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Revamping highly weathered soils in the tropics with biochar application: what we know and what is needed

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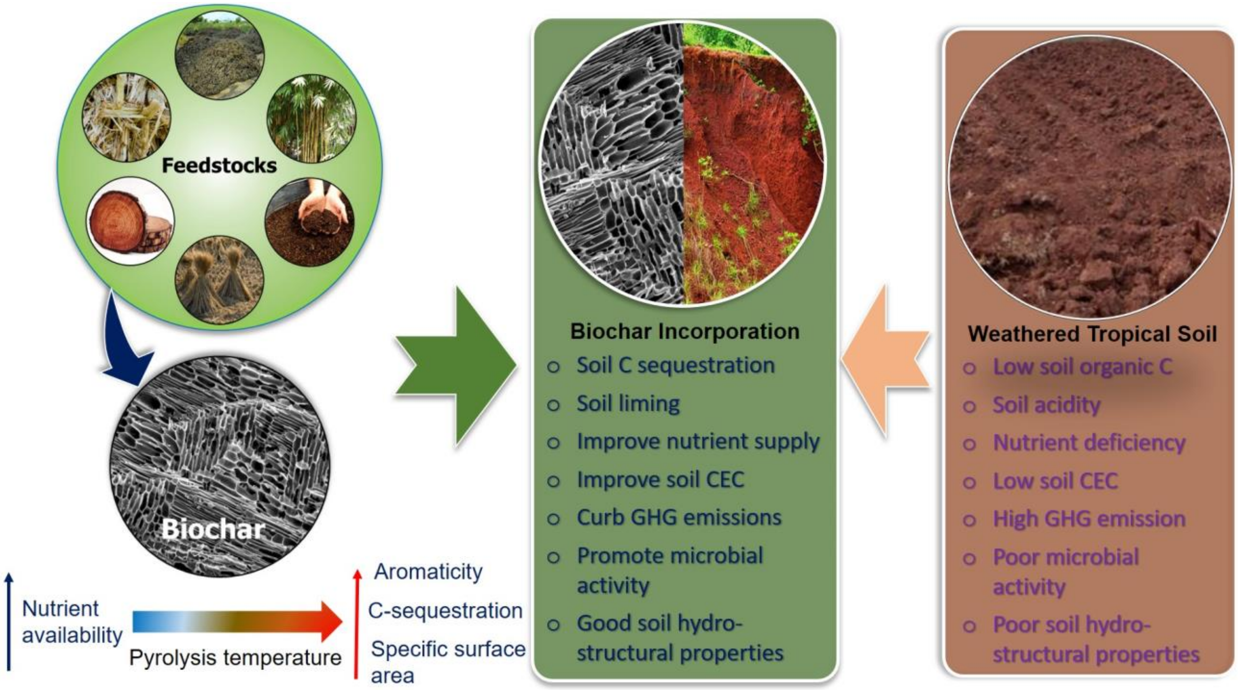
Highlights

- Biochar consistently improved quality of tropical degraded soils and crop productivity.
- Advanced biochar preparation needs innovation to reduce cost using local resources.
- Co-utilization of biochar with organic additives can increase biochar use efficiency.
- Biochar application strategies need location-specific socio-economic feasibility analysis.

Graphical abstract



Abstract

Fast weathering of parent materials and rapid mineralization of organic matter because of prevalent climatic conditions, and subsequent development of acidity and loss/exhaustion of nutrient elements due to intensive agricultural practices have resulted in the degradation of soil fertility and productivity in the vast tropical areas of the world. There is an urgent need for rejuvenation of weathered tropical soils to improve crop productivity and sustainability. For this purpose, biochar has been found to be more effective than other organic soil amendments due biochar’s stability in soil, and thus can extend the benefits over long duration. This review synthesizes information concerning the present status of biochar application in highly weathered tropical soils highlighting promising application strategies for improving resource use efficiency in terms of economic feasibility. In this respect, biochar has been found to improve crop productivity and soil quality consistently through liming and fertilization effects in low pH and infertile soils under low-input conditions typical of weathered tropical soils. This paper identifies several advance strategies that can maximize the effectiveness of biochar application in weathered tropical soils. However, strategies for the reduction of costs of biochar production and application to increase the material’s use efficiency need future development. At the same time, policy decision by linking economic benefits with social and environmental issues is necessary for successful implementation of biochar technology in weathered tropical soils. This review recommends that advanced biochar strategies hold potential for sustaining soil quality and agricultural productivity in tropical soils.

Keywords: Agronomic benefits; Advanced biochar; Tropical soils; Soil amendments; Soil quality.

1. Introduction

About 40% of the Earth’s surface area is located in the tropics supporting approximately 40% of the global human population, and this share may rise to 50% by the end of 2030 (World Population Review, 2021). In most of the tropical soils, sustainable agriculture experiences major challenges due to low nutrient content and rapid mineralization of soil organic matter (SOM) (Nyssen et al., 2015). It is estimated that tropical weathered soils, although occupying a vast global area, contain only one-quarter of the mean terrestrial carbon (C) pools of global soils (Nave et al., 2019). Due to prevalence of hot and humid climate with high annual rainfall in the tropical environment, soils there inherit with low pH ($\text{pH} \leq 5.0$) and small quantity of basic cations (Anda et al., 2015). As a result, soil acidity, low cation exchange capacity (CEC) and poor fertility are the common phenomena in highly weathered soils, and are also considered to be degraded soils for agricultural production (Jien and Wang, 2013). According to the USDA Soil Survey Staff (2014), the weathered tropical soils are categorized in the order Alfisol, Ultisol and Oxisol. The World Reference Base for Soil Resources (WRB) classifies the tropical weathered soils as Acrisol, Ferralsol, Plinthosol and Nitisol (IUSS Working Group WRB, 2015). The nutrient use efficiency of soluble chemical fertilizer is very low in these soils, particularly due to light texture, low water holding capacity, low SOM ($\leq 1.0\%$) and low CEC (≤ 10 cmol kg^{-1}) where heavy rainfall removes soluble nutrients from the root zone quickly by leaching (Butnan et al., 2016; Basak, 2019). As a result, prevalence of nutrient deficiency is quite common in tropical agricultural production system. While the resource-poor farmers living in these regions cannot afford expenses of regular application of chemical fertilizers, the crop yield declines exponentially with the loss of soil quality (Mitchard et al. 2018). Intensive agricultural practices in the highly weathered soils may often lead to further degradation of the tropical soil, impacting productivity (Anda et al., 2015). As the ‘key to soil fertility', restoring and enhancing SOM via C-rich soil amendments therefore might help to revamp highly weathered tropical soils.

Application of organic amendments such as crop residues, manures, composts and mulches have frequently been used for restoration as well as improvement of soil fertility (Alghamdi et al., 2018). However, rapid depletion of applied organic matter (OM) under tropical conditions due to fast mineralization or decomposition reduces the stability of SOM (Hicks et al., 2018; Mangalassery et al., 2019). Potential benefits from applied OM are limited in tropical environment (Palansooriya et al., 2019). Furthermore, emission of greenhouse gases (GHG) such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) upon decomposition of added OM is an environmental concern (Mitchard, 2018; Abagandura et al., 2019). Hence, not only the C content but also the C stability of amendment materials seems important for the refurbishment of tropical soil fertility with minimal consequence to environmental sustainability.

Biochar is a C-rich charcoal like substance derived as a by-product following thermal treatment (pyrolysis at 350-700^{o}C) of organic material or biomass in an oxygen-limited or oxygen-depleted environment (Singh et al., 2014; Lehmann and Joseph, 2015; Brassard et al., 2016; Hussain et al., 2017). Physiochemically biochar is alkaline, hydrophobic in nature, contains both aliphatic and aromatic compounds (El-Naggar et al., 2019). The recalcitrant C fraction is relatively more in biochar than fresh or composted biomass (Zhao et al., 2020). Biochar is also characterized with its porous structure, high specific surface area (SSA), high base saturation and abundant reactive functional groups, imparting high CEC to the material (Hussain et al., 2017; El-Naggar et al., 2019). Biochar has properties that may contribute to recalcitrant C pools in soil, build up SOM, improve hydro-structural properties, improve CEC, increase nutrient retention and plant nutrient use efficiency, and provide habitat to microorganisms in highly weathered soils (Liu et al., 2014;

Khalifa and Yousef, 2015; Liu et al., 2016; El-Naggar et al., 2018). Biochar application has recently been recognized as a promising amendment with high stability in soil, C sequestration and GHG emission reduction (Yadav et al., 2015; Bass et al., 2016), and most importantly, for its potential for improving soil quality and crop productivity (Lehmann and Joseph, 2015; Agegnehu et al., 2016; Bass et al., 2016; Ding et al., 2016; Saha et al., 2019; Bolan et al., 2021; Wu et al., 2021).

Many research and review articles have focused on the potential of specific biochar to improve the quality of specific soil type (Herath et al., 2013; Jeffery et al., 2017). The intensively cultivated tropical soils are typically featured with low pH (≤ 5.0), low SOM (≤ 1.0%), and poor CEC and base saturation (Jien and Wang, 2013). The contrasting features of biochar and highly weathered tropical soils may lead to beneficial outcomes when they interact with each other. The properties of biochar thus make it an effective amendment for rejuvenating highly weathered soils. However, relatively less attention has been paid to the economic and environmental feasibility of biochar application in highly weathered soils of the tropics. Fig. 1 shows the comparative number of publications in the Scopus database (2006 – 2022) based on the key words 'Biochar and Soil' versus 'Biochar and Tropical and Soil' with and without the word 'Amendment'. Studies conducted on soil application of biochar are plenty, but with strikingly less emphasis on tropical soil (Fig. 1). Some discreate information is available on biochar's interactions in weathered tropical soils from small-scale studies, while thorough and comprehensive information concerning soil fertility and crop production (from soil amendment point of view) is hardly available (Fig. 1), especially those from field-scale trials. Unlike temperate soils, tropical soils are exhausted rapidly due to the predominance of agrarian developing countries and hot-humid climatic conditions. Hence, special attention is necessary for revamping tropical weathered soils to achieve the United

Nations Sustainable Development Goals (SDGs) (Smith et al., 2021). Further, advanced characterization of reactive components of biochar responsible for electron transfer between the biochar and soil components is necessary to investigate biochar-mediated soil nutrient cycling (Gul et al., 2015). The electron transfer between biochar particles and soil components (e.g., minerals, OM and microbial cells) is an emerging area that needs further exploration for understanding the biochar-mediated soil biogeochemical processes (Zhu et al., 2017; Yuan et al., 2017). Particularly, a critical analysis is needed to understand the relationships between biochar properties and its impacts on highly weathered tropical soils, which till date has remained insufficient and poorly integrated. Thus, this review aims to integrate the present status of biochar application in highly weathered tropical soils, highlighting the effects on crop productivity and soil quality. As opposed to most previous reviews, the present paper gathered information from published works that were conducted specially under field conditions. This paper has identified promising application strategies for improving biochar use efficiency in highly weathered soils, and discerned between potentials and limitations of biochar application in tropical soils by considering the economic and environmental feasibilities (Fig. 2). This work thus will enable us to develop a road map for future research in this area.

2. Biochar-induced soil health improvement in tropical soils

2.1. Effect of biochar on the soil physical properties

Biochar application to soil has a strong impact on soil physical properties by altering the various parameters such as soil structure, bulk density, porosity, macro-aggregate and water content (Blanco-Canqui, 2017; Alghamdi, 2018; de Jesus Duarte et al., 2020). Owing to high SSA and porosity, and low bulk density (BD), biochar application often resulted in high porosity of the recipient soil, which facilitated easy movement of water and nutrients, and enhanced growth of plant roots (Blanco-Canqui, 2017; Alghamdi, 2018). Studies in weathered soils indicated that the extent of positive impact of biochar application was more for the physical attributes than chemical indicators (Oladele, 2019). The effects of different biochar on soil physical properties are presented in Table 1.

Biochar was shown to effectively decrease the BD of weathered soil of different geographic regions of the world (Obiahu et al., 2020; Jien et al., 2021). Most of the studies indicated that higher the application rate of biochar higher was the capacity to decrease soil BD (Zong et al., 2018). Factors such as pyrolysis temperature of biochar, type and application rate of biochar, recipient soil type and type of plants grown on the recipient soil could influence the impact of biochar on soil BD (Are, 2019). However, biochar application at higher rate (5%) could decrease the soil porosity more than at lower rate (2.5%). The high biochar application rate might facilitate the formation of macro-aggregates by binding together the micro-aggregates, thereby resulting in a decrease in porosity (Jienand Wang, 2013). Straw biochar was found more effective in reducing the BD of a degraded Ultisol soil as compared to sludge biochar (Malik et al., 2018). Biochar was more effective in reducing BD in Inceptisol as compared to Ultisol (Curaqueo et al., 2014), which could be attributed to more macro-aggregate formation in the former soil. Addition of biochar in combination with compost in highly weathered tropical soil resulted in significant improvement of soil BD and porosity only after one year of application (Jien et al., 2021), which indicates that biochar can be included as a long-term adaptation strategy to restore the weathered soil.

Due to highly porous nature of biochar, soil application resulted in the improvement of water movement and retention in terms of field capacity, wilting point and available water (Zong et al., 2018), which would subsequently help crop growth and yield. Curaqueo et al. (2014) reported that water-holding capacity (WHC) only increased in an Ultisol when oat hull biochar (OBC) was applied at high rate (10 and 20 Mg ha^{-1}) on two volcanic soils (e.g., Inceptisol and Ultisol). However, no significant impact was observed when biochar was applied to Oxisol of Central Africa (Kanouo et al., 2019), which might be due to the movement of biochar particles through the soil profile. Contrarily, high biochar application rate (30 and 40 t ha^{-1}) toan upland red soil showed an improvement in field capacity and soil available water content (Jin et al., 2019). Jien et al. (2013) reported that biochar application in an acidic Ultisol resulted in an increase in saturated hydraulic conductivity by 1.8 times. Similar results were reported in a strongly acidic Ultisol where the water holding capacity increased without any impact on available water content (Zong et al., 2016). Soil aggregation is important for sustainable agriculture as it influences the soil physical and biological properties (Demisie et al., 2014). Varying impacts were reported for the formation of water-stable aggregates (WSA) upon the addition of biochar in various weathered soils. Application of biochar in Alfisol (Oladele, 2019) and Ultisol (Curaqueo et al., 2014) at high dose (20 Mg ha^{-1}) increased WSA and mean weight diameter (MWD) in both the soils. However, a stronger effect of biochar on soil aggregate stability was reported in degraded soil with low organic carbon (OC) than high OC content (Demisie et al., 2014; Obia et al., 2016). Even a low dose (2%) of biochar was found effective in improving aggregate stability in a low OC-containing soil (Obia et al., 2016).

The mechanism of biochar to improve soil physical properties in terms of BD could be a physical dilution of dense soil matrix due to the less dense and porous nature of biochar (Jienand Wang, 2013; Zong et al., 2016), which might lead to an increase in soil porosity, and thus a decreased BD (Fig. 3). Biochar in soil also could act as a binding agent by altering the pore size distribution and improving the soil aggregate stability (Obia et al., 2016). Various mechanisms were proposed by various authors for the improvement of aggregate stability in weathered soil upon biochar application (Jienand Wang, 2013; Jien and Wang, 2013; Demisie et al., 2014; Jien et al., 2021), warranting future research to understand the key processes.

The microstructure found in biochar-amended soil indicated that the formation of “circular aggregates” was one of the reasons behind increasing the soil aggregate stability (Jien et al., 2021). Due to highly oxidized surface, biochar could bind soil and clay particles together, and thus help in the formation of macro-aggregates in soil (Jien and Wang, 2013). Demisie et al. (2014) reported that biological mechanism played an important role in the formation of soil micro-aggregates after application of biochar in a red soil. Highsoil β-glucosidase enzyme activity related to polysaccharides formation could have facilitated the improvement of soil aggregate stability (Demisie et al., 2014). Jien and Wang (2013) reported that due to highly oxidized surface, biochar could adsorb soil and clay particles, assisting the formation of soil macro-aggregates. Indeed, numerous complex interacting phenomena are responsible for the formation aggregates in soil after biochar application, which requires future investigations using advanced techniques such as X-ray micro-computed tomography. Few studies also showed that biochar had the potential to reduce erosion in weathered soil due to the improvement of aggregate stability (Jien and Wang, 2013).

Most previous studies concerning biochar’s effects on physical properties in weathered soils concentrated on BD, porosity, water holding capacity and soil aggregation (Table 1; Fig. 3). As weathered tropical soils exhibit poor mechanical strength, studies on impact of biochar on soil mechanical strength is also important from agronomic point of view. Zong et al. (2016) reported that biochar application in an acidic Ultisol significantly increased the soil’s liquid limit and plastic index while decreasing the tensile strength and cohesion value. Similarly, Malik et al. (2018) reported that application of sludge and straw biochar in a red Ultisol reduced soil surface cracks, decreased the tensile strength with slight enhancement (15%) of the internal friction angle, and reduced the cohesion value. Formation of biochar-induced C coating between soil particles might have resulted in low contact between soil particles, reducing the soil cohesion value (Malik et al., 2018). High water repellence around organic compounds on particle surfaces might be another reason behind low cohesion value. Physical dilution of soil particles by biochar particles might also cause a reduction in the soil mechanical strength. Contrarily, biochar addition in light-textured soil resulted in soil shrinkage (Obia et al., 2016), which indicated an initiation of soil structural build-up. Studies on the improvement of soil physical properties following biochar addition are in nascent stage, and require long-term field evaluation.

2.2. Effect of biochar on soil pH and cation exchange capacity

Weathered tropical soils are generally acidic in nature, and a significant reduction in crop yield was reported due to such soil acidity (Hale et al., 2020). High acidity and aluminum ion (Al^{3+}) toxicity, and poor availability of macro- and micro-nutrients are the major factors limiting crop growth in acidic soils (Purakayastha et al., 2019). Since soil pH and CEC are important parameters of soil fertility, reduction in soil acidity may change the soil microbial and biochemical activity and thus nutrient availability, which may improve the crop growth (Dai et al., 2017; Palansooriya et al., 2019). However, effectiveness of biochar in increasing soil pH and CEC depend on various factors such as feedstock, pyrolysis condition (pyrolysis temperature, heating rate and resident time) and rate of application, as well as the inherent properties of the recipient soil.

Table 2 represents the liming effect of biochar in acidic tropical soils. Significant improvement of pH (~1.2 unit) in highly weathered acidic soils (Ultisol) was reported with biochar derived from wood waste (Jien and Wang, 2013). Due to high alkalinity, legume straw (Jien and Wang, 2013) and sludge (Zong et al., 2018) derived biochar were more effective than straw and wood biochar in increasing the pH of acidic Ultisol. On the other hand, combined application of biochar with compost was more effective in increasing the soil pH of highly weathered tropical soil than sole biochar application (Cornelissen et al., 2018; Jien et al., 2021). Other than increasing the soil pH in acidic soil, biochar also could improve the buffering capacity (pHBC) of soil (Shi et al., 2019). Higher the pHBC values slower the re-acidification process, and biochar application might help to reduce the re-acidification, which was demonstrated in a simulated acidification experiment in acidic Ultisol (Shi et al., 2017). Ameliorative potential of biochar for acid soil, i.e., liming potential is also determined as a reduction in exchangeable acidity in terms of hydrogen (H^+) and Al^{3+} dominance in the soil exchangeable complex (Chintala et al., 2014; Raboin et al., 2016). Biochar showed a great potential in alleviating the Al^{3+} toxicity in acid soil (Novak et al., 2018). For example, biochar amendment in the high lands of Madagascar decreased exchangeable Al^{3+} content, and improved yield of maize and beans (Raboin et al., 2016). Similarly, Obiahu et al. (2020) reported that application of *Techtona grandis* biochar in moderately acidic Nitisol soil of Nigeria reduced the exchangeable acidity from 0.60 to 0.39 cmol (p^+) kg^{-1}. However, a non-significant effect in correcting exchangeable soil acidity was found when Miscanthus biochar was used for the remediation of an Al^{3+}-enriched acidic mine spoil (Novak et al., 2018).

Due to high SSA and high charge density, biochar can be effectively used to increase the soil CEC (Fig. 3). Biochar produces several functional groups on the surface, including carboxylic and phenolic groups which can result in high CEC (Diatta et al., 2020). Increase in CEC of weathered tropical soil could enhance nutrient retention and availability by reducing nutrient losses through leaching (Basak et al., 2021). Several studies reported the positive contribution of biochar on soil

CEC of weathered tropical soils (Table 2). Application of wood waste-derived biochar in weathered soil (Ultisol) significantly increased the CEC from 7.41 to 10.8 cmol (p^+) kg^{-1} (Jien and Wang, 2013). However, there was no significant increase in soil CEC when biochar was added to a strongly acidic Ultisol (Zong et al., 2016). Domingues et al. (2020) reported that high ash-containing biochar produced at low temperature was effective in increasing the CEC of weathered Brazilian soil (Oxisol), whereas low ash-containing biochar was effective in increasing the C storage of the soil without changing the CEC. This indicated that a combination of high and low ash-containing biochar might be effective in increasing the soil C storage and CEC without causing negative pH effects to plant nutrients and soil microbial processes. Field application of rice husk biochar in a weathered Alfisol was shown to significantly increase soil CEC consistently over time (three years) under rice–maize cropping sequence (Oladele, 2019). Furthermore, due to aging and oxidation of biochar, an increasing negative charge on biochar surface and consequently an increasing CEC could be expected over time. Thus, biochar may act as both a source and sink of nutrients that are required for plant growth, and it can be strongly recommended for weathered poorly fertile soils for improving the nutrient retention and crop productivity. Apart from improving CEC, biochar could also improve the retention ability of Ca^{2+}, Mg^{2+}, K^+ and NH_4^+ ions in acidic soil (Alfisol) (Jha et al., 2016). However, most of the reports studying the effect of biochar on soil pH and CEC are laboratory based short-term experiments, with very few long-term field studies (Wang et al., 2021). An increase of soil pH only after three years of field application of rice husk biochar in a degraded Alfisol suggested that a long-term residual effect would be possible because of proton consumption by the surface functional groups of biochar and/or due to the ash C build up dominated by biochar’s alkali and alkaline earth materials (Fig. 3) (Oladele, 2019). Since most of the studies indicated that biochar amendment in weathered soil caused a significant improvement in soil pH and CEC, improvements in soil fertility and nutrient retention warrant future long-term investigations under real field conditions.

2.3. Effect of biochar on nutrient availability and retention

Application of biochar in weathered tropical soil could provide a unique opportunity for soil fertility improvement increasing nutrient availability to plants (Jeffery et al., 2017; Li et al., 2019), and ultimately enhancing crop productivity. The positive effect of biochar might be more pronouncing in nutrient-poor soil such as weathered tropical soil (Fig. 3). Regulation of nutrient cycles by biochar might occur due to biochar's large SSA, porosity, organic coating and manipulation of soil pH, improving nutrient availability (Palansooriya et al., 2019). Zong et al. (2018) reported that the application of biochar in a strongly acidic soil increased the total C, and available P and K contents, but the nutrient availability was mostly due to the inherent nutrient content of biochar feedstock (Hussain et al., 2021). Among biochar derived from various feedstock materials (e.g., straw, woodchips, sludge), straw biochar contained the highest K content, and thus it increased the available K content in soil (Aller, 2016). Due to the presence of dissolved organic carbon (DOC) and nutrients, biochar may act as an organic fertilizer (Das and Ghosh, 2021). In general, soil retains plant nutrients due to adsorption on OM and minerals. Nutrients available at the plant root zone are referred as a function of soil CEC which is increased due to addition of biochar or OM to the soil. Since, the improvement of CEC is associated with the application of biochar, it is obvious that biochar application will increase plant available nutrients (Haider et al., 2022). Furthermore, due to the presence of large SSA with complex functional groups, biochar is able to bind several soil nutrients, and thus prevent the leaching loss of nutrients.

Ukwattage et al. (2020) reported that there was almost 50% reduction in leaching loss of P when biochar was applied in a subtropical sandy Ultisol, due to the fixation of P in biochar matrix. Similarly, Kuo et al. (2020) reported that application of sawdust biochar in a coarse-textured sandy loam soil of Taiwan resulted in 30% reduction in NH_4^+ and K^+ leaching, and 68% reduction in P leaching. However, the above studies were carried out in soil column leaching experiments, and their applicability in field conditions needs further verification along with unravelling the exact mechanisms of nutrient binding on biochar matrix.

Biochar application in weathered soil could increase the soil organic carbon (SOC) and macro- and micro-nutrient contents (Table 2). Significant increase in SOC, total N, available P and exchangeable cations (e.g., K^+, Ca^{2+}, Mg^{2+} and Na^+) were reported in biochar-amended degraded Ultisol (Mbah et al., 2017). Oak wood and bamboo biochar were found to be effective in improving fertility status through increasing the total organic carbon (TOC) and DOC in an acidic red soil (Demisie and Zhang, 2015). Encouraging evidences are available to confirm the potential of biochar for sustaining fertility in weathered soil, but reports showed that biochar sustained soil fertility in a degraded Alfisol (Oladele, 2019) and upland red soil (Jin et al., 2019) over a period of three years and then returned to initial status. These results signify that the impact of biochar might not be permanent and re-application would be necessary after certain period of time to sustain the beneficial effects of biochar in weathered tropical soil, which requires optimization through future research. Nevertheless, most of the studies demonstrated that biochar incorporation in soil enhanced soil nutrient cycling, suggesting that biochar could be used effectively for the revamping of weathered/degraded soil.

2.4. Effect of biochar on soil microbial and enzymatic activities

Biochar-soil microorganism interactions are controlled by various complex phenomena, and depend on various factors such as soil microbial composition and functional diversity, type and rate of biochar application, and nature of soil (Dai et al., 2021). Due to high SSA and micro-porosity, biochar could act as a habitat for soil microorganisms, and retain large number diverse microorganisms (Zhu et al., 2017; Zhang et al., 2018), promoting soil microbial activity (Fig. 3). Biochar could stimulate the retention of nutrients and their availability to microorganisms, and promote microbial biomass abundance and activities. Biochar could also be a source of metabolically active labile C which is responsible for altering microbial activity and community structure (Palansooriya et al., 2019).

Biochar application in weathered soils revealed a contrasting and inconsistent impact on soil microbial and enzymatic activities (Table 3). For example, stimulation of microbial population due to biochar application was reported in acidic Ultisol (AzlanHalmi et al., 2018), Oxisol (Yu et al., 2018) and Nitisol (Asfaw et al., 2019). Oladele et al. (2019a) reported that biochar application in a degraded Alfisol resulted in initial stimulation of rhizospheric bacterial population. However, the same study reported an initial inhibition of mycorrhizal fungi after biochar addition in the Alfisol soil. A higher activity of mycorrhizal fungi was reported in biochar-amended poorly fertile soil (Malik et al., 2019). Bacteria and fungi exhibited differential response after short-term incubation of a red oxidized soil with BC (Hu et al., 2014) where a significant shift of bacterial community at genus and phylum level was observed, but for fungi the shift was up to genus level only. This might be due to the more adaptability of bacteria than fungi toward biochar-induced changes in the soil environment or bacteria were more sensitive to biochar than fungi (Dai et al., 2021).

Like microbial population, biochar application was also responsible for impacting soil enzymatic activities. Several studies (Jien and Wang, 2013; Irfan et al., 2019) showed stimulating effects of biochar application on soil microbial biomass pools (e.g., microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN)) in weathered soil. However, the stimulatory effect was only significant at high biochar application rate. Studies in degraded soil showed a linear relationship between soil microbial and enzymatic activities with biochar concentration (Zhang et al., 2018). Furthermore, dehydrogenase enzyme activity was successfully used as a suitable indicator for the extent of recovery of degraded soil following biochar amendment (Bandyopadhyay and Maiti, 2019). Biochar application in highly weathered tropical soil resulted in differential responses to various soil enzymes, such as phosphatase, arylsulfatase, β-glucosidase and urease activities (Jien et al., 2021). High rate of biochar (4% w/w) application sometime reduced soil enzymatic activities due to strong physical protection of SOM in macro-aggregates, preventing those from microbial access. However, application of high rate of biochar (4% w/w) with compost resulted in highsoil enzyme activities in weathered soils (Demisie et al., 2015; Jien et al., 2021). This might be related to the release of labile OM due to the addition of compost along with biochar.

3. Biochar-induced climate change mitigation in tropical soils

Production of biochar is considered as an established carbon negative technology for waste biomass recycling and management, specially to increase the OC storage in soil (Singh et al., 2014). Biochar stability and longevity along with its highly concentrated C content in the soil make the amendment a better choice over other organic amendments (e.g., manure, crop residues, compost) in mitigating climate change (Lehmann and Joseph, 2015; Ding et al., 2016). In addition to directly adding stable C to soil, biochar addresses climate change via reducing the emission of non-CO_2 GHG (e.g., CH_4 and N_2O) (He et al., 2017; Shen et al., 2017; Abagandura et al., 2019). As discussed earlier, biochar is a porous material which contains high proportion of recalcitrant C and high pH value. Biochar application therefore reduces soil C mineralization either due to the addition of high proportion of recalcitrant C or due to adsorption of soil C in the surface/ pores of biochar. High porosity of biochar could also improve soil aeration, enhancing CH_4 oxidation (He et al., 2017; Abagandura et al., 2019). Immobilization of soil mineral N could be triggered due to high C:N ratio of biochar, which could reduce N availability to nitrifying and denitrifying microorganisms (Case et al., 2015; Abagandura et al., 2019). Increased number of denitrifying bacterial colony due to increased soil pH after biochar application also could curb N_2O emission by stimulating the N_2O reducing activities (Huppi et al., 2015). From a meta-analysis, Crippa et al. (2021) concluded that land-use change in tropics and subtropics was the second largest source of anthropogenic GHG emissions. Currently, data on non-CO_2 GHG emission due to biochar application are limited, but the trend is encouraging to obtain a net reduction in GHG emission through biochar application.

3.1 Soil carbon sequestration

Biochar's climate-change mitigation potential and nature-based 'carbon sink' solution stem primarily from its carbon's hallmark nature of recalcitrance and resistance to decay and long-term stability in soil. This becomes important for maintaining soil fertility in low SOC-containing weathered tropical soil (Amoakwah et al., 2020). The stable C (50% or above) stored in biochar from biomass, following application to the soil, can sequester that high C quantity into the soil for centuries (Amoakwah et al., 2020). Biochar application to soil contributes to CO_2 sequestration because more C is removed from the atmosphere than the amount emitted (Hussain et al., 2017).

Biochar is considered as a very stable, but not an inert component of SOC (Lehmann and Joseph, 2015). Biochar OC cannot be decomposed easily by microorganisms, which significantly augments recalcitrant SOC fractions (aromatic content) and decreases CO_2 emission from soil (Zhao et al., 2013; Taketani et al., 2013). In conservation farming, application of pigeon pea biochar (4 t ha^{-1}) improved SOC stock in a light-textured Acrisol in Zambia (Munera-Echeverri et al., 2020). Soil C sequestration is often positively correlated with the amount biochar incorporation (Mitchard, 2018; Abagandura et al., 2019). In contrary, Amoakwah et al. (2021) reported higher active C, and C and N lability indices in soil treated with 30 t ha^{-1} of corn-cob biochar than that of 15 t ha^{-1} dose in a weathered tropical soil.

Biochar OC was found 10-100 times more stable than native SOM (Jeffery et al., 2011). A meta-analysis (n=128 observations) study indicated that the mean residence time (MRT) of biochar labile C fraction (pool size 3%) was 108 days, while the MRT of biochar non-labile C fraction (pool size 97%) was 556 days (Wang et al., 2016). The above study suggested that about 97% of biochar C could be sequestered in soil for long time. Reports also showed that native SOC mineralization was inhibited by biochar addition (Wang et al., 2016; Zhang et al., 2018). Cornelissen et al. (2018) reported that maize cob and soft-wood biochar treated tropical degraded soils of Zambia recorded 3 to 10 times higher SOC storage than untreated soil. Application of sugarcane bagasse biochar (4.2 t ha^{-1} yr^{-1}) increased the C stock by 2.35 ± 0.4 t C ha^{-1} yr^{-1} in an Oxisol of Brazil cultivated with sugarcane (Lefebvre et al., 2020). Therefore, increased soil C retention is most commonly observed in biochar treated weathered tropical soils (Table 4), while its effectiveness is not always significant and depends on quantity, duration of biochar applications, land use management and environmental conditions (Pandian et al., 2016; Lefebvre et al., 2020).

3.2 Greenhouse gas emission

Biochar has a negative GHG emission potential owing to (a) reduced biomass decay due to stabilization of OM (Zimmerman and Gao, 2013; Singh and Cowie, 2014), (b) indirect net effects including lowered CH_4 and N_2O emissions (Van Zwieten et al., 2015; Sun et al., 2021), and (c) enhanced plant productivity (Novak et al., 2010). Diverse mechanisms of GHG formation in various soil types and heterogeneous interactions between biochar and GHG evolving/consuming microorganisms in the soil could result in a mixed effect of biochar on net GHG emission from a biochar-treated soil under identical climatic and environmental conditions (Amoakwah et al., 2020; Zenero et al., 2021). The GHG emission issue is more pronounced in weathered tropical soils than temperate soils due to low pH and poor nutrient use efficiency, particularly nitrogenous fertilizer (Jeffery et al., 2017). Here, secondary impact of biochar on climate change comes from biochar-induced reduction of N_2O emission from soil (Abagandura et al., 2019) and modulation of CH_4 emission rates in tropical soil (Jeffery et al., 2017). Some of the incubation studies indicated significant decrease in CH_4 and N_2O emissions due to biochar application in acidic tropical soils (Butnan et al., 2016). However, very few studies are available on biochar-mediated CH_4 and N_2O emissions at field scale (Table 4). Willow-wood derived biochar amendment in a maize field of Queensland, Australia, reported significantly decreased seasonal CO_2 (reduced by 11%) and N_2O (reduced by 52%) emission than the plots receiving compost (Agegnehu et al., 2016). Similar trends were observed in acidic Oxisol of Brazil (Abbruzzini et al., 2017) and China (He et al., 2016) and Ultisol of Thailand (Butnan et al., 2016). Field experimental results from Columbian and Kenyan weathered soils showed about 80% suppression of N_2O emission and considerable reduction of CH_4 emission, respectively, due to biochar addition (Renner, 2007). Overall, biochar could play a dual role by reducing GHG emission and simultaneously enhancing soil C sequestration (Zenero et al., 2021), which warrant field scale studies in the future.

4. Biochar-induced crop productivity in weathered soils

Due to inherent nutrient content in biochar and improvement of soil physical, chemical and biological activities, application of biochar often resulted in increase in crop yield and productivity (Bolan et al., 2021). Jeffery et al. (2017) in their meta-analysis indicated that almost 20-25% increase in crop yield was envisaged due to application of biochar in highly weathered and degraded soil of the tropics, whereas the effects were insignificant in temperate soils. Numerous pot experiments and field trials were carried out in nutrient poor and degraded soils to determine biochar's impacts on crop yield and growth parameters (Table 5). However, effects of biochar on crop productivity in weathered soil could depend on experimental set-up of concerned studies. Generally, pot experimental conditions provided more prominent positive effects of biochar on crop performance (He et al., 2020) than field trials (Haefele et al., 2011; Cornelissen et al., 2018). As weathered acid soil contributes ~40% of world land area (Shetty and Prakash, 2020), increased number of field-scale studies on biochar affecting crop yield should be concentrated on weathered acidic soil (Elias et al., 2020; Shi et al., 2020). Impacts are stronger in acidic soil due to alleviation of soil acidity and thus increment of nutrients availability and finally crop yield. In addition to improving the physical, chemical and biological properties of soil (Haider et al., 2022), as discussed earlier in the paper, biochar could also act as slow-release fertilizer to improve crop productivity in weathered tropical soil (Pandey et al., 2020).

However, the effects of biochar application were not consistently beneficial. Long-term (successive five years) biochar application in an acidic red soil of China under wheat-millet rotation in pot trial found to sustain the soil productivity over a time and increased the straw and grain yield (He et al., 2020). However, biochar application was not consistently beneficial in field studies with weathered soils in other trials (Haefele et al., 2011; Cornelissen et al., 2018). Cornelissen et al. (2018) reported that application of cacao shell and rice husk biochar increased the maize yield of acidic humid tropical soil of Sumatra, Indonesia. However, the effects were faded after 3 to 4 seasons for cacao shell biochar, and second season onwards for rice husk biochar. Fading effect of biochar after multiple seasons might be attributed to leaching of alkali metals from biochar, signifying the need of reapplication of biochar. Similarly, Fachini et al. (2021) found that positive effect of biochar on crop growth faded over time in an acidic soil of Brazil. Conversely, a few studies demonstrated biochar’s positive effects on crop yield from second season onwards, indicating the effect of biochar aging on nutrient retention and supply to plants (Major et al., 2010; Griffin et al., 2017).

Integrated application of biochar with inorganic fertilizer was found to be more effective in improving crop yield and productivity in wreathed tropical soils than sole application of either biochar or fertilizer (Jien et al., 2017; Oladele et al., 2019b; Elias et al., 2020). Elias et al. (2020) reported that biochar application in degraded acidic soils of Malaysia increased the leafy vegetable *Amaranthus* yield in very strongly (17-53%) and strongly acidic soil (54%) but only when applied with chemical fertilizers. The integrated use of biochar (especially with high application rate) along with nitrogenous fertilizer in a red soil provided higher productivity of a rapeseed-sweet potato cropping system (Jin et al., 2019). However, there are contradictory research evidence on biochar application on crop growth and productivity, which seek for efforts towards understanding of mechanistic reasons for improvement of crop growth after biochar application. A meta-analysis with the output of recent research in various weathered soil across the different region of world may help to provide a site/region specific recommendation for improving the crop growth through biochar application.

5. Advanced strategies for biochar application in tropical soils

5.1. Advanced biochar production

Most of the studies complied in this work (Table 5) indicated a promising yield benefit derived from biochar application in tropical soils. The stimulating effect of biochar on crop yield under highly weathered tropical soils is largely derived from fertilization and liming potential of biochar, possibly acting in combination. Therefore, identification of biochar properties suitable for tropical soils (Fig. 4) and their simulation in biochar production are important to get the maximum benefit of biochar application. At the same time, suitable application strategies and co-deployment of biochar (composited/blended) with other suitable additives is another promising area for improving efficiency of biochar for agricultural application.

5.1.1. Feedstock and pyrolysis condition

The potential benefits of biochar to improve soil properties are mainly determined by the pyrolysis process and feedstock used (Wallace et al., 2019). Recent studies on biochar production showed a trend to shift from conventional to advance biochar preparation methods which would introduce the concept of surface modified/designer biochar (Hussain et al., 2017). The process of biochar production could be customized to have specific characteristics of designer biochar based on the purpose of its application. This can be achieved by adjusting biomass source and adopting advance pyrolysis methods such as micro-wave assisted pyrolysis, steam assisted pyrolysis, hydro/wet pyrolysis, co- pyrolysis and catalytic pyrolysis (Rajapaksha et al., 2016; Mandal et al., 2016; Lee et al., 2020). The above principles should be followed for producing biochar with favorable properties to address the issues of deeply weathered tropical soils.

The biomass feedstock type and size are predominant factor determining porosity and SSA of biochar (Aller, 2016). For example, higher SSA was observed in biochar produced from hardwood and nut/shell biomass as compared to straw and algal biomass. The SSA of biochar was found well correlated with lignin content in biomass feedstock (Tomczyk et al., 2020). In general, lignin-rich feedstock (woody and nut/shell) generate biochar with lower ash and mineral content than manure and green waste (low lignin) feedstock (Tripathi et al., 2016). For example, switch grass and corn stover biochar had more mineral element contents (e.g., P, K, Ca, Mg, and Si) than hard word biochar produced under same pyrolysis condition (Aller, 2016). Similarly, N-rich biomass such as manure and algae could be a promising feedstock for preparation N-enriched biochar, whereas P-rich biomass such as chicken litter and animal carcass could produce P-enriched biochar (Chen et al., 2020; Hossain et al., 2021). It was observed that variation in pH, EC and CEC of biochar was due to differences in mineral content in feedstock (Chintala et al., 2014). Ash content in biochar had a positive correlation with pH, EC and CEC values (Aller, 2016). Similarly, biochar produced from lignin-rich biomass contained high OC, whereas biochar produced from green waste and manures had a large proportion of inorganic C (Suliman et al., 2016). High nutrient values were found in biochar produced from manure and green waste, while low contents were found in wood and nut/shell biochar (Aller, 2016; Hussain et al., 2021).

The pyrolysis methods (i.e., temperature, duration, heating rate and resident time) are also key factors determining physical and chemical properties of biochar (Aller, 2016). In general, relatively higher pyrolysis temperature (>400 ^{o}C) generates biochar with higher pH, SSA and CEC (Aller, 2016), but lower available nutrients (Mukherjee and Zimmerman, 2013). However, biochar produced at low pyrolysis temperature (<400 °C) showed more agronomic potential due to the presence of more labile C and available nutrients (Hussain et al., 2017; Gul et al., 2015). Biochar generated in fast pyrolysis (FP) at low temperature had more labile C and nutrients, while biochar generated in slow pyrolysis (SP) at high temperature had more recalcitrant C and less available nutrients (Zhao et al., 2013). The SP- and FP-derived biochar also behaved differently upon soil application. For example, FP-derived biochar had more C sequestration potential than SP-derived biochar. Similar to C, N and P contents, their speciation in biochar was also significantly influenced by pyrolysis temperature. In general, total N (TN) content in biochar decreased in high temperature product (Hossain et al., 2021). Such decrease of TN in biochar would vary with type of feedstock. For example, the highest reduction of TN was observed in biochar from manure, and the smallest in biochar made from lignin-rich materials. Similarly, biochar produced at low temperature was found to have high mineral ($NH_4^+ + NO_3^-$) N or available N than biochar produced at high temperature (Aller, 2016; Rodriguez et al., 2020). Total P (TP) content in biochar was found to increase with pyrolysis temperature up to 600°C, but available or soluble P was reported to decrease in biochar produced at high temperature (Aller, 2016).

The feedstock and pyrolysis methods can be optimized to get designer biochar that have specific properties to match selective physicochemical constraints of highly weathered (degraded) tropical soils to be addressed through biochar application (Fig. 4). The benefits of biochar are only possible to harness if biochar production is well synchronized with the specific problem of local soil and an easily accessible suitable feedstock (waste biomass) is used (Oni et al., 2019).

5.1.2. Biochar co-composting

The interaction of biochar with SOM is well acknowledged in various literature. Recently, synergistic effects of co-composting of biochar have been highlighted in some studies (Khan et al., 2016; Sanchez-Monedero et al., 2018). Co-composting of biochar with other organic material could enhance biochar properties by charging its surface with nutrients. Since biochar serves as a habitat for soil microorganisms and acts as a source of substrates for microbial metabolism, it is expected that biochar addition in the initial stage of composting would have positive effect on the microbial community. Similarly, high temperature and microbial activity prevailing during the composting process might cause chemical changes in biochar surface, which significantly could alter the surface reactivity of biochar (Sanchez-Monedero et al., 2018). The surface reactivity of biochar evolves due to a process called ‘oxidative ageing’ or ‘weathering’ which involves the formation of functional groups on biochar surface through chemical oxidation (Steiner et al., 2015). Another process that leads to surface modification of biochar during co-composting process might be the organic coating of biochar via adsorption of compost-derived materials, particularly dissolved organic matter (DOM) and microbial residues (Wiedner et al., 2015). The adsorption sites (SSA) are expected to reduce due to clogging of biochar micropores by organic coating (Sanchez-Monedero et al., 2018). The organic coating of inner porous surface of biochar could act as a ‘glue’ for plant nutrients, allowing their slow-release in the soil environment. It was also hypothesized that organic-coated biochar could hold soluble nutrients by the ‘glue’ effect, thus preventing their leaching losses (Conte and Laudicina, 2017). Due to the ageing process and adsorption of DOM, an increase of oxygenated functional groups (Agyarko-Mintah et al., 2017), particularly acidic carboxylic groups (Wiedner et al., 2015) was observed on biochar surface. As a result of such modification in biochar surface, improvement in CEC, and therefore nutrient retention ability of biochar could be expected. However, the surface area of biochar was found to decline during co-composting process due to the clogging of microspores by adsorption of compost-derived DOM leachate (Prost et al., 2013). The ageing of biochar during co-composting could induce beneficial changes in surface chemistry of biochar. Interaction of biochar with composting substrates could enhance nutrient retention capacity but alter surface properties of biochar (Fig. 4).

The co-composted biochar (COMBI) could be a more effective soil amendment than sole biochar in highly weathered tropical soil which is naturally deficient in OM and soluble nutrients. Sufficient literature is available on the characterization of biochar and biochar-composted mixtures. However, very few works reported the impact of COMBI on soil properties, plant performances and other environmental benefits (Wang et al., 2019). Few studies reported the role of COMBI as a controlled- and slow-release fertilizer in poorly fertile soil. For example, Wang et al. (2019) showed that COMBI application significantly increased grain yield in cereal crops (e.g., wheat, barley, maize and oat) as compared to treatment without COMBI. Application of COMBI recorded significant yield improvement in banana (Bass et al., 2016), grape (Oldfield et al., 2018; Sanchez-Monedero et al., 2019), tomato (Sanchez-Monedero et al., 2019) and leek (Oldfield et al., 2018) over sole application of biochar and compost. Similarly, application of COMBI significantly improved CEC, total SOM and available nutrients in a red soil (Ferrosol) as compared to sole application of biochar and manure (Agegnehu et al., 2016). Therefore, properties of both biochar and compost were improved to a great extend during co-composting, which resulted in improvements in soil health and crop productivity (Antonangelo et al., 2021). Future studies are needed to develop novel co-composted materials by making suitable match between biochar and compost raw materials which are locally available in abundant quantity at minimal cost.

5.1.3. Enriched biochar composite

The application of biochar is known to improve the quality of agricultural soils of the tropics (Jeffery et al., 2017). However, low nutrient content and high requirement of biochar (Hossain et al., 2020; Saha et al., 2019) had challenged the scientific community for the development of low-cost, nutrient-rich and environmentally friendly mineral-enriched biochar for sustainable crop production and soil quality improvement (Ye et al., 2016; Hossain et al., 2020; Basak et al., 2021). In recent years, mineral enrichment of biochar has been done by using different clay minerals, calcite, dolomite, rock phosphate, waste mica and other Ca-, Mg-and Fe-containing compounds. The mineral enrichment of biochar could lead to the formation of biochar-mineral complexes or composites (BMC), which results in the improvement of physicochemical properties and stability of the biochar (Chia et al., 2014; Ashiq et al., 2019; Basak et al., 2021). For example, the production of mineral-enriched biochar had brought a tremendous alteration in the nutrient composition, and increased SSA, pore-volume, pore structure, thermal stability, pH, CEC and EC of the final product (Basak et al., 2021; Abriz and Golezani, 2021). The BMC also showed an increased aromaticity, surface functional groups and nutrient contents (Lin et al., 2013; Ye et al., 2016). A low dose application (~0.1 t ha^{-1}) of BMC fertilizer was found to increase foliar nutrient concentrations, plant height, biomass and crop yield, and provided additional benefits in terms of nutrient improvements in the soil and leaf tissues of wheat, sorghum and ginger compared to conventional organic and inorganic fertilizers (Blackwell et al., 2021; Ferrera et al., 2018; Basak et al., 2021). The BMC application demonstrated improved soil physicochemical and biological properties, including soil pH, CEC, nutrient content and availability, and soil microbial and enzymatic activities (Blackwell et al., 2015; Ferrera et al., 2018; Basak et al., 2021). The improved surface characteristics with the slow-release property of BMC made it an excellent alternative amendment to chemical fertilizers for sustainable crop production and management of soil quality, particularly in highly weathered tropical soil.

5.2. Improving biochar use efficiency

Apart from production of smart and enhanced biochar, application strategies and methods should be developed to improve biochar use efficiency, especially in weathered tropical soils. To make biochar a viable technology for agronomic, environmental and economic sustainability, more emphasis should be given to develop biochar application strategies (e.g., optimum application rate, application in plow layer, and co-application with fertilizer and other additives) for improving biochar use efficiency, which would reduce biochar application cost (Fig. 4). The use of farmers' own waste collected in a cooperative manner could reduce the cost of biochar production and provide them an extra economic benefit. Furthermore, biochar technology should be encouraged in combination with positive policy reforms (e.g., awarding C credit), which will prove beneficial to farmers.

5.2.1. Rate and methods of biochar application

It is important to know the optimum amount of biochar application to harness the maximum agronomic benefits without compromising other soil functions and avoiding untoward environmental concerns. The main focus should be to use minimum application of biochar to get optimum crop yield and soil functions because application of an excessive biochar amount is not economically viable (Lehmann and Joseph, 2015). A meta-analysis indicated that nearly 30% experiments used biochar rate < 10 t ha^{-1}, while around 60% studies used biochar rate < 30 t ha^{-1} (Liu et al., 2013). A biochar application rate of 16 t ha^{-1} was able to increase the water holding capacity of a loamy Entisol (Liu et al., 2016). This information suggested that biochar application rate was likely to be soil, climate and crop dependent. Since arable tropical soils have low pH, poor fertility and small fertilizer inputs, a relatively high application rate of biochar might be needed to obtain intended agronomic benefits in those soils (Jeffery et al., 2017). For example, positive yield effects of biochar application up to 140 t ha^{-1} were reported in a weathered tropical soil (Lehmann and Rondon, 2006). When estimating the optimum biochar loading capacity (BLC) of a weathered tropical soil, the functions of the soil and transport of biochar fine particles to surface and ground water should also be considered apart from crop productivity (Verheijen et al., 2010). Therefore, biochar application rate or BLC needs to be developed considering the 'long-term cumulative rate' (i.e., t ha^{-1} yr^{-1} over 10 or 25 years) as well as 'per application rate' for better use efficiency and profitable economics of biochar application.

The method of biochar application into tropical soil could potentially modify the stability and fate of biochar in soil environment (Ding et al., 2016). Most studies on biochar application to soil included surface spreading (or broadcasting), incorporation in plow layer and deep banding that involve adding a significant amount of biochar (>5 t ha^{-1}) into the soil to a depth of 60-100 cm (Bamminger et al., 2018). Only a few studies explored how biochar application in different soil layers would influence its fate and soil properties. Proper application method could lead to enhanced biochar use efficiency, ultimately reducing the application rate and cost. The particle size of biochar is also an important consideration during top-dressing and top-soil application methods. Unwanted loss due to wind and migration through the soil profile could be minimized by applying biochar of ~2 mm particle size (Edenborn et al., 2015). Variation in soil pore types and total porosity regulates soil's hydraulic and leaching characteristics, and biochar application to different soil layers (i.e., topsoil, sub-soil and whole plow layer) might govern the mobility and fate of inorganic N and DOC (Castellini et al., 2015; Li et al., 2018). The sensitivity of surface soil processes to atmospheric temperature could be increased following biochar application to the top 20 cm soil layer (Ding et al., 2019). Addition of biochar to deep soil layer might not show such effects (He et al., 2016). Incorporation through plowing or cultivation would cause greater soil mechanical disturbance as compared to surface spreading and deep banding (Joseph et al., 2010; Li et al., 2016). An exposure of the native OM to microbial attack could occur due to mechanical disturbance of soil aggregates resulting from cultivation, which could facilitate a faster decomposition of biochar than in an undisturbed soil. The impact of biochar application methods on soil microorganisms and C use efficiency is thus a scientific question worth studying in details (Xu et al., 2018).

5.2.2. Co-application of biochar with other additives

Biochar could be mixed with certain proportion of other additives such as organic manure, fertilizer and clay mineral prior to application to soil. Due to high SSA and porosity, biochar retains mineral nutrients in soil for long period of time and stimulate microbial activity (Sadaf et al., 2017). A combined application of biochar with compost and chemical fertilizer would create controlled nutrient release pattern that would lead to a reduction of nutrient losses through leaching and gaseous emissions (Saha et al., 2019; Sadaf et al., 2017). Application of biochar along with vermicompost significantly improved CEC, available nutrient status and crop productivity as compared to no biochar treatment (Doan et al., 2015). Similarly, application of biochar (20 Mg ha^{-1}) mixed with compost (50 Mg ha^{-1}) had improved fertility status of a sandy soil significantly higher than the compost application alone (Liu et al., 2012). Biochar applied along with crop straw and chemical fertilizer increased the fertility of a sandy soil to a greater degree than only a biochar treatment (Liang et al., 2014; Saha et al., 2019). D'Hose et al. (2020) demonstrated synergistic effects of biochar-blended compost on crop yield and chemical properties of a poorly fertile acidic soil as compared to application of biochar and compost individually. On an average, biochar effectively reduced 30% inputs of fertilizer or compost in agriculture (Baranick et al., 2011). The nutrient status (through improving N and P availability) and quality of highly weathered soils were shown to enhance with the combined application of biochar and compost (Lee et al., 2018; Jien et al., 2021). Furthermore, co-application of biochar with clays and other minerals may be targeted to harness the synergies and co-benefits of both the products. Soil fertility and crop yield could be improved by the nutrient values of mineral powder and biochar (Zhu et al., 2019).

In the above context, the 'terra-preta' model could be implemented for promoting sustainable agriculture in weathered tropical soils. The 'terra-preta' is a product of inorganic (e.g., ash, bones, etc.) and organic (e.g., biomass, manure, urine and char) constituents stabilized by microbial metabolism and humification in weathered tropical soils (Glaser and Birk, 2012). Promoting the formation of new 'terra-preta' ('terra-preta nova') by applying biochar along with other locally available organic and inorganic amendments could help improving the fertility and productivity of weathered tropical soils.

5.2.3. Economic feasibility and policy issues

Currently, quantitative data are lacking for assessing the economic feasibility for land application of biochar because the biochar technology is still considered to be at its early stage. Despite having potential benefits of biochar in weathered tropical soils, biochar application is limited to small-scale due to the issue of economic feasibility. Relatively higher production cost of biochar as compared to other soil amendments such as manure and compost might restrict large-scale adoption of the biochar technology (Oni et al., 2019). Average price of pristine biochar was found around \$1200 ton^{-1}, while the average price of compost was only \$40 ton^{-1} (Baranick et al., 2011). However, this comparison may not be appropriate if long-term benefits of biochar application in tropical soil are considered. The mean residence time (active period) and multiple functional benefits of biochar (e.g., improvement of soil structural and chemical properties) in weathered tropical soil should be considered in the above calculation. A comprehensive economic analysis over long period is needed to work out the cost and benefit of biochar in comparison to other soil amendments.

The cost-benefit ratio is a key factor which could determine the adoption of biochar as a soil amendment just like any other inputs in agricultural production. There is an urgent need of planning for business model by biochar companies or ‘biochar industry’ to manufacture and market biochar at a farmer’s affordable price. The commercial viability of biochar industry is usually maximized when it targets multiple outputs (e.g., biochar, syngas and bio-oil) under a full-set of waste biomass valorization plant. The economic benefits of biochar production could be achieved using locally available waste biomass to address the issue of local area, which could effectively reduce the cost involved in feedstock and transport (Lehmann and Joseph, 2015). Most of the biochar companies (> 90%) focused on marketing the product for small-scale agricultural and environmental applications (Verheijen et al., 2010). Up-scaling the production system to meet large regional and national demands is essential to make the biochar business model economically viable.

In addition to biochar’s value as a soil amendment or an additive and energy source (pyrolysis-derived energy co-products), biochar’s value for C credit should be accounted (Verheijen et al., 2010). The economic feasibility of biochar could be increased by considering the C offset credit.

The long-term benefits of biochar application to soil for C sequestration and CO_2 emission reduction should be accounted in biochar C credit. An estimate in the USA indicated that the benefit of biochar amendment could range from \$12.05 to 100.52 ton^{-1} CO_2 when the price of C offset was \$1 and \$31 ton^{-1} CO_2, respectively (Galinato et al., 2011). Therefore, biochar has the future potential of contributing to the lucrative C offset market. However, biochar is not yet a universally recognized tool for regenerating C credit across countries (Baranick et al., 2011). In developing countries, where weathered tropical soils are often prevalent, the biochar C offset credit may play an encouraging role, and thus farmers of developing countries may get directly benefited by C offset payment, if biochar becomes an approved C offset technology in the near future. Policy measures concerning net zero targets in the agricultural sector across the globe will greatly influence biochar's inclusion in the carbon credit calculation.

6. Conclusions

Biochar has been found as a potential soil amendment that plays a significant role in the rehabilitation of weathered tropical soils – directly and indirectly. Biochar can improve the quality of weathered tropical soils through reducing the acidity, and increasing CEC, water and nutrient availabilities, thereby creating a congenial environment for better crop growth and productivity in the humid tropics. Current research findings depict the exceptional benefits of biochar application in weathered tropical soil as compared to fertile healthy soils. However, the biochar technology till date has not been fully exploited to harness the maximum benefits under weathered tropical soil conditions. To get the maximum economic benefits, cost of biochar production should be minimized and application should be optimized, improving the biochar use efficiency under field conditions. The above can be achieved either by designing smart biochar, biochar co-composite materials and enhanced biochar, or by improving biochar use efficiency through optimum application, co-application with other organic and inorganic additives and co-composting. Co-composted biochar, enhanced biochar composite and co-application with other additives are promising and effective ways to harness the full potential of biochar in weathered soils of the humid tropics. Overall, biochar in weathered tropical soil holds enormous potential to combat the low fertility and productivity issues, but requires long term evaluation combining with diverse agro-ecological conditions and farming practices.

7. Future research areas

In lights of the above extensive analysis, the beneficial value of biochar for increasing crop yield under tropical conditions should be re-examined and optimized. Biochar may not be always a win-win technology if not well synchronized with agro-ecological conditions of the application location and socio-economic status of the end-users. Considering the evidences presented in this article and existing knowledge gaps (Table 6), the following research directions need urgent implementation to testify large-scale adoption of the most efficient biochar application strategies for revamping the degraded soils across the tropics.

- Bring innovation in making ‘tailored’ or ‘engineered’ or ‘designer’ biochar products from locally available feedstocks matching local and regional needs;
- Optimize biochar use efficiency in amending tropical degraded soils under long term field trials;
- Evaluate biochar’s C credit by considering energy, agriculture, environment and economic footprints;
- Link social and environmental benefits of biochar technology with policy decision;

- Bring in policies for high quality, safe and sustainable supply of biochar worldwide for soil application through initiatives of global (e.g., International Biochar Initiative), regional (e.g., European Biochar Standards) and country specific (e.g., UK Biochar Research Centre) organizations.

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Author contributions

B.B. Basak and B. Sarkar conceptualized the work. B.B. Basak, B. Sarkar and A. Saha prepared the first draft of the manuscript with subsequent inputs from remaining authors. All authors critically reviewed and edited the manuscript.

Declaration of interest

The authors declare no competing financial interests for this study.

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Figures

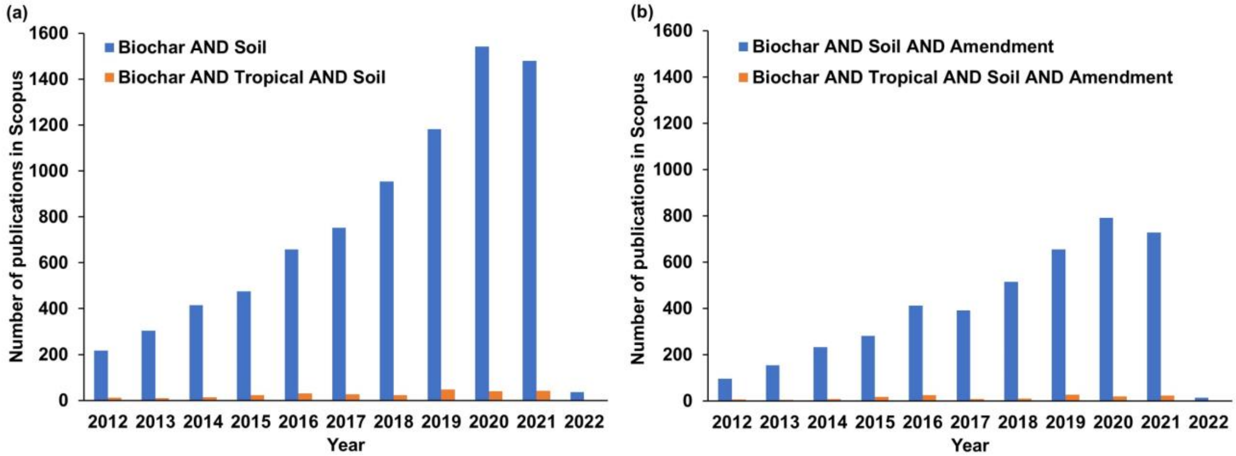

Fig. 1. Comparative numbers of publications in the Scopus database during 2006 – 2022 based on key words ‘Biochar and Soil’ versus ‘Biochar and Tropical and Soil’ with and without the word ‘Amendment’ (searched on 16/09/2021). Journal articles, books and book chapters published in English irrespective of subject areas were included in the search results.

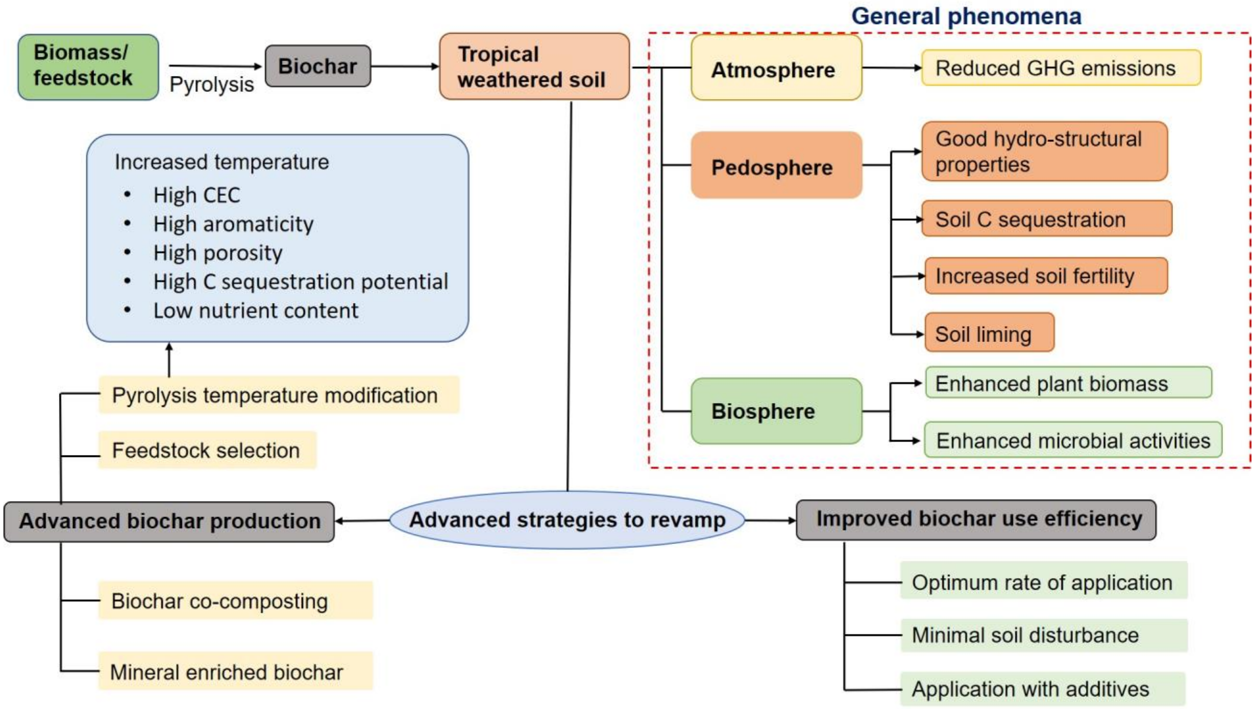

Fig. 2. A flowchart representing roles of biochar and advanced biochar in highly weathered tropical soil.

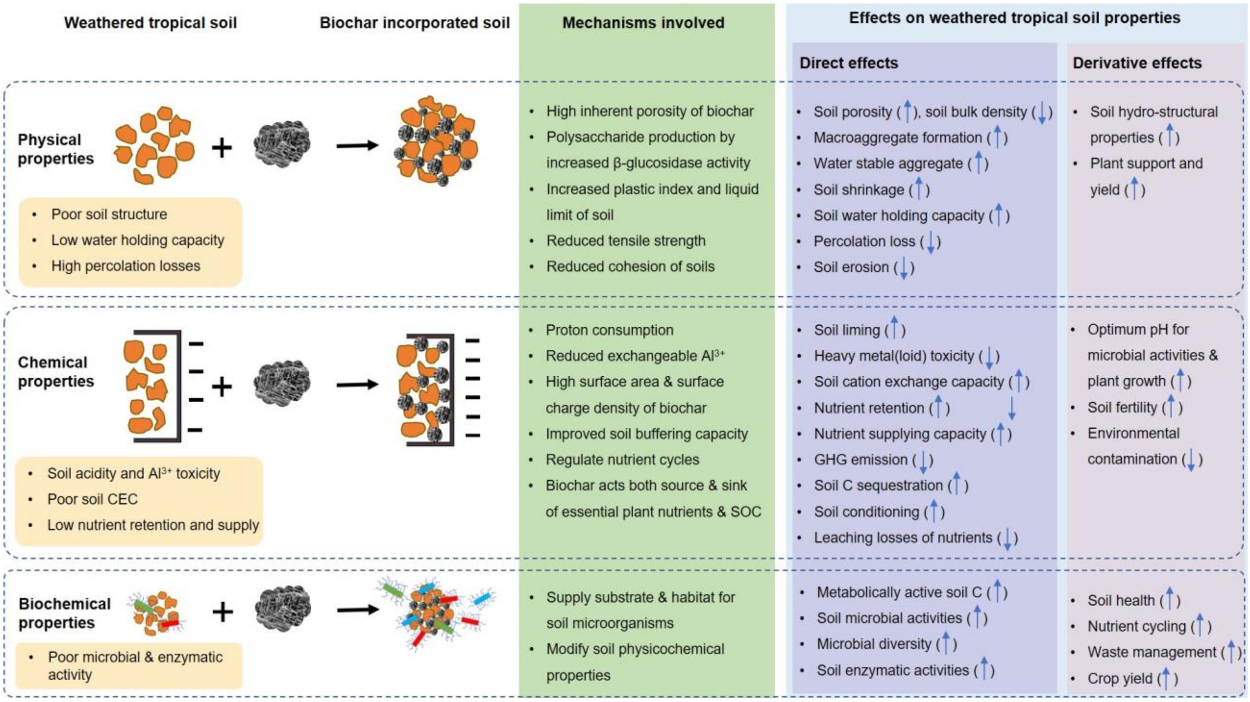

Fig. 3. Biochar induced mechanisms for the modification of properties in highly weathered tropical soil.

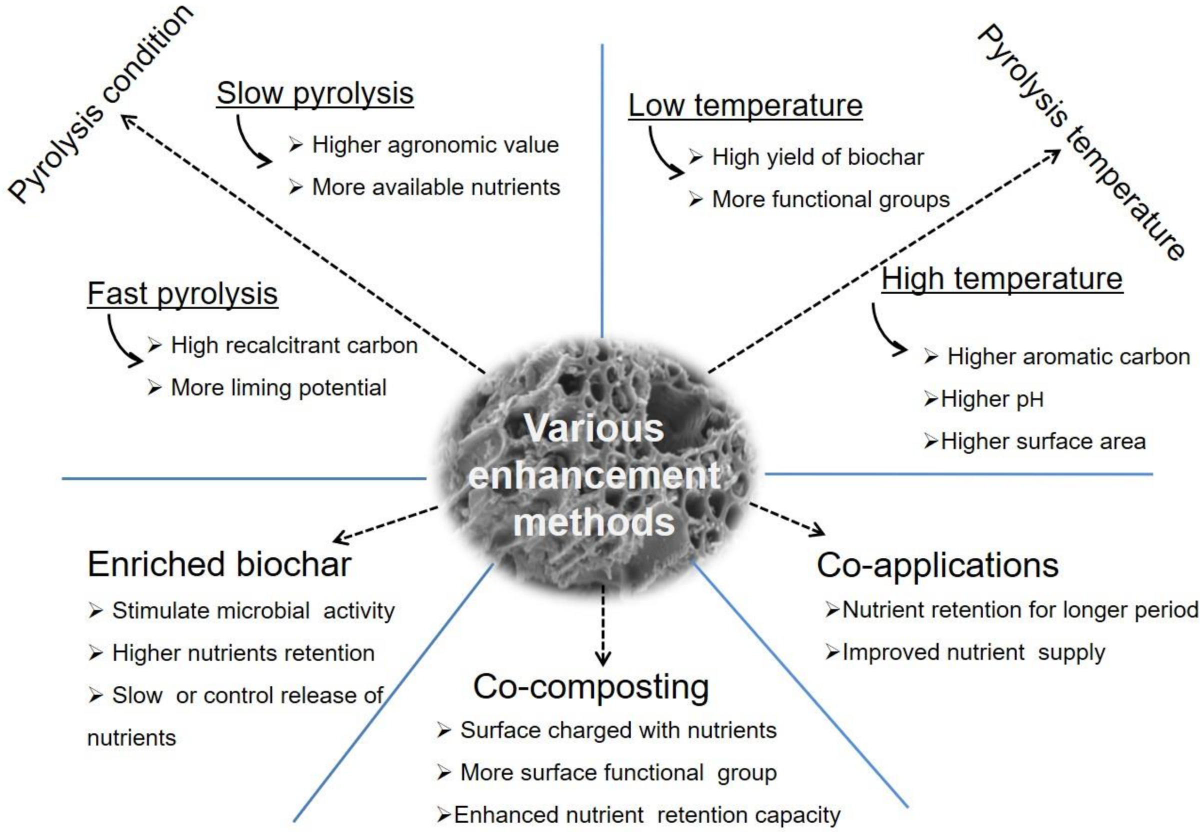

Fig. 4. Various enhancement approaches (pyrolysis temperature & condition, co-application, co-composting and enrichment of biochar etc.) for improving effectiveness of biochar in weathered tropical soils (adapted from Gul et al., 2015; Ding et al., 2016; Wang et al. 2017; Sanchez-Monedero et al., 2018).

Tables

Table 1. Biochar induced changes in physical properties in weathered tropical soils

Biochar feedstock	Rate of application	Soil type	MWD	Aggregate stability	WHC	Soil porosity	Bulk density	Reference
White Babool	5% (w/w)	Acidic Ultisol	8.8% (↑)	-	-	21% (↑)	31.5% (↓)	Jien and Wang (2013)
Wheat straw	40 t ha^{-1}	Red soil	28% (↑)	32.8% to 69.7% (↑) macro-aggregates	-	-	-	Liu et al. (2014)
Wheat straw	16 t ha^{-1}	Loess Plateau	-	105.8% (↑) macro-aggregates	-	-	-	Zhang et al. (2017)
Wastewater sludge	4% (w/w)	Ultisol	(↑)	Macro-aggregates (↑)	23% (↑)	-	-	Zong et al. (2018)
Wheat straw	4% (w/w)	Acidic Ultisol	-	-	-	-	18% (↓)	Malik et al. (2018)
Rice husk	12 t ha^{-1}	Alfisol	-	23% (↑)	25% (↑)	-	18% (↓)	Oladele (2019)
Wheat straw	40 t ha^{-1}	Red soil	-	-	9.7% (↑)	-	0.43 g cm^{-3} (↓)	Jin et al. (2019)
Zelkova	4% BC + Compost 1% (w/w)	Weathered tropical soil	-	-	-	22% (↑)	16% (↓)	Jein et al. (2021)

MWD: Mean Weight Diameter of soil aggregates; WHC: Water Holding Capacity; ↑: increase; ↓: decrease

Table 2. Biochar induced changes in chemical properties and nutrient availability in weathered tropical soils

Biochar feedstock	**Rate of application**	**Soil type**	**Impacts on chemical properties**	**Impact on nutrient availability**	**Reference**
White Babool	5% (w/w)	Acidic Ultisol	pH (23.5% ↑); CEC (31.4%↑); base cation (75.4% ↑); SOC (33.1% ↑)	-	Jien and Wang (2013)
Hardwood	22.4 t ha^{-1}	Aridisol	SOC (36.4 % ↑)	Available P (↑); mineral N (NO_3^- & NH_4^+) (↑)	Elzobair et al. (2016)
Wheat straw	16 t ha^{-1}	Loess Plateau	SOC (79.6% ↑)	Total N (24.1%) (↑)	Zhang et al. (2017)
Wastewater sludge	4% (w/w)	Ultisol	pH (2.33 unit) (↑); total C (94%) (↑); exchangeable acidity (↓)	Available N (18%), P (94%) and K (84.4%) (↑)	Zong et al. (2018)
Chicken manure and Coffee husk	20% (w/w)	Red and Red-Yellow Latosol	pH (4-5.4 unit) (↑); CEC (2-10 fold) (↑); SOC (10.0-16.9%) (↑)	-	Domingues et al. (2020)
Eucalyptus sawdust and Sugarcane bagasse	20% (w/w)	Red and Red-Yellow Latosol	pH (0.7-1.2 unit) (↑); SOC (3.1-11.2 fold) (↑)	-	Domingues et al. (2020)
Corncob	20 t ha^{-1}	Ferralsol	pH (↑); CEC (↑); SOC (↑)	Total N (↑); available P, K, Ca & Mg (↑)	Apori and Byalebeka (2021)
Rice husk	10 g kg^{-1}	Costal savanna (Haplic Acrisol)	pH (0.28 unit) (↑); CEC (2 fold) (↑); TOC (1.9 fold) (↑)	Total N (40%) (↑)	Frimpong et al. (2021)

Corncob	10 g kg^{-1}	Costal savanna (Haplic Acrisol)	pH (0.41 unit) (↑); CEC (1.5 fold) (↑); TOC (1.9 fold) (↑)	Total N (10%) (↑)	Frimpong et al. (2021)

TOC and SOC: Total and Soil organic carbon; TN: Total nitrogen; ↑: increase; ↓: decrease

Table 3. Biochar induced changes in microbial activity in weathered tropical soils

Biochar feedstock	**Rate of application**	**Soil type**	**Impact on microbial activity**	**Reference**
Wheat straw	40 t ha^{-1}	Weathered acidic soil	DHA (↑), AlkP (↓), β-glucosidase (↑)	Chen et al. (2013)
White Babool	5% (w/w)	Acidic Ultisol	33.8% rise in MBC	Jien and Wang (2013)
Forest litter	5 % w/w	Red oxidized loam soil	Bacterial diversity (↑); fungal diversity (↓)	Hu et al. (2014)
Oak wood & Bamboo	0.5 % w/w	Ferrosol	MBC (↑); MBN (↑) urease activity (↑)	Demisie and Zhang (2015)
Rice husk	12 t ha^{-1}	Alfisol	MBC (↑), MBN (↑) and MBP (↑), CO2 flux (↑)	Oladele (2019)
Rice husk	10 g kg^{-1}	Costal savanna (Haplic Acrisol)	-	Frimpong et al. (2021)
Corncob	10 g kg^{-1}	Costal savanna (Haplic Acrisol)	MBC (↑)	Frimpong et al. (2021)
Zelkova	4% BC + Compost 1% (w/w)	Weathered tropical soil	Phosphatase (↑), β-glucosidase (↑), and Arylsulfatase (↑)	Jien et al. (2021)

MBC: Microbial biomass carbon; MBN: Microbial biomass nitrogen; DHA: Dehydrogenase; AlkP: Alkaline phosphatase; AcP: Acid Phosphatase

1391 **Table 4.** Biochar induced climate change mitigation in weathered tropical soils

Feedstock	Application rate (t ha^{-1})	Crops	Type of soil	Experiment type	Impact of GHG emission and C sequestration	Reference
Wood	20 t ha^{-1}	Maize-Soybean	Oxisol (Colombian savanna)	Field experiment	After 4 year of continuous cultivation, total C content in soil increased by 4% over the treatments devoid of biochar	Major et al. (2010)
Maize cob	50 g kg^{-1} soil	Maize	Acrisol (slightly acidic sandy loam soil)	Field experiment	Organic C content increased by 8 times over control	Cornelissen et al. (2013)
Bamboo	700 g t^{-1} soil	Maize	Acrisol (slightly acidic loamy soil)	Mesocosm experiment	Carbon content increased by 12% over control	Doan et al. (2015)
Red gram stalk	2.5 t ha^{-1}	Groundnut	Alfisol (slightly acidic sandy soil)	Field experiment	Significant and 22% increase in C stock was recorded over chemical fertilizer	Pandian et al. (2016)
Eucalyptus	4 g 100 g^{-1} soil	-	Ultisol (loamy sand)	Soil incubation	Decreased emissions of CO_2, CH_4 and N_2O	Butnan et al. (2016)
Rice straw	50 g kg^{-1} soil	-	Oxisol (acidic clay loam)	Soil incubation	Reduce 14% cumulative N_2O emission	He et al. (2016)
Rice straw	50 g kg^{-1} soil	-	Oxisol (acidic sandy loam)	Soil incubation	Significantly reduced (37%) cumulative N_2O than control	He et al. (2016)
Waste willow wood	10 t ha^{-1}	Maize	Red Ferralsol (moderately acidic clay soil)	Field experiment	Significantly decreased seasonal CO_2 (11%) and N_2O (52%) flux than composted field	Agegnehu et al. (2016)
Sugarcane straw	Biochar at 50 t ha^{-1}	-	Oxisol (highly acidic sandy soil)	Soil incubation	Significant reduction (35%) in N_2O production than the treatments containing filtercake and vinasse	Abbruzzini et al. (2017)

Rice husk	Biochar at 3-2 t ha^{-1}	Rice	Alfisol (acidic sandy clay loam soil)	Field experiment	Significantly decreased the soil CO_2 flux	Oladele et al. (2019)
Sugarcane bagasse	Biochar at 4.2 t ha^{-1} $year^{-1}$	Sugarcane	Oxisol	Field experiment	Increased in soil C stocks by 2.35 ± 0.4 t C ha^{-1} $year^{-1}$ in sugarcane fields can be obtained and could reduce e 50 Mt of CO_2 equivalent $year^{-1}$	Lefebvre et al. (2020)

1393 **Table 5.** Biochar induced improvement of crop productivity in weathered tropical soils

Feedstock	**Application rate (t ha^{-1})**	**Crops**	**Type of soil**	**Experiment type**	**Yield response (% increase over control)**	**Reference**
Poultry litter	10	Radish	Alfisol	Pot	42	Chan et al. (2008)
Black carbon	20	Maize	Oxisol	Field	28-140	Major et al. (2010)
Rice straw	2.4	Maize	Ultisol	Pot	146	Peng et al. (2011)
Wheat straw	40	Rapeseed	Red soil	Field	36	Liu et al. (2014)
Wheat straw	40	Sweet potato	Red soil	Field	53.8	Liu et al. (2014)
Rice husk	15	Maize	Ultisol	Field	100	Cornelissen et al. (2018)
Cacao shell	15	Maize	Ultisol	Field	100	Cornelissen et al. (2018)
Wheat straw	40	Rapeseed	Red soil	Field	77.1	Jin, et al. (2019)
Wheat straw	40	Sweet potato	Red soil	Field	83.9	Jin, et al. (2019)
Rice husk	6	Rice	Alfisol	Field	78	Oladeleet al. (2019)
Rice husk	6	Rice	Ultisol	Field	83	Oladeleet al. (2019)

Rice straw	22.5	Wheat-Millet rotation	Red soil	Pot	138	He et al. (2020)
Wood biomass	15	Amaranthus	Nitisol	Pot	54	Elias et al. (2020)
Hard wood	4.7	Cucumber	Nitisol	Field	77.3	Obiahu et al. (2020)

Table 6. Future research directions for biochar amendment in weathered tropical soils based on current evidences and existing knowledge gaps

Categories	Existing knowledge gap	Future research direction
Smart /Enhanced biochar	Most of the studies (co-composted and mineral enriched biochar) restricted to production and characterization. Limited information on evaluation in plant growth as well as soil quality improvement study	Intensive plant growth experiment is needed to evaluate the full potential of designed/smart biochar as well as co-application with other additives (clay, natural mineral and microbes) for phasing out the chemical fertilizers
Application rate	Studies reported wide range of biochar application rate (2.5-30 t ha^{-1})	Biochar application rate need to be optimized considering 'long-term rate' (over 10 or 25 years) as well as 'per application rate' for better use efficiency
Experimental condition	Pot experiments often only with plant biomass data. Most of the field experiment data are available for only 1-2 years.	Long-term studies are needed combining biochar with other soil and crop management parameters (tillage, type of crops and cropping intensity)
Economics	Little quantitative information available on the economics of biochar (production, transport and application etc. cost)	Comprehensive study on economic analysis over multiple time horizons is needed in comparison to other soil amendments
Policy matter	Currently biochar is not recognized as an official method of producing carbon credits	Evaluation of biochar carbon credit through policy measures on energy, agriculture and climate change