inorganic carbon	[323,391–395]
Nitrogen	[396]
Soil organic matter (SOC)	[377]
Soil moisture	[334]
Soil texture	[397,398]
Soil salinity	[399,400]

10. Evaluation of the Biological Activity of Biochar-Amended Soil Using VIS-NIR Diffuse Reflectance Spectroscopy

Incorporating biochar into soil enhances the presence and proliferation of several microorganisms (such as bacteria and fungi) beneficial to the soil [22]. The factors that influence the functioning of the microbial diversity of the soil also contribute in the same direction. The critical issue that needs further investigation is the relationship between biochar and soil microflora. Numerous studies conclude that the interaction of biochar with soil microbes is a necessary process that can help improve soil quality (as a soil modifier), enhancing its nutrient content, binding soil water, remediating pollutants, and making plants resistant to pathogens [22].

According to Singh et al. [401], biochar's morphology and physicochemical properties make it an excellent hub for developing and integrating the microbial community. This vital interaction between microorganisms and biochar can take place for a short or long time after the application of biochar to the soil, and the microbial characterization can be determined by the properties of the biochar [22]. It is also important to systematically assess the effects of biochar on soil microbial diversity, which is critical to soil multifunctionality [402]. The effect of soil-incorporated biochar on the microbial community varies depending on the biochar feedstock and preparation conditions [403]. The specific biomass can increase the growth of a particular microbial community and suppress others [264]. Studies explicitly addressing the interaction between biochar and soil microbial communities are scarce [63,404,405].

Soil fertility depends on holistic soil management while at the same time maintaining intense biodiversity [43]. The effects of biochar on soil organisms have been much less studied than their effects on soil chemical properties. The mechanism of the effect of biochar on the soil microbial environment still needs more investigation [57]. Soil microbial diversity is a soil property most sensitive to changes in its quality and is a critical indicator of its function [406]. Medium to high soil microbial diversity generally indicates good soil quality [96]. Biochar soil amendment is a novel, cost-effective, easy-to-implement practice that increases soil microbial activity [22]. It has been proposed to improve soil health by enhancing soil fertility by increasing or altering its microbial activity [407]. Nevertheless, the improvement of soil aeration [408], porous structure, large specific surface area, high cation exchange capacity, and high moisture and nutrient absorption capacity of biochar [404] leads to a strengthening-increasing trend of biological properties of soil by increasing microbial diversity [409], stimulating microbial activity, and creating a suitable environment for microbial load [410].

However, the indirect effects of biochar may depend on the type of soil or the type of experiments, i.e., whether the experiment is conducted in the field or with laboratory incubations [411]. When studies are conducted at different experimental sites with different soil types and climatic conditions, it will be difficult to draw a general conclusion about the direction and extent of biochar in soil microbial communities [412]. In general, the porous structure of biochar is an advantage for soil aeration and an excellent condition for aerobic microorganisms and soil biodiversity. However, there are also anaerobic organisms. In a situation where aerobic soil microorganisms consume all the oxygen in the soil, a good atmosphere is also provided for anaerobic soil microorganisms to thrive. Moreover, biochar favors the formation of aggregates and reduces the chances of soil erosion [43]. The large specific surface area of biochar is likely to lead to better water-holding capacity [413]. Due to biochar's abundant carbon and nutrient content, it is an important source of nutrition for microbial growth [381].

Biochar properties can increase nutrient storage and availability for microorganisms [404]. The oxygen functional groups of biochar adsorb cationic nutrients, preventing the loss from the soil of cationic nutrients added through fertilization [414]. For example, the increase in atmospheric nitrogen in beans was found to be enhanced by the addition of biochar to degraded soil, mainly through the mechanism of higher micronutrient availability [415]. The biochar space has been reported to provide a suitable environment for microorganisms, providing comprehensive protection. Several studies hypothesize that biochar resources function as a refuge and microbial niche for protection from natural predators [22,258]. Better adhesion and possibly physical protection of microorganisms within the pore structure explain higher bacterial growth rates with biochar. Applying biochar at high rates has been reported to stimulate changes in soil microbial community composition [416,417]. This change in microbial community composition could be explained by the increase in soil pH [418] and the addition of soluble organic C to the soil [419], leading to broader C/N ratios [184].

In general, biochar application affects the interactions between soil systems, plants, and microorganisms [408] and is an alternative practice to increase microflora for soil restoration [258,420]. In order to understand the relationship between biochar and soil microbial communities, it is imperative to study how biochar enhances soil microbial activity [22]. First, soil pH plays a vital role in the vitality of soil microbes [421]. Hardy et al. [422] report biochar's long-term effects on microbial communities' properties in arable and forest soils. Sheng and Zhu [409] investigated the response of soil microbes and the CO_2 emission potential of biochar produced from rice straw at different pH values. In the acidic soil, CO_2 emissions were higher due to higher biochar degradation, increased organic carbon bioavailability, and bacterial abundance.

In contrast, CO_2 emissions and organic carbon decreased in the alkaline soil with the enhancement of the population of oligotrophic bacteria. He et al. [4] found that adding corn-derived biochar to soil increased the number of beneficial microbial communities (actinomycetes and bacteria) due to changes in soil physicochemical properties such as nutrients and pH. Therefore, the organic coating on the biochar particles and the interaction of the biochar with other organic molecules present in the soil increases its life extension in the soil, protecting its surface from the degradation process. Thus, the formation of organic overlay is due to microbial activity [22].

Several research results agree that when incorporated into soil alone or with some fertilizer, biochar increases soil microbial biomass carbon [412] and the enzymatic activity of urease, phosphatase, and dehydrogenase [422,423]. Furthermore, Zhang et al. [424] concluded that soil amended with biochar significantly increased the microbial load (bacteria, fungi, and actinomycetes) in different soil types. The application of biochar enhanced the biological fixation of nitrogen due to the creation of favorable conditions such as pH and increased availability of nutrients [425]. Xu et al. [183], in an experiment carried out in pots with acidic soil, concluded that soil amended with biochar improved plant growth, soil pH, total carbon, total nitrogen, C/N ratio, cation exchange capacity of the soil, as well as the composition of the soil microbial community. The exact interaction mechanism between soil biological matter and organic matter is still under study and needs more investigation [426]. Research on the dynamic role of soil microbial biomass after biochar application will help to understand the priming mechanism of soil organic matter and biochar [240,427].

Biochar addition can increase soil microbial biomass and can also affect soil biological composition, affecting nutrient cycling, plant growth, and greenhouse gas emissions, as well as the mineralization of soil organic carbon mentioned above [404]. A significant component of microbial matter is microbial biomass carbon (MBC). Its spatial variation is considerable, and its presence is insignificant in total soil SOC stocks, but it contributes significantly to litter decomposition, soil energy transport, and nutrient cycling. Additionally, it is pointed out that significant increases in microbial biomass were observed only in acidic and neutral soils but not in alkaline soils [428].

Enzymes in the soil are another critical component of vital importance, as they contribute to the decomposition of organic matter, nutrient cycling, physical and chemical soil properties, vegetation, and microbial activity. This enzyme is called enzyme dehydrogenase (DHA), and its presence in the soil is not constant because it depends on the slope of the soil, the changes in the properties of the soil, its microsites, and the depth. Thus, MBC and DHA's microbiological parameters directly relate to the soil's clay and organic carbon content. Basal respiration, which indicates total microbial activity, is the measurement of the rate of CO_2 emission in an airtight jar incubated for three days at 30 °C and quantified via NaOH titration (ISO 16072, 2002). The measurement of basal soil respiration has been applied to various research studies and is an accepted key biological indicator to measure changes in soil quality, while it is often used to quantify changes in soil microbial community activity [429]. Microbial biomass is responsible for 80–90% of biochemical processes in soil and contributes significantly to carbon cycling, nutrient cycling, and energy flow in the soil system. However, microbial biomass represents only about 5% of soil's total organic carbon content. Therefore, MBC is not expected to lead to spectral observed ranges of change; Thus, predictions are directly correlated with soil organic matter [430].

Biochar tends to stimulate the activity and diversity of the soil microbial community through its porous structure, high CEC, and high adsorption capacity. The properties of biochar enhance the availability of nutrients to microorganisms and influence the processes between soil, plants, and microorganisms. Consequently, biochar incorporation into the soil increases microbial biomass. Its porosity ensures a constructive growth environment, ensuring protection from predation and desiccation. The ability of biochar to simultaneously contribute C and minerals is additionally essential. The alkaline pH of the biochar and the addition of labile C to the soil are responsible for the C/N ratio, which affects microbial activity [431]. Monitoring is necessary for the above factors concerning improving and controlling soil health.

A viable and alternative method for monitoring microbiological parameters is visible-near-infrared (VIS-NIR). According to Heinze et al. [432], the overall assessment of biological properties using VIS-NIR is insufficient, and it is unclear which soils or soil samples it can take place or how accurate these predictions can be. The results indicate that NIR spectral analyses can be used to monitor biochar application to soil [351], but C derived from biological activity cannot be accurately determined. According to the literature review, the effect of biochar on soil biological properties shows controversial results and discrepancies due to various interactions between communities of living matter, soil, biochar characteristics, and environmental conditions.

Research with wood waste biochar incorporated into a wheat crop and left in the soil for three months. The research results proved that only the pH and average respiration of the microbial substrate had significant changes [43]. Effect of rice and straw biochar on fungal and bacterial communities in tobacco cultivation: Some microbial communities increased while others decreased after soil amendment with biochar [258]. Biochar incorporation into soil affects the microbial community, microbial activity, and soil enzyme activity [433]. In a field study, adding biochar and fertilizer to the soil increased the MBC index [182]. In another study, applied biochar in acidic soil increased microbial activity and the MBC index [434]. Liang et al. [413] observed a 43–125% increase in microbial mass. Biochar soil amendment showed the highest value of microbial biomass's C:N ratio after four years of application [427]. In the meta-analysis by Zhou et al. [433] comparing 413 studies, the increase in MBC was 25%, and MBN was 22%. Its use promotes the conversion of microbial populations into beneficial fungi and rhizobacteria [151]. It also favors some pathogens to develop zoospores [184]. Its addition caused a 30.1% increase in basal respiration [435] and a decrease in dehydrogenase and esterase activity [433]. Biochar increased the AMF (arbuscular mycorrhizal fungal) index, stimulating AMF spore germination. However, other research concluded that biochar reduced or did not affect the AMF index [436]. Consequently, VIS-NIR reflectance spectroscopy also shows discrepancies in determining biological properties (Table 11).

Table 11. The spectral determination of soil biological properties.

Biological Properties	References
Microbial biomass carbon	[437,438]
Breath of the soil	[437,439]
Prediction of acid phosphatase by urease activity	[437]
Study of four enzymes (arylsulfatase, dehydrogenase, phosphatase, urease)	[440]
Ergosterol content	[437,441,442]
Prediction of microbial biomass carbon (MBC)	[443]

11. Conclusions and Prospects

Yang and Sheng [354] state that biochar characterization is a fundamental process for both its energy and ecological utility. As a soil amendment or improver, it is increasingly used and studied, as reflected in the many published research papers. The effect of incorporating biochar in the soil and, by extension, in the plant can present positive, negative, and neutral variability. This effect is due to a broad framework of various variables such as raw material temperature, pyrolysis characteristics, application, crop type, soil type, and environmental and biological stresses.

For this reason, the heterogeneity of biochar and the complexity of exogenous environmental effects and processes that take place cause a different effect of biochar, both on the soil and on plants. Using biochar as a soil amendment has led to expanding research efforts to understand its properties and how it affects the soil. It is known from the international literature that two main categories of factors affect biochar's stability in the soil. These categories include intrinsic biochar properties and soil conditions. However, this may provide us with a potential opportunity to use biochar with properties better suited to a specific soil type, specific hydrological characteristics, climatic conditions, and land use [24]. The beneficial effects of biochar on soil have been widely highlighted. However, some studies show that the application of biochar to the soil had a negative effect, and this is because there is a complete lack of characterization of the physicochemical properties of the biochar surface. For this reason, detailed information about its structure and physicochemical properties should be provided before incorporating it into the soil. Its stability in the soil makes it a material that will remain unchanged and durable for many years. However, its residence for prolonged periods changes its physical and chemical properties and affects soil properties.

Although the number of studies related to biochar is increasing, its long-term impact on the environment has been much less investigated compared to other research areas, such as its use as a soil conditioner. Further research is needed to better understand how aging due to both abiotic and microbial processes in the soil will affect the C sequestration potential of biochar [292]. Many studies have evaluated the effect of fresh biochar on the agroecosystem. Few studies have investigated how agroecosystem functions are affected as biochar undergoes aging [162,274,444], particularly assessing and determining properties using VIS-NIR diffuse reflectance spectroscopy. Diffuse reflectance spectroscopy (VIS-NIR) (0.25 μm to 2.5 μm) is an emerging and promising non-destructive technique providing information about soil properties. In addition, the factors affecting the wettability of biochar have been poorly investigated [284], suggesting that biochar production and the possible pretreatments that take place should be tailored specifically for the soils to which they will be applied. The most suitable material for its longevity and environmental carbon sequestration should be recommended.

Therefore, applying appropriate biochar to the appropriate soil type should be considered when seeking improvement in a specific soil function. In addition, the biochar application rate, soil conditions, and agro-climatic conditions are very different, thus making it difficult to fully document the potential of biochar to increase crop productivity and help address climate change. Therefore, it is crucial to investigate how variations in microclimatic conditions, soil type, soil pH, soil nutrients, and biochar type affect the performance of specific crops [77]. Many studies have reported that biochar stimulates soil microbial activity, but very little is known about changes in microbial activity due to biochar aging, especially in soils contaminated with heavy metals. On the other hand, soil microorganisms play an essential role in the biochar aging process [287]. The degree of biochar's effect may change with the aging process. Currently, there are no widely accepted guidelines for producing and using biochar [279].

Soil management practices, which ensure appropriate crop growth conditions and quality conditions, require systematic and continuous monitoring of soil properties. The soil's complex chemical, physical, and biological changes require modern, reliable, and rapid analysis and characterization methods. Therefore, it becomes imperative that modern agriculture provides alternative soil property assessment methods to ensure soil productivity and health using sustainable management strategies such as biochar. Conventional land property assessment methods are time-consuming and expensive.

However, reflectance spectroscopy is a relatively modern method that is easy to use and provides rapid property prediction, providing information on soil health. This non-destructive method has been successfully used to predict soil properties. However, the systematic monitoring of soil properties gives us a wealth of information to determine how to manage the plot and reliably ensure all the appropriate conditions for growing crops and maintaining soil quality. Information about soil type and fertility is an important criterion for soil management and applying precision agriculture techniques. To ensure a sustainable economy, in the context of sustainable development and soil sustainability, biochar can contribute positively to implementing good agricultural land management practices. It should be investigated how the presence of biochar in the soil can affect the assessment of various soil properties by DSR and whether biochar incorporation and retention can be spectroscopically mapped spatially (e.g., different climatic conditions, different types of soils) and temporally. Further research is needed to investigate the mechanisms of organic carbon mineralization (priming effect) caused by fresh and aged biochar [105].

Consequently, research is needed to confirm whether soil texture affects soil biochar stability [105]. Furthermore, there is a lack of knowledge, and the effects of biochar on soil properties at neutral or alkaline pH should be evaluated [209]. The establishment of innovative methodological approaches will help determine biochar–soil–climate system interactions [43]. At the same time, there is a need to detect biochar interactions with climate factors in long-term field experiments at a larger spatial scale [125]. Typically, researchers choose to study the biochar–soil relationship in the field less often than in a smaller-scale laboratory or greenhouse setting. As the results of such surveys differ from the corresponding field surveys due to variations in soil properties under actual environmental conditions, it is essential to conduct more field experiments [209]. In general, most studies evaluating the effect of biochar on soil properties were conducted over less than two years. This is why it is important to conduct long-term studies, as the properties of biochar can change with the aging process. Longer-term studies will provide an increased understanding of the impact of biochar over time on soil properties and help define timeframes for its reapplication.

Appropriate biochar production methods [13] should be designed with complete characterization, and the performance of biochar-amended soil with different properties and application rates should be examined. However, artificial intelligence and machine learning have been proposed to select the appropriate raw material and effective biochar [445,446]. In general, there is no knowledge about increasing the sustainability of biochar and its long-term use in carbon sequestration [447]. In addition, research studies should more often incorporate comprehensive economic analyses in addition to the studies of biochar effects on soil quality, plant physiological indicators, and nutrient management [95,448–450], which are more commonly done. Diffuse reflectance spectroscopy has not been widely used for soil biological properties [353], but studies on the impact of biochar aging on soil microbial communities are also limited [13]. By extension, a systematic study is required to examine the effect of biochar aging on the microbial community [279]. More research is needed to find critical variables and optimize the biochar production process to develop an optimal model with machine learning to help predict its performance [451].

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