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Biochar: A Vital Source for Sustainable Agriculture

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Abstract

The emerging concerns in sub-Saharan Africa are non-sustainability of agricultural and soil management practices threatening food security and environmental safety. Biochar, solid material obtained from thermochemical conversion of plants and/or animal biomass in an oxygen limited environment, is of great importance both agriculturally and environmentally. This chapter reviews the contributions of “biochar technology” to environmental sustainability and food security. This strategy addresses the declining food security issues, depleting soil and plant health challenges. When properly exploited, biochar will enhance soil fertility recovery, guarantee resilience to climate change challenges, and satisfy food production needs of growing global population. The positive impacts of biochar utilization on soil beneficial organisms in harnessing and controlling pests and diseases as well as revitalization of ecological niche make it a preferred option. Unfortunately, there is dearth of information on biochar mechanism to enhance bioremediation technology, which is still facing some challenges that need attention for adequate soil remediation. Many researchers have demonstrated bioremediation in laboratory scale under controlled environmental conditions; it may however be very problematic to establish the growth/survival of these biological entities in situ on heavily polluted soil where the environmental conditions cannot be controlled.

Keywords: biochar, plant productivity, environmental safety, bioremediation, food security

1. Introduction

Food security and environmental safety are the emerging concern in sub-Saharan Africa due to non-sustainable agricultural and soil management practices [1]. Thus, giving rise to the limiting influence of biotic and abiotic stress factors on the plant and soil health [2]. Besides the resulting declined in agricultural production, the contributory effect of soil contamination by industrial pollution and excessive use of chemical in agriculture presently constitute a threat to food security and environmental safety. Therefore, this review examined the prospects of biochar in the sustainable agricultural production, plant protection and soil restoration. Biochar is a solid waste material obtained from thermochemical conversion of plant or animal biomass or both in an oxygen limited environment [3].

The thermal process is carried out on sources of biomass including agricultural wastes, green-waste, and animal manures (biomass feedstock) at temperatures ranging from 200 to 900°C [4, 5]. Biochar addition to soils was engineered by Amazonian terra preta soils, which were characterized by high levels of fertility as compared to adjacent soils where no organic carbon addition occurred [6]. The overall benefit of biochar to environment and production systems is based on three sustainability factors; use of sustainable biomass, sustainable production processes, and sustainable end-use [7]. While the main applications which prompted its recent scientific research include: its mitigation of climatic change, efficient and cost effective waste management, and the use of biochar as amendment to improve soil quality and sustain crop yield [8, 9]. Therefore, biochar amended soil causes alterations in soil health and this encompasses physical, chemical and biological features while it as well maintains the functions of both natural and managed ecosystems essential for sustainable agricultural fertility and productivity [10, 11].

2. Interaction of biochar with soil, plant, and microorganisms

2.1 Interactions between biochar and soil

Biochar exhibits natural oxidation through the formation of functional groups, thereby providing sites that can retain nutrients and other organic compounds [12]. Through the association of biochar particles with clay and silt-sized minerals, oxidized biochar particles may be bound to soil minerals, thereby decreasing the potential of its decomposition [13]. Hence, enhancing the ability of soil biochar complex to adsorb organic compounds present in the soil while biochar also interact directly with organic matter of soil by sorption [14]. Generally, soil health are restored with amendments by balancing its pH, increasing organic matter content and water holding capacity, re-establishing microbial communities, alleviating compaction and structure thereby allowing establishment of vegetation, recreate ecological function of soils, decrease bioavailability of toxic pollutants, leachability and mobility of contaminants, erosion, improve soil drainage and reduce costs compared to traditional remediation techniques [15]. The cations in biochar after pyrolysis are transformed into oxides, hydroxides, and carbonates (ash) which act as liming agents when applied to soil. Biochar is composed of low density material that reduces soil bulk density, thereby increasing water infiltration, root penetration, soil aeration and aggregate stability [16]. Biochar amendments on soil have positive effects on nutrient retention, particularly in highly weathered soils with low ion-retention capacities [17]. Biochar application to medium and coarse textured soils increased soil water holding capacity when analyzed [18]. Thus, biochar serves as soil amendment and carbon sequestration medium [19].

2.2 Impact of biochar on nitrogen fixation

Biochar as soil amendment enhances the biological nitrogen fixation, the nitrogen available in soil is usually lower than that of the biochar due to the high carbon/nitrogen (C/N) ratio of the biochar, and the resulting N immobilization [17, 19], as well, contains higher availability of nutrients, N, and almost neutral pH value [20]. Combination of factors related to soil nutrient availability and simulation of plant microbe interaction, along with nitrogen/nutrient levels also increases when biochar was applied to soil resulting in increased colonization of the host plant roots

by *Arbuscular mycorrhiza* fungi (AMF). Biochar amended soils enhanced biological N-fixation in leguminous crops as reported by Rondon et al. [21]. The increase in the availability of major plant nutrients due to application of biochar occurs as the biochar also releases some small amounts of nutrients that would be available to soil biota [22].

2.3 Effect of biochar application on plant productivity

The prevailing scientific understanding of biochar degradation in soils is that some portions of it are quite readily decomposable, while the core structure of the material is highly resistant to degradation. However, biochar promotes plant productivity and yield through several mechanisms, it changes the physical conditions of plants; its dark color alters thermal dynamics and facilitates rapid germination, allowing more time for growth compared with biochar un-amended soil [23]. Although, there are no specific recommended application rates for any soil but amendment of soils must be done based on extensive field testing. Chan et al. [24] reported that application of 5–50 tons of biochar per hectare, with appropriate nutrient management had positive effects on crop yields. Single application of biochar can provide beneficial effects over several growing seasons in a field due to its recalcitrance to decomposition in soil [25]. Therefore, biochar does not need to be applied in all cropping season, as is usually the case for manures, compost, and synthetic fertilizers. Its effects on yield also occur as a result of changes in soil nutrition, water holding capacity and microbial activity and these effects vary due to soil type [26].

Many researcher has affirm the importance of biochar in plant growth enhancement, hardwood biochars and poultry manure biochars possesses nutrients, such as, high N content, which often enhance positive yield increases [26]. Petter et al. [27] reported that *Eucalyptus* biochar positively affected upland rice yields since the first year of its application. Biochar produced from wood, paper pulp, wood chips and poultry litter have also been found to positively affect crop and biomass yield [18]. In the studies of Glaser et al. [17] and Chan et al. [24], corn, cowpea and radishes grown on poultry litter biochar, each of their yield was improved by 140, 100 and 96% respectively. Field application of biochar below 30 tons/ha was reported to increase crop productivity and varied with crop type with greater increases for legume crops (30%), vegetables (29%) and grasses (14%) compared to cereals, such as, corn (8%), wheat (11%) and rice (7%) [28, 29]. Furthermore, wastewater sludge biochar was applied to cherry tomatoes at the rate of 10 tons/ha and resulted in 64% increased production above the control soil conditions [30].

Combined application of pine woodchip biochar at the rates of 5 and 10 mg/ha with N fertilizer to a fertile silt loam soil in northwest Arkansas significantly increased corn yield compared to sole application of N fertilizer [30]. Combined application of biochar with cow urine to the root zone of pumpkin also significantly increased pumpkin yield compared to all other soil amendment treatments. Ndor et al. [31] reported that rice husk and sawdust biochar significantly increased N, P and K uptake by maize plant, and also significantly increased maize number of leaves, plant height, fresh and dry weight of cobs. In another study, amendment of an alkaline soil with biochar derived from vegetable waste and *Eucalyptus*-leaves had significant effects on seedlings dry matter, shoot and root lengths of maize [32]. According to Fru et al. [33], *Talinum triangulare* responded positively in growth, nutrient uptake and yield when cultivated in poor and acidic soil amended with biochar. Instances of decreasing yield due to a high biochar application rate were reported when equivalents of 165 tons of biochar/ha was added to a poor soil in a

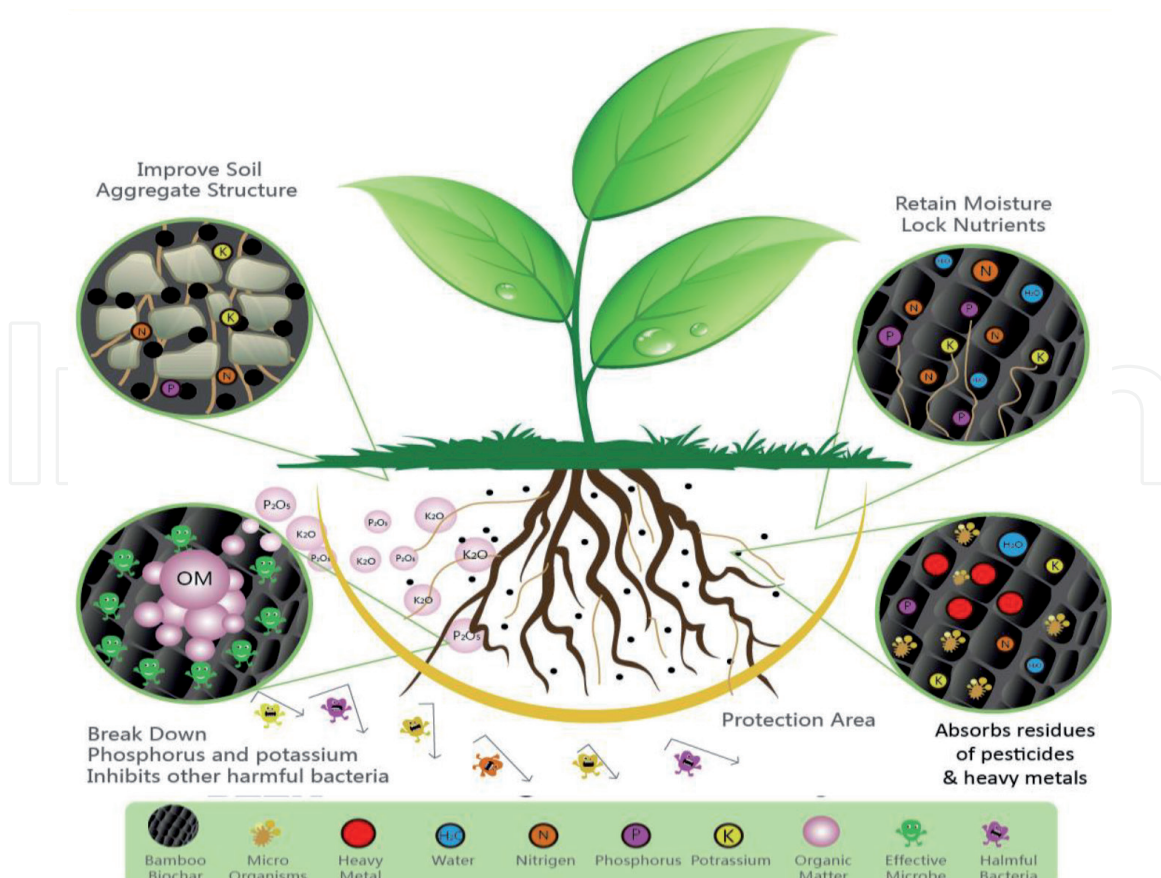


Figure 1.

Effect of biochar on the soil mineral component. Source: Bamboo biochar—Bio-organic fertilizer [35].

pot experiment [21]. Yield increase was reported in maize and wheat when biochar was combined with either organic residue/compost or mineral fertilizer, this indicates that wood biochar may raise nutrient use efficiency when added to organic/inorganic fertilizer/crop residues [34] (**Figure 1**).

2.4 Effects of combined application of biochar and fertilizer

Application of biochar in combination with fertilizer to soil has been found to have positive effects on crop growth, this was probably due to the positive interaction between biochar and applied fertilizer that improved the availability of nutrients associated with enhanced plant uptake and reduced losses of these nutrients [25, 35, 36]. Most biochar materials are not substitutes for fertilizer, so adding biochar without necessary amounts of nitrogen (N) and other nutrients cannot be expected to provide improvements to crop yield [21]. Application of *Eupatorium* (Syn. *Chromolaena*) weed-derived biochar to soil increased the yield of pumpkin crop to 85% above the unamended soil. A normal application rate in the range of 5–20 t/ha of biochar similar to other amendments, such as, compost under normal conditions can positively affect crop yield while excessive application rates (>50 t/ha) may negatively affect crop response. However it will be difficult to establish an exact threshold above which negative effects appear [37]. Negative effects on crop growth are mostly reported with biochar obtained from municipal waste, food waste, and sewage sludge because their excessive sodium contents increase soil salinity [28]. Other negative effects from plant- and wood-based biochars are due to one of the following causes: high application rates, high volatile matter contents detrimental to crop growth, reduced plant available nitrogen, or negative liming effect in alkaline and calcareous soils [35].

3. Role of biochar in sustainable plant disease management

3.1 Plant disease management: the good and the bad

Due to the increasing global population, there is an ever increasing desire to increase agricultural efficiency in terms of producing maximum crop yields and produce. This is only achievable if pest and disease agents limiting crop productions are adequately checked. Cultural, biological, chemical and regulatory measures are the key methods of plant disease management. Since its introduction over a century ago, chemical method had assumed a position of importance and preferred over the existing cultural method due to its effectiveness in the control of diseases, pests or weeds. The relatively low cost of the chemicals, the ease with which they can be applied, availability, stability and fast-acting limits the damage done to crops. However, with the realization of the havoc caused by continuous and persistent use of chemicals either by misuse or abuse, with the consequent degradation of ecological community of most of the farm sites based on their effects on both the target and non-target organisms, has led to the destruction of beneficial organisms and the natural predator in the eco-system. They also obstruct the normal functioning of the ecosystem if the pests and organisms' develop resistance to the chemicals used, thus resulting in pests evolution. However, agricultural workers often suffer occupational exposure to pesticides while exposure of the entire population is exposed to pesticides pollution primarily through the food chain and drinking water contaminated with pesticide residues which are carcinogenic [38, 39].

3.2 Biological control: novel strategy to safe agricultural practices

Humanity does not only dependent on the direct contributions of microbes within our bodies but also on the way they shape and maintain essential functions of our environment, including agricultural production systems where they provide "ecosystem services". Therefore, the use of biological control in the management of pest and diseases pre-dates the modern pesticide era [40]. The host specificity, longer residual effect and non-toxicity to human and the environment makes biological control a novel strategy to safe agricultural practices and sustenance of the ecosystem structure [40]. Some of the control measures that have been widely explored in the management of plant pathogens include the use of beneficial organisms [41]. These are mostly members of the bacterial genera *Bacillus*, *Pseudomonas*, *Serratia*, *Stenotrophomonas*, and *Streptomyces* and the fungal genera *Ampelomyces*, *Coniothyrium*, and *Trichoderma* being used as the model organisms to demonstrate their influence on plant health [42]. The growth and health enhancement of *Arbuscular mycorrhizal* fungi (AMF) has been well investigated [43–45] while the use of plants which involves its extracts, metabolites and bioactive products had been widely explored and yielded positive responses in the management of phytopathogens of varying kind of agricultural plants [46–48].

3.3 Influence of biochar on soil biota

Soil biota is important to the functioning of soils and provides many essential ecosystem services. According to Wuddivira et al. [49], biochar amended soil provides suitable pH for the growth of microbes, especially fungal hyphae due to its porosity. Application of biochar into soils leads to initial degradation of biochar

by chemical oxidation and microbial processes [50]. These processes that influence the energy flow and organic matter within the soil will impinge on bacterial and fungal-based energy channels, which will have impact at higher trophic levels [51]. Biochar and earthworms increased the availability of mineral nutrients in growing seedlings suggesting that this mechanism played important role [52]. Microbial population could be higher in black carbon rich soil, thus the interaction between biochar as a soil amendment approach plays a vital role in soil biota [53]. More so, biochar amendment resulted in increased soil microbial biomass and changes in the composition of soil microbial community [54].

3.4 Biochar: the refuge for microorganisms

Biochar provides “sanctuary” for microorganisms experiencing harsh environmental conditions and also provide a more habitable space for their proliferation. The types of biochar and soil environment are factors that are vital to how the char will affect the soil microbiota [41, 55]. The ability of biochar to act as refuge for soil microorganisms from their predators; protozoa, beneficial nematodes, and microarthropods was affirmed in the report of Verheijen et al. [56] which showed the electron microscopic images of bacteria and fungi on the surface or inside biochar pores. The larger biochar pores which are mostly the structural remnants of wood xylem, phloem vessels and other larger features have diameters $>10\text{ }\mu\text{m}$ [57]. According to IUPAC conventions, biochar porosity has been classified by distinguishing between; micropores ($<2\text{ nm}$), mesopores ($2\text{--}50\text{ nm}$), and macropores ($>50\text{ nm}$) [58, 59]. Whereas, the organisms that predate soil bacteria, including protozoa and nematodes, have diameters $<10\text{ }\mu\text{m}$ therefore making access to the larger pores relatively easy [57]. Further protection from predation offered to the microbes by biochar has been associated with the hydrophobic adsorption of biochar although the hydrophobicity can decrease over time. Some microorganisms can be strongly attached to hydrophobic surfaces which create biofilms of several bacterial layers thick [57, 59].

3.5 Role of biochar in environmental safety and sustainable agriculture

The benefits of biochar on crop productivity and plant health have been related to four main mechanisms which include; increase in soil pH which is beneficial to acidic soils [18]. Biochar's high water retention capacity results to improvement of water regime of the soil, this is of special advantage to sandy soil area where biochar will reduce the leaching away of moisture, thereby reducing water loss, while it reduces the risk of water-logging in clay soil by promoting water drainage [60, 61]. The third mechanism is associated with the capability of biochar to adsorb and neutralize phytotoxic organic molecules including anthropogenic, xenobiotics and natural allelopathic compounds. This detoxifying capability is directly related to the dramatic increases of specific surface area that occur during pyrolysis [62–65]. The fourth mechanism is related to its capability to stimulate beneficial microbes, in bulk soil as well as in the rhizosphere [66]. By serving as a source of reduced carbon compounds and by increasing the availability of micronutrients, biochar may be beneficial to microbial populations, such as, *Arbuscular mycorrhizal* fungi (AMF) [19, 67], plant-growth-promoting microbes [68, 69]. Therefore, biochar applications increase the microbial biomass of the beneficial organisms with related changes in microbial community functionality [66, 69]. However, the increase in microbial biomass resulting from microbial growth following biochar application has been reported to be as a result of the; effect of water and nutrient retention, formation of active surfaces that provided optimal habitat for microorganisms,

weak alkalinity and partial inhibition of destructive and simultaneous support for beneficial microorganisms [70, 71].

3.6 Biochar-microbe interaction: mode of action in plant disease control

Treatments with resistance inducers or beneficial microorganisms have been reported to provide long-lasting resistance for plants to a wide range of pathogens [72]. More so, induced resistance can be also conferred by plant-associated microorganisms, including beneficial bacteria and/or fungi [41]. Biochar does not have an indigenous population of microorganisms that can potentiate disease suppression, due to the high thermal treatment in its production [7]. However, its addition influences microbial populations and communities, thus causing changes which may include increase in beneficial microorganisms that directly protect plants against soil pathogens by; producing antibiotics, out-competing the pathogens, or grazing on the pathogens [7, 9, 73]. Investigations conducted on biochar and microbe interaction collated by Bonanomi et al. [9] proposed five different mechanisms by which biochar mitigate against plant diseases and these include: (i) induction of systemic resistance in the host plants; (ii) enhanced abundance and/or activities of beneficial microbes; (iii) modification of soil quality in terms of nutrient availability and abiotic conditions; (iv) direct fungitoxic effects of biochar; (v) sorption of allelopathic and phytotoxic compounds. This attributes have been further verified in some of the recent investigations [19, 72, 74, 75], thus biochar is an evolving strategy and a potent tool in plant pathology research, **Figure 2**. Therefore, biochar is gaining importance day by day as its application touches all facet of agriculture and has attracted tremendous attention in the practice of sustainable agriculture.

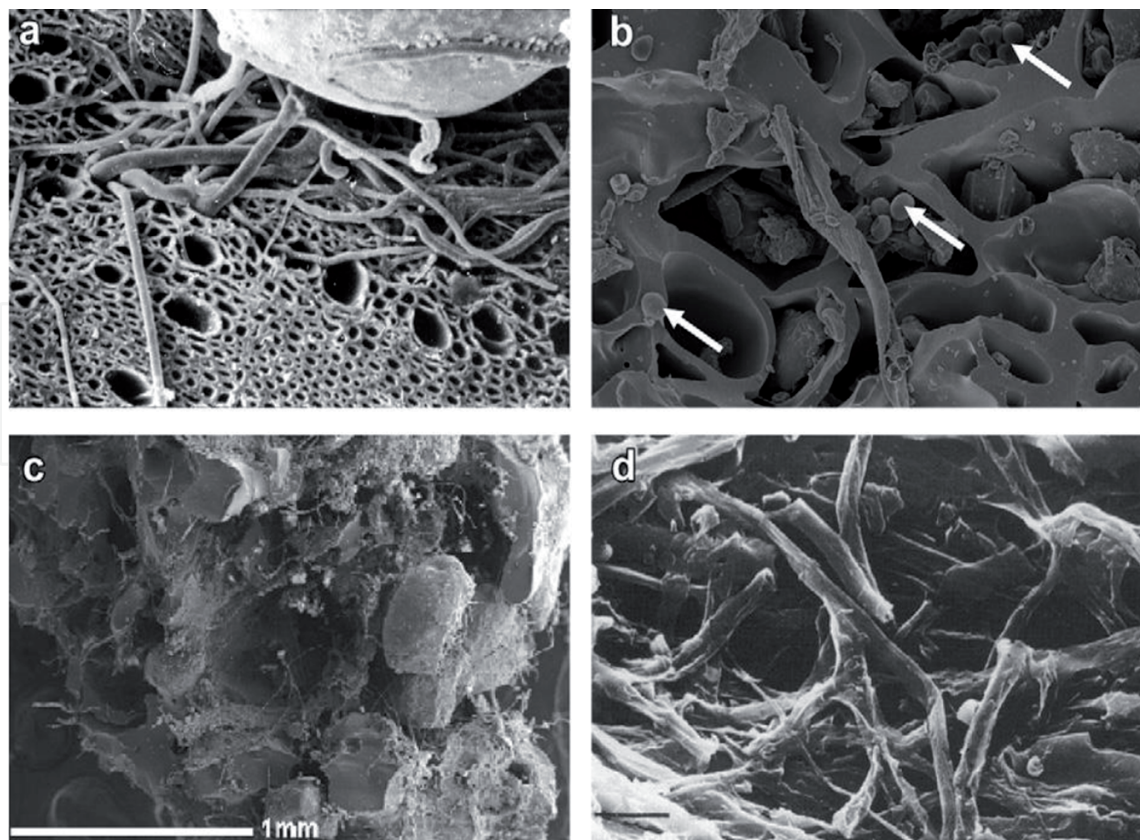


Figure 2. Spatial association and colonization of biochar by microorganisms (a) fresh biochar showing fungal hyphae; (b) fresh corn biochar showing microorganisms in pores (arrows); (c) 100-year-old char from a forest fire isolated from a frigid entic Haplorthod; (d) 350-year-old char from a forest fire in a boreal forest soil. Source: Lehmann et al. [19].

3.7 Biochar interaction with mycorrhizae

Biochar and *Arbuscular mycorrhizal* fungi (AMF) interaction in soil will alter levels of nutrient availability that affects both plants and mycorrhizal fungi communities and modifies plant-mycorrhizal fungi complex which serves as a refuge from hyphal grazers and soil predators [76]. Biochar soil amelioration in degraded landscapes has the potential to increase grassland plant production, enrich soil microbial populations, and stimulate *Arbuscular mycorrhizal* persistence while addition of biochar to soil increases root colonization by AMF [22]. In addition to the mineral supplement of AMF by biochar, it also acts against biotic and abiotic stresses in nature thus increasing the ability of AMF to assist their host in resisting infection by plant pathogens [73].

4. Effects of biochar application on greenhouse gases

Global surface temperature has increased by 0.8°C in the last century primarily because of increased anthropogenic emissions of long-lived greenhouse gases (GHGs), such as, carbon (iv) oxide (CO₂), nitrous oxide (N₂O) and methane (CH₄). Greenhouse gases are those that adsorb and emit radiation within the thermal infrared range [77]. Application of biochar to soils can impact soil GHG fluxes by changing the composition and activity of soil microbes, soil pH and soil biogeochemical processes [24]. Effects of biochar amendment on soil GHG fluxes depend on the study conditions, duration of the experiment, biochar application rate, biochar feedstock and pyrolysis methods [78].

4.1 Effects of biochar application on soil CO₂ emissions

Soil CO₂ emissions can be derived from native soil organic matter, the mineralization of added carbon compounds (such as, dead plant material), root exudates or dead roots and the direct respiration from plant roots [79]. Lehmann et al. [19] suggested that a co-benefit of biochar amendment is a reduction of soil CO₂ emissions and associated long-term increases in soil organic carbon (SOC) in the soil. Although the mechanisms governing the effects of biochar amendment on soil CO₂ emission are uncertain, some authors suggested that increased CO₂ emissions from soil might be as a result of the following mechanisms: biochar reduces the albedo of the soil increasing soil temperature; addition of liable carbon, increased substrate for soil carbon mineralizing enzymes [80]; agglomeration of soil carbon, microbes, nutrients on biochar surface and increased carbon use efficiency; reduction of carbon mineralizing enzymes activity and soil-derived CO₂ precipitation onto the biochar surface as carbonates [81]. Wang et al. [82] reported that addition of wheat derived-biochar to acidic soil increased soil organic C and CO₂ efflux on average by 61 and 19%, respectively.

4.2 Effects of biochar application on soil N₂O emissions

Nitrous oxide is produced in soils primarily by microbial activity through nitrification, nitrifier denitrification, NO₃ ammonification and denitrification [83]. Biochar amendment to soil can have significant effects on soil N₂O emissions; however, the magnitude of effect varies widely. According to Yanai et al. [84] and Stewart et al. [85] short-term laboratory incubations have shown that biochar amendment can suppress soil N₂O emissions, while Spokas [86] and Jones et al. [87] concluded that soil N₂O emissions were not suppressed with biochar

amendment in the longer term (up to 3 years after biochar addition). Biochar amendment causes changes to a range of soil physical and chemical properties that regulate N-cycling processes [86]. Some authors have explained the mechanisms of the effects of biochar amendment on soil N₂O emission and these include: increased water holding capacity and decreased bulk density of the soil, increased soil aeration thereby reducing the activity of denitrifying microorganisms [84, 88], reduced N substrate for nitrifying and denitrifying enzymes thereby reducing enzymatic activities of soil microbes as a result of immobilization of soil inorganic N through absorption to biochar surface or increasing microbial immobilization [86], the N₂O:N₂ emission ratio produced during denitrification decreases as a result of increased soil pH [89]; N₂O:N₂ product ratio of denitrification is reduced by increased effects to the soil [90], reduced activity of soil nitrifying/denitrifying organisms through substances emitted by the biochar, such as, ethylene, α -pinene, PAHs, VOCs [91]. Rondon et al. [92] reported that biochar amendment reduced N₂O emissions from pasture land and soybean soil by 80 and 50% respectively, because microbial conversion and denitrification were restricted. Application of biochar at a rate of 40 t/ha decreased N₂O emission from paddy rice and maize fields by 21–28 and 10.7–41.8%, respectively but increased CH₄ emission from a paddy rice field by 41% and CO₂ emission from a maize field by 12% [93, 94]. Cayuela et al. [95] reported that biochar reduced soil N₂O emissions by 28% in a similar field. Wang et al. [82] reported that addition of wheat derived biochar to acidic soil did not affect the annual N₂O emissions (26–28 kg N/ha), but reduced seasonal N₂O emissions during the cold period. Fan et al. [96] reported that biochar amendments generally stimulated the NH₃ emissions with greater enhancement from wheat straw biochar than swine manure biochar.

4.3 Effects of biochar application on soil methane (CH₄) emissions

Methane are produced by methanogens as a metabolic by-product of organic matter mineralization in anaerobic conditions; the two primary pathways being through CO₂ reduction by H₂ or through acetotrophy [97]. Soil methanotrophs are the only known biological sink for atmospheric methane, which oxidize methane and produce CO₂ as a by-product [98]. Soil methanotrophs require oxygen as a terminal electron acceptor and their activity is highest around 60% water-filled pore space (WFPS) and decreases above this moisture content [88, 99]. Zhang et al. [93] and Wang et al. [100] reported that there are limited evidence to suggest that biochar amendment affects soil CH₄ emissions, and evidence that supports it are mostly from studies in rice paddies. In saturated soils, such as, rice paddies but not in other aerobic crop soils, CH₄ emissions are generally significant [97]. Increased availability of liable C substrates for methanogenic bacteria may explain increased methane emissions following the addition of biochar to soil [100]. Soil CH₄ emissions were increased by 37% with biochar amendment in a paddy rice field [100]. Similar observation of an increase in soil CH₄ emission from the same land use were also reported by Zhang et al. [93] and Knoblauch et al. [101]. Increased in soil methane uptake within arable soils following biochar amendment was observed by Karhu et al. [88]. In similar studies, with other crop types, no significant effect of biochar amendment on CH₄ emissions in arable and pasture soils were reported [100, 102, 103] while in Finnish agricultural soil, a 96% increase in methane uptake was reported in biochar amended soils [88]. Application of biochar to waterlogged paddy rice soil in the laboratory, decreased CH₄ and CO₂ emissions in the soil and this was attributed to the restriction in methanogen activity and limitation of carbon on microbial biomass, as well as rise of pH value [104]. However, increase in CH₄ and CO₂ emissions were reported by Ameloot et al [105] and Van Zwieten et al. [106]

studying the short-term CO₂ and N₂O emissions and microbial properties of biochar amended sandy loam soils, and effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility, respectively.

5. Characterization of biochar as an effective mediator of bioremediation mechanisms

5.1 Biochar as a soil additive to enhance soil restoration/remediation

Soil remediation efforts should be based on feasible, environment friendly and cost effective technologies, and many scientists today are advocating bioremediation mechanisms for meeting these criteria. It has also been widely reported that bioremediation can be enhanced through the use of traditional resources, such as, the application of soil additives. The basis for the use of soil additives during bioremediation is for enhanced bio-stimulation and bio-augmentation; these two mechanisms form the bed-rock for the immense roles of soil additives in bioremediation as reported by many researchers [45, 107–112]. Biochar applications as a soil additive in contaminated soil is a potential management strategy for feasible and cost effective agricultural sustainability using degraded soils hence improving the food security. Many reports have identified biochar with high sorption capacity for many contaminants including persistent organic pollutants (POPs) and many inorganic pollutants, such as, heavy metals [113, 114]. It was reported, however, that the physicochemical properties of the original crop residue used for biochar preparation may determine its sorption efficiency [115, 116]. However, good knowledge of the pollutant type and its concentration may help in predicting the type of biochar that would be of best fit. Thus it is a crucial factor to clarify the correlation between the sorption efficiency and properties of a particulate. The use of biochar in nutrient sequestration according to Barrow [117] was from the discovery of “terra preta” which is a charcoal-rich fertile soil located at the central Amazon basin that is known for diverse agricultural roles. The importance of such biochar to soil has been reported [28, 105, 117–122].

In a study by Gomez-Eyles et al., biochar was shown to reduce PAH accumulation in earthworm (*Eisenia fetida*) tissue; this organism was incubated in soil treated with biochar for 28 and 56 days. Their study suggested that biochar can be used in PAH polluted soil to avoid their entrance into the food chain and this was corroborated in another study reported by Wang et al. [110] in which the bioavailability of pesticide called chlorantraniliprole was reduced by biochar amendment and prevented its absorption in earthworm tissues. The use of biochar as amendment for enhanced bioremediation is gaining attention at an exponential rate as it enhances soil nutrients and water availability [115–117]. It was also reported that it functions by immobilizing/degrading many soil and water contaminants [123, 124]. Unlike other amendments, biochar is thought to be perfect in Carbon sequestration in soil making it stable for several years [122].

5.2 Biochar as a potential catalyst for phytoremediation

The use of plants for bioremediation is called “phytoremediation”; its success depends on establishment and good development of vegetation on the polluted site brought about by healthy root and shoot biomass [125, 126]. However, the major problem of phytoremediation is the establishment of degree/level of pollution of the polluted site. Many soil pollutants are very persistent, many form complexes with humus and soil nutrients and thus make them unavailable for plant use. In

addition early research have reported that many soil pollutants, such as, aromatic and polycyclic hydrocarbons can create anaerobic condition and make seed germination and plant establishment difficult on the polluted soil. However, the use of amendments, such as, organic materials can enhance plant biomass yield and improved plant health growing on polluted sites [1, 111, 127]. The use of biochar for the amendment of polluted soils has been reported to enhance re-establishment of plants and supports massive plant biomass [125, 128]; this is a potential approach for effective phytoremediation mechanism [128]. Prendergast-Miller et al. [129] and Prendergast-Miller et al. [130]. The above reports present biochar as good candidate for positive soil enhancement although this is not yet fully exploited in contaminated sites. Biochar as soil amendment enhances nutrient availability and improves the activities of soil microorganisms around the root rhizosphere for effective nutrient mobilization for root uptake [116, 131–133]. This promotes root expansion and hence has potential to support phytoremediation. It was reported that plant growing on polluted soil may develop some disease malformations due to their response to the toxic pollutants [111] and reduced resistance to pests.

Biochar has however been reported to increase plant resistance to several soil and air-borne pathogen, it was reported that biochar stimulates several plant's defense pathways and related gene expression [7, 134, 135]. Biochar has also been well reported for its pH enhancement capacity as it enhances the soil CEC [136–139] and minimizes salt toxicity in polluted soils (142). According to Cheng and Lehmann [140] and Singh et al. [115], biochar is able to oxidize in soil to raise its carbon exchange capacity (CEC) as it disintegrates during tilling and weathering and there are some commercially available biochar purposefully used as soil nutrient enhancement. This can be very helpful in the enhancement of plants health during phytoremediation. Many researches have suggested the combination of phytoremediation with biochar for effective soil remediation. Hartley et al. [141] and Fellet et al. [142] reported that biochar's combined use with *Miscanthus* increased phytostabilization, while in another experiment, Hartley et al. [141] reported an increase in As extracted by *Miscanthus* plant in three soils treated with biochar made from hardwood. Combined biochar and phytoremediation have also been reported in Cd-polluted soils using *Brassica napus* L. by Houben et al. [143]. Many more results have proved that biochar is suitable for enhancement of phytoremediation mechanism and this seems plausible for their exploitation in remediation of multi-contaminated soils. Biochar can be used prior to plant colonization of acidic soils however; these two approaches still need more confirmatory researches to depict their synergistic mechanisms for effective and sustainable set-up.

5.3 Biochar as a potential catalyst for enhancement of microbial response and bioremediation

The nutrient and soil amendment capability of biochar cannot be overemphasized. The fact that biochar improves soil nutrients means that it has some beneficial effects on the soil microbiota, this has been well studied [115], Ippolito et al. [144, 145] and Kuppusamy et al. [146] and they reported that biochar amendment was found to enhance increment in microbial biomass, diversity and enzyme activities [14, 147, 148]. Biochar was thought to increase bacterial and fungal population as they easily form pore habitats in biochar, although the mechanism could be varied but the overall effect might be as a result of nutrient recycling and soil water retention as enhanced by the biochar and this of course increases the resources available for the microbes to use.

Furthermore, microbial community shifts brought about by biochar amendments may vary due to particular characteristics, microbial response to soil

conditions set by the biochar treatments, especially based on the biochar surface characteristics and its bioavailable compounds, as well as pH changes induced by the treatment [149]. Zimmerman et al. [80], for example, reported an increase in C mineralization in soil treated with biochar that was made from grasses under low temperatures of 250–400° C compared to biochar that was made from hard woods under higher temperatures of 525–600°C. In another study, Steinbeiss et al. [150] explained that fungi adapted more with biochar that was created from yeast but Gram-negative bacteria responds well to those created from glucose. Anderson et al. [151] reported varying results in microbial population dynamics due to different biochar treatments. The exploitation of biochar to increase microbial population for faster bioremediation requires complete understanding of the relationship of a particular biochar to be used and the type of native or introduced bacteria or fungi involved. Theoretically, biochar is not a degrading substrate and therefore cannot be degraded by microbes [149, 152]; however, it has a potent labile C source in itself [153]. When used in soil, biochar adsorbs active enzymes and nutrients and make them available for usage by microorganisms [154].

5.4 Prospects of biochar as a potential mediator for synergistic bioremediation mechanisms

Interest in combining different biodegradation mechanisms, such as, the use of plant and microbial communities for effective synergistic bioremediation has been vogue in some years past. It is believed that bioremediation which provides an environmentally friendly mechanism has gained acceptance by scholars and environmental managers. Biochar is a synergistic bioremediation mechanism known to yield speedy soil remediation if correctly implemented [155]. The synergistic combination of two or more biological entities for effective soil bioremediation requires that the two or more organisms to be combined must integrate well and can coexist together leading to exchange of mutual benefits between one another. This requirement is paramount in such settings as bioremediation such that many researchers have suggested the use of soil supplements/additives to enhance this technology [112, 155]. Having established the importance of biochar for plant and microbes, the smart way therefore is to think about using it for combine plant-microbial bioremediation technology. Nutrient enhancement by biochar fosters root elongation and hence increases the microbial populations in the rhizospheres [18, 156]. It is anticipated that effective combinations of different bioremediation technologies may eventually yield a feasible, speedy and effective means of restoration of many polluted soils, and basic roles of biochar in this area cannot be overlook. However, this requires a good understanding and interest in biochar properties, mode of production and their actions in different polluted environments need to be well studied. Large and small scale laboratory and field trials are needed for proper exploitation of this technology.

6. Conclusion

Considering the arrays of biochar benefits, it is a potentially untapped asset for sustainable soil health. However, the dearth of adequate research and knowledge of biochar use as soil amendment today is a still big gap. This therefore necessitates mechanistic understanding and research to unveil the mechanisms of biochar action on soil health. It would as well enhance knowledge on the optimal rate for a particular biochar application, its quality parameters/suitability to different soil and climatic conditions, in relation to economic factors, feedstock properties and

optimize designed pyrolysis conditions needed for its production toward specific end use. In addition, most of the studies on biochar so far are generally based on short term; long-term experiments are needed to understand the effect of biochar aging. Having fulfilled these recommendations, biochar may well be one of the prominent scientific breakthroughs for benefit of mankind.

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