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Biochar Application in Soil Management Systems

Theophilus Olufemi Isimikalu

Abstract

Due to its potential for improving soil fertility and reducing greenhouse gas emissions, biochar is frequently used as a soil amendment. This chapter presents an overview of its application and soil conditioning mechanisms as a technique for long-term carbon sequestration and lower greenhouse gas emissions, as well as an option for improving soil fertility. It focuses on biochar amendment for improved soil properties that support plant nutrient uptake and crop yield improvement, soil properties and biochar carbon sequestration dynamics, biochar degradation processes, and soil interactions and conditioning mechanisms that influence biochar carbon stability in soils. Current biochar stability assessment techniques used in academic studies are also addressed, along with their suitability for use with various goals and situations.

Keywords: biochar, soil, management

1. Introduction

Sustainable soil management in agriculture aims at developing economically sound and environmentally safe crop management systems that build the quality of soils while being utilized for food production. Such systems are associated with efficient management of soil organic carbon (SOC) and soil fertility, the credible measurement of which Lal [1] regarded as an indicator of soil quality and health. Biochar, which the International Biochar Initiative defined as a solid material derived from the thermochemical conversion of biomass in an oxygen-limited environment, has received wide attention in the past two decades for its documented potential to improve soil fertility and mitigate greenhouse gas emissions.

Studies report that biochar application can enhance soil fertility, reduce greenhouse gas (GHG) emissions [2], increase stable carbon forms in soil [3], improve nutrient and water retention, reduce heavy metal toxicity [4], and increase soil ability to suppress soil-borne pathogens. Woolf et al. [5] stated that the use of biochar in soil could mitigate as much as 1.8–9.5 Pg (10^{15} g) carbon dioxide carbon emissions annually, globally.

Biochar's soil fertility improvement mechanism is through the manipulation of soil properties such as increased soil microbial activity, soil water holding capacity, soil porosity, soil reaction (pH), soil aggregation, soil organic carbon, among others. When these soil physical and chemical properties are improved, soil nutrient retention and uptake to support plant growth improve. Many studies have reported

increased agronomical crop performances following biochar amendment such as in Asai et al. [6]; likewise, others, including Butnan et al. [7], have reported none or unfavorable crop yield responses.

A suppression of greenhouse gases emission is another benefit of biochar addition to soil that has been widely proven in earlier research [8, 9]. Biochar's production in an oxygen-limited environment gives it a chemically recalcitrant carbon-rich solid property, being produced from biomass by heating in an oxygen-limited environment. Although biochar is expected to be largely resistant to biological degradation, research shows that some of its components are relatively easily biodegradable. Thus, several studies have examined its soil and crop yield improvement, and carbon sequestration potential, and widely varying responses have been reported [10, 11]. This has resulted in varying mean resident time (MRT) estimates of biochar-C, ranging from decadal to centennial scales.

The stability of biochar in soil is of high importance to its use as an organic amendment. Lehmann and Rondon [12] defined stability as the determining factor on how long C in biochar will be sequestered (remain in soil) to mitigate climate change and how long a biochar material will continue to benefit soil and plants. The wide variation in research observations has made it very hard to generalize findings on biochar-C stability in soils and thus makes it very important to study its stability in individual soils and under peculiar prevalent environmental conditions. Currently, variations in biochar effects in soils have been attributed mainly but not solely to soil properties such as soil texture and mineralogy, feedstock material, production conditions, environmental characteristics, and the interaction of these elements. Of these factors, biochar feedstock and production conditions are two factors more easily controllable in biochar use in soil.

1.1 Biochar production and basic properties

Biomass pyrolysis is generally classified according to the rate of reaction into slow, fast, and flash pyrolysis. Through the pyrolysis process, biomass can be transformed into bio-oil, syngas, and biochar (the percentage of each component depends on the pyrolysis condition). The two major thermal conversion processes widely used in biochar production, however, are slow and fast pyrolysis [13]. Slow pyrolysis is most widely used and carried out at lower temperatures ($\sim 350^{\circ}\text{C}$) and heating rates and longer residence times compared with fast pyrolysis ($\sim 1000^{\circ}\text{C}$), which optimizes biochar yields over energy production.

Lehmann [8] among other researchers found that the chemical and physical properties of biochar depend majorly on the properties of the original feedstock material and the production conditions (essentially temperature and charring time). Ogawa et al. [14] described biochar chemical structure as one containing different aromatic C structures and considered it a transitional form with intermediate properties between carbohydrate-based biomass and graphite carbon that can appear as a microcrystalline structure. The chemical structure also contains macro-, meso-, and micro-pores, which are derived from cellular fractures of plant cells. Downie et al. [15] similarly characterized biochar as having large surface area, which in addition to its chemical properties and structure gives it high sorption capacity as is the case with other organic compounds. Its composition is widely differentiated into a relatively recalcitrant C, labile (leachable C) and ash (**Figure 1**).

Schmidt and Noack [16] reported that the chemical difference between common OM sources and biochar is that it contains a higher proportion of aromatic carbon that has a fused structure, which differs from the aromatic structure seen in other

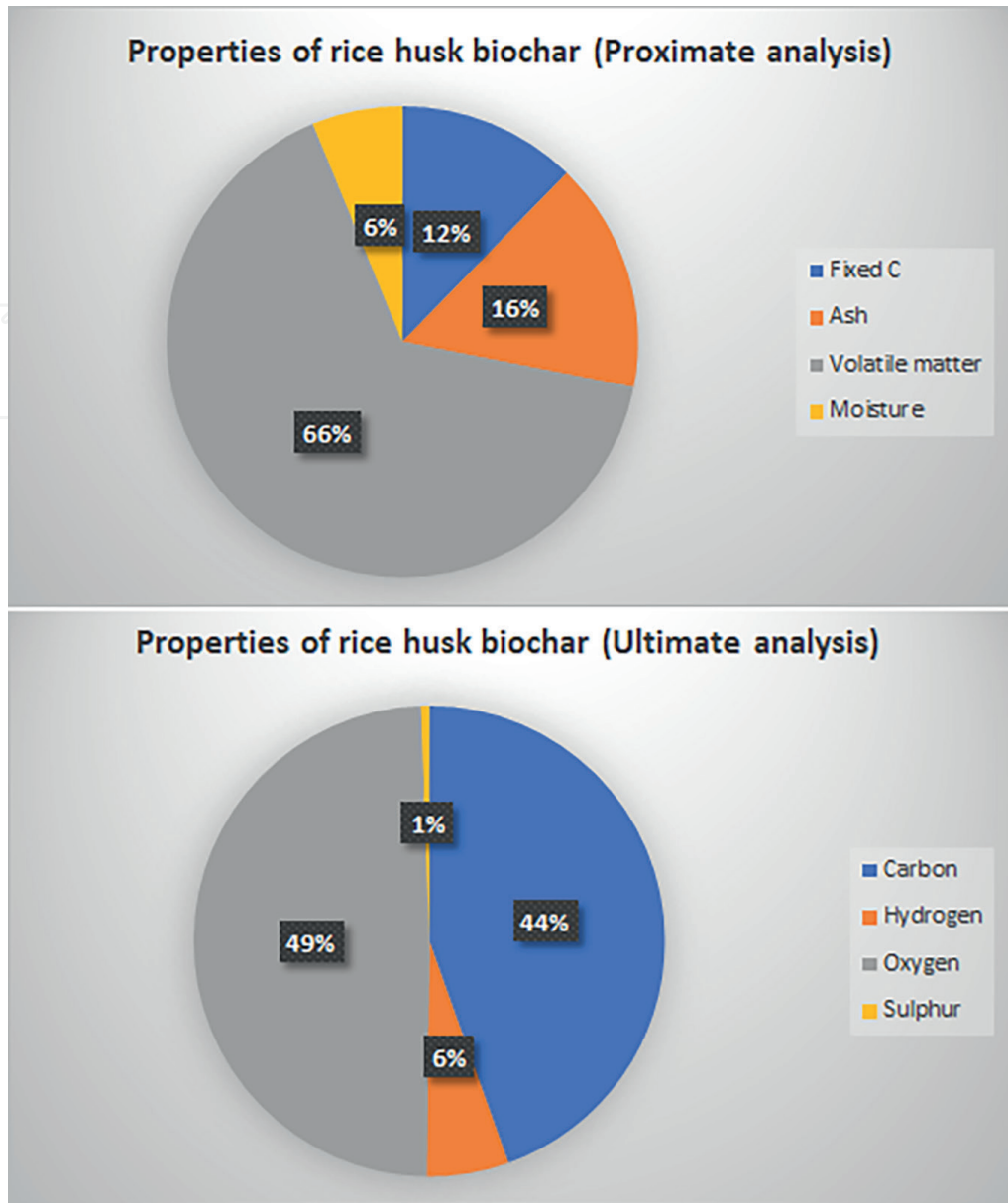


Figure 1.
Biochar properties analyzed using proximate and ultimate analytic procedures [9].

OM sources such as lignin. The fused aromatic structure can also vary, depending on the production temperature. Nguyen et al. [17] stated that these forms can include amorphous and turbostratic C, which occur at low and higher pyrolysis temperatures, respectively. It is this C structure that gives biochar the chemical stability that makes it hard for microorganisms to readily utilize its C, N, and possibly other nutrients it contains as energy source (**Figure 2**).

Lehmann and Joseph [19] reported that a fraction of biochar may be readily utilized or leached, and this fraction depends on the biochar type. Steiner [20] also noted that biochar may stimulate microbial activity and increase their abundance in soil due to its composition of essential macro- and micro-nutrients, which may serve as biological energy substrate. Some of the most important research applications of biochar-aiding soil functioning are as follows: (1) the improvement of soil fertility and adequate biomass production, (2) storage and cycling of carbon, and (3) alleviation of chemical toxicity and sustenance of soil biodiversity. Ever-increasing human populations and the attendant pressures on soil resources have resulted in extensive

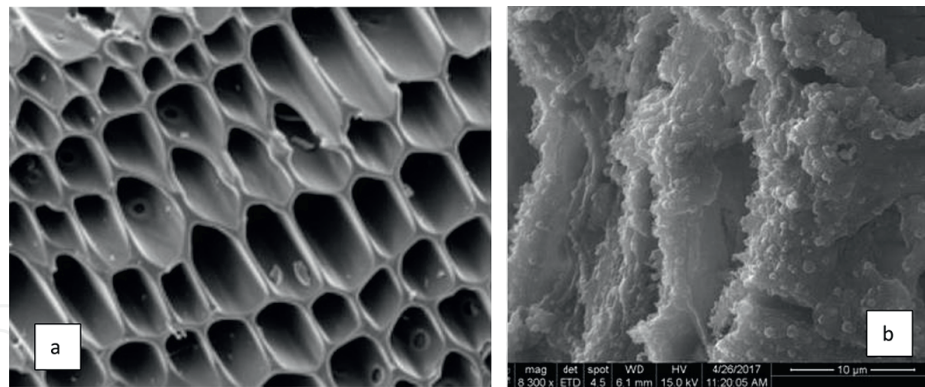


Figure 2.
a. Microscopic imagery of fresh wood biochar; b. imagery of the surface of aged wood biochar (image source: Joseph et al. [18]).

use of pesticides and other intensive management techniques, which has negative climate change impact, and threatens soil quality and human survival. These factors make the aforementioned potentials of biochar highly attractive in agricultural production today.

2. Biochar applications in soil management systems

This section discusses the applications of biochar along soil fertility and crop yield improvement, carbon storage and cycling, and soil remediation potentials of biochar. **Figure 3** shows biochar processes in the environment.

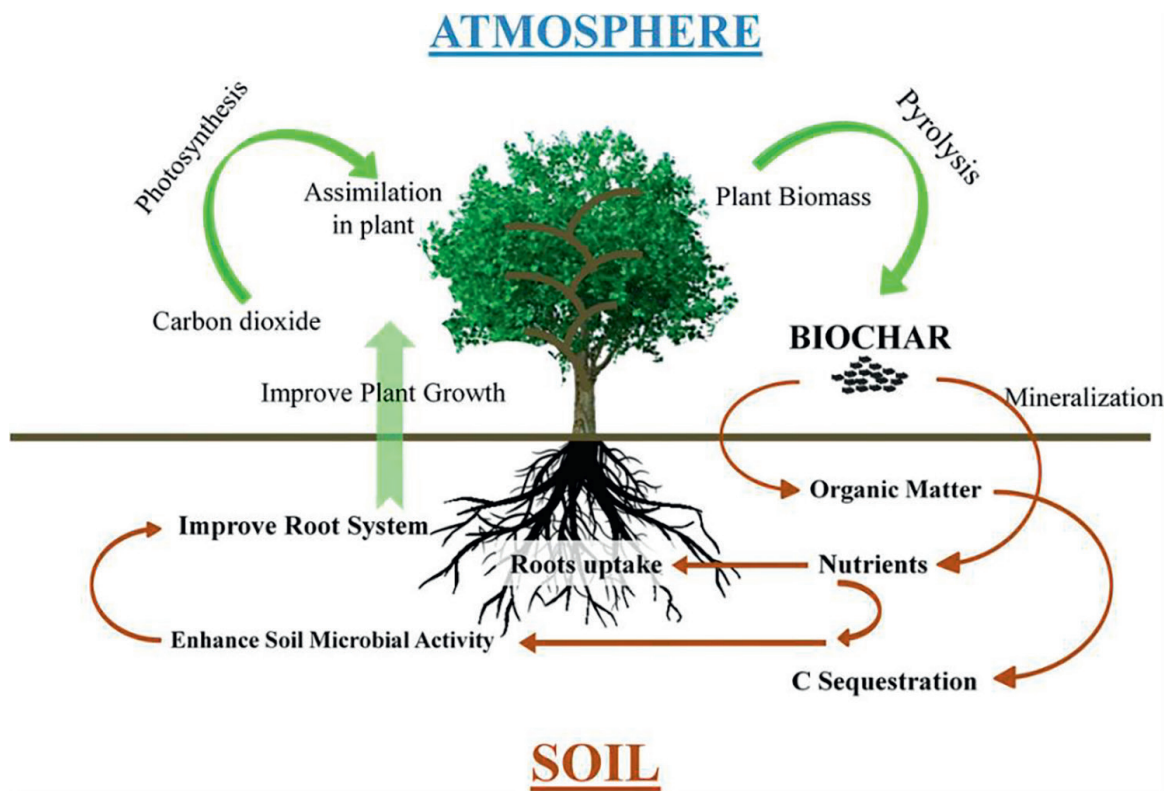


Figure 3.
Applications of biochar in soil (image source: [21]).

2.1 Biochar application for soil fertility and crop yield improvement

Improvement in crop yield following biochar amendment has been reported in many previous research studies such as that of Rondon et al. [22] in acidic and weathered tropical soils. Few numbers of research studies such as Husk and Major [23] have also reported positive effects in highly fertile temperate soils. In a meta-analysis, Biederman and Harpole [24] analyzed results of 371 individual studies and found that biochar amendment resulted in higher above-ground crop productivity, soil microbial biomass, K^+ concentration in plant tissue, rhizobial nodulation, soil N, P, K^+ , and C in comparison with control conditions. There was, however, no obvious trend in soil productivity with biochar addition, and crop productivity varied with increase in application rates. **Figure 4** shows the properties of biochar from different feedstock materials.

In addition to the neutral or negative effect of biochar recorded in some previous studies, there also appear to be an upper limit beyond which biochar addition does not result in improved crop productivity. Lehmann et al. [25] reported that crop responses to biochar addition were positive at rates up to 55 t/ha, while a reduction in growth was recorded at higher application rates. Rondon et al. [22] on the other hand reported a much higher threshold of 165 t/ha. According to them, biochar application of >165 t/ha to a poor soil in a pot experiment resulted in yield decrease that equaled to that of unamended control.

Some other authors have reported yield decreases at lower levels of application. Asai et al. [6], for example, reported the highest rice yield at 4 t/ha biochar application rate in comparison with 8 and 16 t/ha. They reported that yields dropped to the level of the control treatment at 16 t/ha application rate. Jeffery et al. [26] reported that more positive responses from biochar addition to soil have been reported in pot than in field experiments, in acidic than in neutral soils, and in sandy than in loam and silt soils. Increases in yield in comparison with controls range from <10 to >200%.

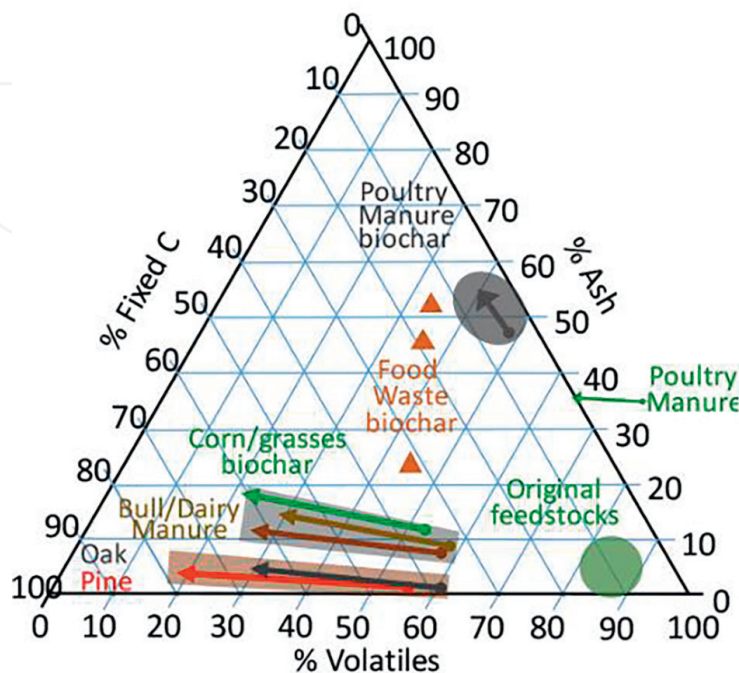


Figure 4.
Approximate properties of biochar derived from different feedstock materials (image source: Joseph et al. [18]).

2.2 Biochar carbon sequestration dynamics

Woolf et al. [5] and other authors have proposed biochar use in soil as a means of long-term C sequestration and reduced GHG emission. The main mechanism of biochar-C sequestration is through its incorporation into soil as a highly stabilized C produced through pyrolysis of biomass. Because pyrolysis progresses in the absence of oxygen, the C content of feedstock material is locked in the biochar, which is then applied to soil. Although Lehmann and Rondon [12] reported up to 50% loss of biomass C in biochar production, they reported that a considerably greater fraction of the locked stable C in biochar remained in soil for longer time periods in comparison with direct biomass input in agricultural fields.

Woolf et al. [5] also suggested another potential C negative benefit of biochar as the reduction in emission of CO₂ through reduced fertilizer demands to achieve crop yields. This idea is premised on the potential of biochar to improve soil water and nutrient retention capacity of soils. In addition to CO₂ emission reduction, Spokas et al. [27] reported reduced N₂O emission following biochar addition, and Leng et al. [28] reported that biochar addition resulted in reduced methane (CH₄) emission from agricultural soils through the improvement of soil aeration and reduction.

In a meta-analysis, Wang et al. [29] showed that biochar application could stimulate soil CO₂ emissions by as much as 28–32% and revealed that average biochar decomposition rate in studies lasting for <6 months was 0.023%/day. This suggests possible priming effects of biochar on SOC or other indirect interactions resulting in CO₂ emission from soil following biochar addition. CO₂ losses observed in previous research studies following biochar amendment vary widely, and attributed causes include variations in biochar feedstock, production conditions, duration of experiment, and environmental variables.

While Bruun et al. [30] reported cumulative C loss of 2.9 and 5.5% in a sandy loam amended with wheat straw biochar produced from slow and fast pyrolysis, respectively, some other studies such as Fang et al. [31] have reported lower biochar C mineralization rates of 0.1–3% of applied biochar-C mineralized per year. In summary, the carbon sequestration value of biochar is hung on its degradation in soil and the environmental factors that influence it.

2.3 Biochar-pesticide interactions in soil environments

Despite the fact that biochar was initially developed as a soil amendment because of its beneficial effects on carbon sequestration, greenhouse gas emissions reductions, and soil fertility improvement (Spokas et al., 2009) [32], it has recently drawn more attention for its potent ability to lower the bioavailability of pesticides [33, 34]. It has also been acknowledged that the presence of biochar in soil influences the nature of sorption mechanisms and the bioavailability of pesticide residues for living organisms in addition to improving the sorption of various pesticides [35].

By reducing the leaching of sprayed pesticides, the use of biochar in agricultural soils near bodies of water may also successfully lower the risk of pollution of subterranean water [33, 36]. Pesticide sorption ability of biochar have also been reported in previous research [37]. This is accomplished by using biochar's impacts on pesticide adsorption mechanisms and desorption behavior as a powerful tool to alter pesticide bio-accessibility and toxicological effects.

The repair of contaminated soils has been proposed using procedures such as soil washing, soil flushing, bioremediation, and soil vapor extraction. However, due to limited effectiveness, high maintenance costs, fertility loss, nutrient leaching, and soil

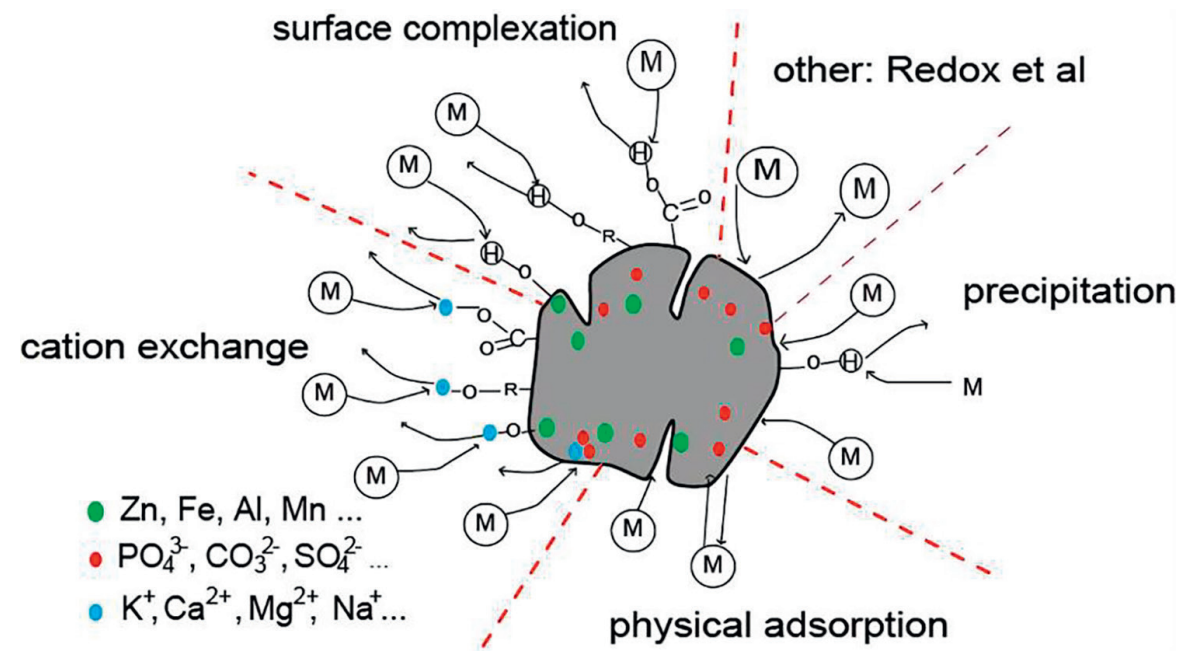


Figure 5.
The removal mechanism of heavy metals by biochar [41].

erosion, among other factors, these approaches are typically inapplicable in field settings [38]. Application of biochar as an *in situ* form of amendment for contaminated soil has thus shown promise as a method that represents a financially prudent alternative to address remedial demands [19].

By (1) binding pesticides to minimize their potential motility into water supplies and living beings, and (2) supplying nutrients to encourage plant growth and drive ecological restoration, biochar is a less disruptive approach of remediating pesticide-contaminated soil [39]. Additionally, applying biochar to soil requires only a small amount of pretreatment because it is an organic substance made from biological matter [34].

Khoram et al. [40] studied the functions of biochar in fundamental processes of pesticides in the environment and summarized those roles in remediating pesticide-contaminated soils as follows: (1) enhancing pesticide adsorption capacity; (2) reducing desorption and mobility of pesticides in soil layers; (3) reducing the amount of pesticides that are bioavailable in soil pore water, which is thought to be the portion that is bioavailable to soil organisms; (4) enhancing soil microbial activity by supplying necessary nutrients; and (5) enhancing soil physicochemical characteristics such as pH, CEC, and water holding capacity. Biochar amendment has also been shown to help in the remediation of heavy metal pollution in the environment (**Figure 5**).

The mode and other application variables of biochar to soil are a group of significant parameters that affect biochar reaction and stability in soil. It is thus important to be mindful that the complete lifecycle costs of handling and using biochar at scale must be kept as low as possible in order to maintain biochar management as a carbon-negative practice.

3. Mode, frequency, and rate of biochar application to soil

Wide-varying application rates have been used in previous research, ranging from <5 t/ha to >100 t/ha. IBI (2010) in its biochar fact sheet recommended rates



Figure 6.
Particles of biochar derived from different feedstocks.

of 2–22 t/ha in field trials and lower levels of 2–5 t/ha for large-scale agricultural use. Handling and application should generally determine particle size. The adsorption of ammonium and hexavalent chromium ions from aqueous solution was found in tests to be more effective with fine biochar particles [42, 43]. **Figure 6** shows biochar particles derived from different feedstock materials.

Comparative studies on soil fertility revealed that cowpea biomass production and nutrient uptake were unaffected by biochar particles with diameters of 1 or 20 mm [44] and 10 mm or less [45]. The specific surface area and the resulting accessibility of binding sites in biochar are, however, characteristics that are expected to vary depending on particle sizes and should be considered in biochar application to soil. A thorough understanding of the relationship between the properties of biochar and its applicability will allow for the establishment of appropriate process conditions to produce a biochar with the desired characteristics.

Currently, there are no standard application rates of biochar to soil for different agricultural aims due to varying responses from numerous tests. Variabilities result from biochar feedstock material and production conditions, among others factors as discussed earlier. These factors influence biochar characteristics including nutrient levels, ash content, carbon recalcitrance, etc., which all influence application rate. Due to the expected recalcitrance of biochar in soil, researchers such as Major et al. [46] suggest that a one-time application could provide positive benefits for more than one growing season.

Studies have, however, shown that unless a biochar material is derived from manure or is blended with nutrient-rich materials, it may not substitute for chemical fertilizers. Research has also shown that the level of biochar application to soil affects soil processes such as carbon dioxide (CO₂) emission rates [9], which is an important aspect of biochar use for carbon sequestration in soil.

4. Biochar-soil interaction and soil conditioning mechanism

Soil response to biochar has been shown to be a complex physical, chemical, and biological interaction. Kuzyakov et al. [47] among other authors report that the type and rate of interaction between biochar and soil depend on factors such as feedstock composition, conditions of the pyrolysis process, biochar particle size, soil properties, and local environmental conditions. Also, Mukherjee et al. [48] stated that biochar surface area has aromatic and aliphatic functional groups, which facilitate direct and indirect bonds

with soil organic and mineral phases to form complexes in the inner core of biochar material. This complex formation may occur through specific bonding between biochar surface functional groups and soil mineral phase, sorption of soil OM on biochar-mineral phase, or through metal-organic cation bridging. Six et al. [49] in an earlier study showed that specific bonding of soil OM and minerals can inhibit the microbial decomposition of soil organic matter (SOM) and enhance aggregate formation.

To measure the influence of production conditions on biochar-C stability, Bamminger et al. [50] applied maize silage biochars produced through pyrolysis at 600°C and hydrothermal carbonization at 220°C to a forest and an arable soil. They reported that 13–16% of the hydrothermal-produced biochar was mineralized in 8 weeks, and the char exerted a positive priming effect on native SOM. On the other hand, 1.4–3% of the pyrolysis biochar was mineralized and a negative (–24 to –38%) priming effect on native SOM was recorded.

Due to the wide variations in mineralization rates of biochar in different research, biochar-C MRT varies widely in the literature. While Keith and Singh [3] in a 3-month soil-biochar incubation experiment reported MRT of 62–248 years, Murray et al. [51] reported half-life time of between 22 and 1506 years, and Wu et al. [52] reported MRT of 617–2829 years. The majority of differences in observations were attributed to influences of biochar, soil, and environmental properties.

4.1 Biochar-soil texture-soil mineralogy interactions

Kleber et al. [53] stated that clay type, functional groups and their distribution, the concentration and composition of cations and anions, and the polarity of soil compounds are some of the important factors that determine the interactions between OC and clay mineral surfaces in soil. They further highlighted the possible mechanisms of biochar/minerals interactions in soil such as cation bridging, ligand exchange, H bonding, and direct electrostatic interactions through hydrophobic and hydrophilic interactions. Lehmann and Sohi [54] also suggested that biochar-C may be concentrated within soil microaggregates, which supports the proposal of organo-mineral associations to enhance biochar-C stability in soil.

Brodowski et al. [55] reported higher stabilization of biochar-C in soils of higher clay content. Fang et al. [31] also observed the lowest biochar-C mineralization in a clayey Vertisol and higher mineralization in sandy clayey loam Entisol and sandy Inceptisol. They stated that oxides and oxyhydroxide minerals in an Oxisol contributed more to biochar-C stabilization than smectic minerals in the Vertisol. Research results in contrast to these findings have also been reported. Wattel-Koekkoek et al. [56], for example, in their study reported that there was no relationship between OM content in the clay-sized soil fractions and soil clay mineralogy in six kaolinite- and smectite-dominated soils obtained from different countries.

5. Biochar degradation processes

Many research studies have shown that the mechanisms of biochar degradation in soil are similar to those of other OC sources in soil. They categorized biochar degradation mechanisms into biotic and abiotic oxidative and nonoxidative degradation, and loss due to other phenomena. The biotic degradation path involves the breakdown of biochar materials by soil microorganisms, while the abiotic path

involves the surface oxidation and bulk oxidation of biochar confirmed by the fact that CO₂ consumption correlates strongly with oxygen consumption during incubation experiments [57].

Another evidence of abiotic oxidative biochar degradation is the report of Bruun et al. [13], which showed that during incubation experiments, there is a lack of lag phase in the release of CO₂, which would be expected if soil microorganisms are inoculated in incubation samples. Investigations on the oxidative degradation of biochar by Nguyen et al. [17] also reported a permanent increase in C loss following temperature increase from 30 to 60°C. The increased biochar mineralization despite temperatures that are unfavorable for soils microorganisms suggests the presence of an abiotic degradation pathway.

Many research studies have shown that biochar addition to soil results in an immediate increased CO₂ emission that lasts for about 14 days after which it decreases exponentially. As is the case with mineral weathering, water availability, which plays a major role in soil processes such as hydration, hydrolysis, dissolution, carbonation, and decarbonation, is also expected to affect biochar weathering in soil and soil biota activities. Rates of these reactions are expected to depend on the nature of the reaction, biochar type and properties, and pedo-climatic conditions. This is demonstrated in the study by Isimikalu et al. [58], which evaluated the effect of soil moisture and temperature on biochar C degradation. In their study, they found that C mineralization declines under elevated moisture and concluded that C losses relating to soil water may be more connected to the leaching of dissolved organic carbon.

In a meta-analysis, Wang et al. [59] discovered that the amount of soil clay, the length of the experiment, the feedstock, and the temperature of the pyrolysis all significantly affect the pace of biochar breakdown. The MRTs of the labile and recalcitrant biochar C pools were calculated to be around 108 days and 556 years, respectively, with pool sizes of 3 and 97%. The findings demonstrated that only a tiny portion of biochar is accessible for degradation and that a significant portion (~97%) directly contributes to long-term carbon sequestration in soil. Additionally, they discovered that the mineralization of soil organic matter (SOM; overall mean: 3.8%, 95% CI = 8.1–0.8%) was modestly delayed by the addition of biochar in comparison with soil without the amendment.

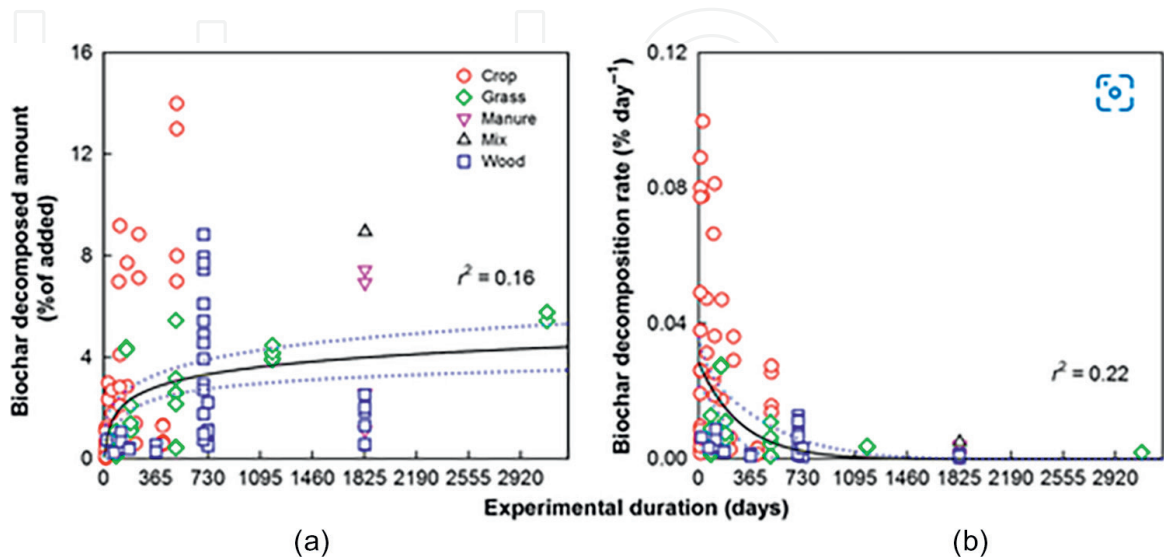


Figure 7. Relationships between the decomposed amount (A) and rates of decomposition (B) using 128 observations of different feedstock biochar-derived CO₂ from 24 studies with stable (¹³C) and radioactive (¹⁴C) carbon isotopes. The dotted line indicates the 95% confidence band (source: Wang et al., [59]).

The C storage value of biochar materials is commonly assessed by the fraction of biochar-C that remains in soil for >100 years [60]. This proposition is based on the 100-year time horizon used in assessing the global warming potential of GHGs following IPCC [61], which is used in defining permanence in carbon offset. To determine longer-term stability from short-term measurements (research), data are extrapolated to 100 years' duration. **Figure 7** shows biochar decomposition trends in from several studies and feedstock types.

6. Biochar stability testing methods

IBI [60] categorized biochar stability testing methods into three: alpha, beta, and gamma methods based on the measuring techniques and working principles of the systems. Also, Leng et al. [62] categorized and ranked C stability testing methods into three as follows: analysis of biochar-C structure and composition, determination of biochar oxidation resistance, and evaluation of biochar persistence through incubation and modeling. This classification corresponds to alpha, gamma and beta methods, respectively, under IBI [60] categorization.

According to Leng et al. [62], only biochar persistence measurement through incubation and modeling gives the specific duration of biochar-C in soil and thus regarded it as the core method of biochar stability assessment, which serves as the basis of the other two methods. This is because analyzing biochar-C structure, composition, and oxidation resistance only shows a relative stability and not the actual persistence unless they are correlated with incubation and modeling data.

6.1 Alpha biochar stability measurement methods

Alpha methods are the cheapest and are used to execute routine estimations of biochar stability. The methods are time conserving—in the range of hours, and two of these alpha methods are mainly used in scientific research. These are the determination of volatile matter (VM) content and determination of hydrogen to OC (H/C_{org}) and oxygen to C (O/C ratio) molar ratio [60]. They are regarded as indirect methods of stability measurement and require calibration using a beta or gamma method.

6.2 Beta biochar stability measurement methods

Beta methods of biochar stabilization measurement currently most used in research studies are the laboratory and field-based incubations and to a lesser extent, the field-based chronosequence measurements [60]. Beta methods are applied in combination with modeling in order to estimate biochar loss and stability over a period much longer than the incubation duration. An attribute of these methods is that they directly quantify biochar loss over a certain time period. Using the knowledge gained by the beta techniques, an alpha method can be calibrated to provide a quick tool to estimate biochar stability. The time required to conduct a beta stability test is, however, much longer in comparison with an alpha test, and they consequently cost more.

6.2.1 Laboratory and field incubation studies

Incubation experiments could be executed in a laboratory environment or in natural field conditions. In laboratory incubation, soil samples are incubated in the

absence of plant roots. In the field, however, CO₂ emissions may represent C decomposition and root respiration. In order to separate CO₂ sources in this type of studies, isotopic labeling of C is required, which both requires intensive instrumentation and costs that may not be readily available to researchers.

Zimmerman [57] showed that many studies use a simple evaluation that measures the total CO₂ efflux that does not require CO₂ source measurement. In such an assay, biochar-C mineralization is not separated from SOC mineralization, and the priming effect of each component on the other cannot be assessed. A common way of determining C loss from different sources in this type of trial is to deduct C loss under control treatment from losses under amended treatments.

6.2.1.1 Incubation duration

The trend of C mineralization from previous studies shows that C decomposition decreases until it reaches a constant rate 600–700 days after incubation. This, according to Chao et al. [63], possibly indicates that the biochar-C left may have a higher level of stability. Due to this phenomenon, incubation duration is seen as an important factor in biochar stability determination. The effect of this is that longer incubation time results in higher MRT owing to the lower rates of mineralization used for modeling. Generally, C mineralization experiments have lasted from 14 days to 8.5 years in the study by Kuzyakov et al. [64].

Kuzyakov et al. [64] in their 8.5 years' research reported that labile form of biochar-C was mineralized almost completely after about 3.5 years of incubation, and only about 6% of added biochar-C was mineralized in 8.5 years. Leng et al. [62] among other researchers therefore suggest that studies spanning less than 2 years may only reflect the mineralization of the labile component of biochar-C and recommend care in extrapolating C MRT with such data to avoid underestimation. Long duration of experimentation allows a long enough time to discriminate labile and recalcitrant C pools, which facilitates the use of a two-pool model for extrapolation, thereby taking care of the differences in mineralization rates of different OC pools.

6.2.2 Chronosequence measurements

Chronosequence measurements are taken from a sequence of soil samples at varying time intervals starting from the time biochar is applied [60]. Based on the obtained data, the long-term stability of biochar is estimated using a model. A disadvantage of this technique, however, is that results are affected by transport processes such as erosion and leaching. As such, the technique is less commonly used.

6.3 Gamma biochar stability measurement methods

As defined by IBI [60], gamma methods use measurements of molecular properties and chemical composition related to the long-term stability of an OC material. The equipment needed to perform these tests are very expensive, but require a short time to complete. Gamma methods are very reliable and are often used to calibrate alpha and to lesser extent beta methods, which can be used for routine analysis. Examples of gamma stability tests commonly used are different kinds of nuclear magnetic resonance (NMR) spectroscopy, analytical pyrolysis, and a method based on the amount of polycarboxylic acids.

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