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Review

The role of biochar and biochar-compost in improving soil quality and crop performance: A review

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ABSTRACT

Multiple nutrient deficiencies related to severe soil fertility depletion have emerged as the major constraint to the sustainability of agriculture on a global scale. Use of biochar and biochar-compost mixtures from different alternative organic sources have been proposed as an option for improving soil fertility, restoring degraded land, and mitigating the emissions of greenhouse gasses associated with agriculture. We review the findings of 634 publications in the last decade on biochar and biochar-compost mixtures as soil amendments in order to identify the potential gaps in our understanding of the role of these amendments in agriculture. We found that: i) the majority of published studies have been carried out in developed countries where soils are less impaired in terms of food production capacity than in many developing countries; ii) studies on biochar produced in small kilns are more common than biochars produced at commercial scale in developed countries, whereas biochars produced using traditional techniques are more commonly used than biochars produced in modern pyrolysis units in developing countries; iii) laboratory and greenhouse studies are more common than field studies; and iv) wood and municipal wastes were the major feedstock for the preparation of biochar compared to crop residues and manures. Although, biochar-compost application proved to be more generally effective in improving soil properties and crop yields (field crops and horticulture crops) than biochar alone, along with desired soil properties, could be a feasible alternative to remediate the degraded soils and improve their productivity potential in the long-term. Overall, a lack of long-term, well-designed field studies on the efficacy of biochar and biochar-compost mixtures on different soil types and agro-climatic zones are limiting our current understanding of biochar's potential to enhance crop production and mitigate climate change. We further suggest that greater collaboration between researchers, biochar producers, and policy makers is required to advance the research and uptake of this important technology at a global scale.

1. Introduction

Severe soil fertility depletion and declining agricultural productivity due to a reduction of soil organic matter (SOM) and nutrient imbalances are major constraints in most tropical agricultural soils (Lal, 2015b; Pender, 2009; Sanchez, 2002). Global soil acidity occupies 30% of ice-free land (Von Uexküll and Mutert, 1995). Soil salinization (20% of world irrigated land) is also a serious environmental issue, affecting about 8.31×10^8 ha of soil worldwide (Metternicht and Zinck, 2003; Pitman and Läuchli, 2002), roughly ten times the size of Venezuela and 20 times the size of France, with secondary salinization occupying an additional area of 7.7×10^7 ha, of which 58% occurs in irrigated areas (Li et al., 2014a). More than half of all African people are affected by land degradation, making it one of the continent’s most urgent development issues with significant costs. For example, an estimated US $42 billion in income and 6 million ha of productive land are lost every year due to land degradation and declining agricultural productivity (Bationo et al., 2006).

Soil nutrient depletion is an important concern, directly linked to food insecurity due to unsustainable intensified land use (Henao and Baanante, 1999). Total nutrient deficits at the global scale have been estimated to be 20 Teragram (Tg, 10^{12} g) of which 75% occurred in developing countries, 14% in developed countries and 11% in least developed countries. Considering a total NPK deficit for four crops (rice, wheat, maize, and barley) with an individual nutrient deficit in the form of N accounted for 28%, (5.5 Tg), P for 12% (2.3 Tg), and K for 60% (12.2 Tg) (Tan et al., 2005). Assessments have shown that nutrient losses are only partially compensated by natural and man-made inputs, thus the nutrient balance for the total of Sub-Saharan Africa (SSA) appears to be negative, being currently minus 26 kg N, 3 kg P, and

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19 kg K ha^{-1} yr^{-1} (Drechsel et al., 2001). Sheldrick et al. (2002) developed a conceptual model for conducting nutrient audits at regional and global scales by which the global average nutrient depletion rate in the year 1996 was estimated to be 12.1, 4.5, and 20.2 kg N, P, and K ha^{-1} year^{-1}, respectively, implying a corresponding nutrient use efficiency of 50%, 40%, and 75%. Many tropical soils are poor in inorganic nutrients and rely on the recycling of nutrients from soil organic matter to maintain fertility. It has been determined that agriculture without supplementary fertilization can be economically viable for 65 years on temperate prairie but only for six years in cleared tropical semi-arid forest lands (Tiessen et al., 1994). An extremely nutrient-poor Amazonian soil showed no potential for agriculture beyond the three-year lifespan of the forest litter mat inputs, once biological nutrient cycles were interrupted by slash-burning (Tiessen et al., 1994).

The benefits of inorganic fertilizers have been widely demonstrated since the ‘green revolution’ (Vanlauwe et al., 2010), and inorganic fertilizers have played a significant role in increasing agricultural production and productivity over the last half century. However, the highly productive fertilizer and seed technologies introduced over the past decades may be reaching a point of diminishing returns (Gruhn et al., 2000; Rosset et al., 2000). The increase in human population pressure has decreased the availability of arable land and it is no longer feasible to use extended fallow periods to restore soil fertility in the tropics (Lal, 2008). In some areas the fallow period, which would previously have restored soil fertility and organic carbon, is so reduced that it cannot now regenerate soil productivity, in turn leading to the unsustainability of some farming systems (Bationo et al., 2007; Nandwa, 2001). Shrinking land area per capita and declining soil quality have led to a constant increase in the rate of inorganic fertilizer application from year to year to maintain or enhance agricultural productivity (Srivastava, 2009). However, the application of chemical fertilizer alone is not a sustainable solution for improving soil fertility and maintaining yield increases; rather, it has been widely realized that application of excessive inorganic fertilizer, especially N, may cause soil deterioration and other environmental problems due to more rapid organic matter mineralization and resultant decreases in soils carbon stocks (Foley et al., 2005; Liu et al., 2010; Palm et al., 2001).

Soil degradation is the most serious bio-physical constraint limiting agricultural productivity in many parts of the world (Lal, 2015b; Pender, 2009). Soils are becoming degraded (Fig. 1) in many areas worldwide (UNEP, 2002). The long-term benefit of assigning more land to agriculture will not offset the negative environmental impacts of land degradation in the future (Tilman et al., 2002). Instead, a more promising approach to ensuring food security is to increase yield from currently cultivated land where productivity is low (Foley et al., 2011). Sustainable agricultural intensification, increasing productivity per unit land area, is thus necessary to secure the food supply for the increasing world population (Godfray et al., 2010; Tilman et al., 2011). In most tropical environments, sustainable agriculture faces significant constraints due to low nutrient status and rapid mineralization of SOM (Zech et al., 1997). Decline in SOM content leads to decreased cation exchange capacity (CEC). Under such circumstances, the efficiency of applied mineral fertilizers is low (Agegnehu et al., 2016c; Glaser et al., 2002). In addition, most small-scale and subsistence oriented farmers cannot afford to apply the recommended mineral fertilizers regularly due to high costs. Thus, nutrient deficiencies prevalent in many crop production systems of the tropics continue to constrain productivity.

The majority of the agricultural production depends on synthetic fertilizers. In the 21st century, agriculture faces various challenges. It has to meet food and industrial needs of the growing population while protecting the environment. In 2015, the world population was 7.35 billion while projections show that population will reach 9.72 billion by 2050 (UN, 2015). Thus, the world food production must increase by ~70% from its current level to satisfy food needs by 2050 (FAO, 2009). The majority of the agricultural production depends on synthetic fertilizers, and one of the major problems is over application of fertilizers, especially N fertilizers such as urea. The total global demand for NPK fertilizer was 180 million tons in 2012, of which nitrogen fertilizer alone constituted 110 million tons (~61%). The world nitrogen fertilizer demand is expected to be around 116 million tons in 2016 at an annual growth rate of 1.3%. Of the overall increase in demand for 6 million tons nitrogen between 2012 and 2016, 60% will be in Asia, 19% in America, 13% in Europe, 7% in Africa and 1% in Oceania (FAO, 2012). Assuming a 33% N recovery efficiency (Raun et al., 2002) and \$USD 255 ton^{-1} (World Bank, 2015) this equates to an \$18.8 billion annual loss in N fertilizer costs. On the other hand, the global bio-fertilizers market size (nitrogen fixers and phosphate solubilizers account for 75% and 15%, respectively, of global revenue share) is estimated to be \$USD 535.8 million in 2015. The North America bio-fertilizer market is the largest followed by Europe, accounting for over 54% of the global revenue, produced using organic wastes such as struvite and compost acting as substitute to chemical-based fertilizers (www.grandviewresearch.com).

Maintaining an appropriate level of soil organic matter and ensuring the efficient biological cycling of nutrients is crucial to the success of soil management and agricultural productivity strategies (Bationo et al., 2007; Vanlauwe et al., 2010). These practices include the application of organic and inorganic fertilizers combined with knowledge of how to adapt these practices to local conditions, aiming to maximize agronomic use efficiency of the applied nutrients and thus crop productivity (Vanlauwe et al., 2010). However, in the tropics, naturally rapid mineralization of soil organic matter is a limitation on the

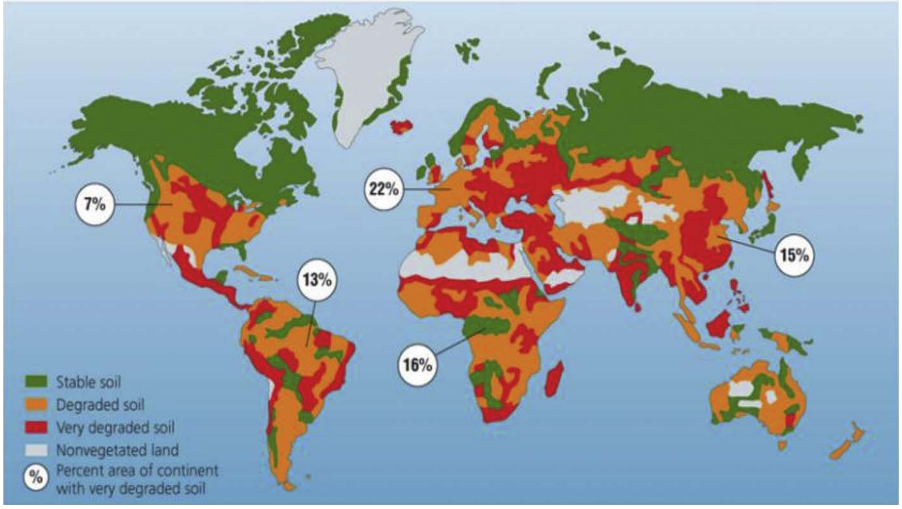

Fig. 1. Soil degradation: A global concern (UNEP, 2002); 2013 Pearson Canada Inc.

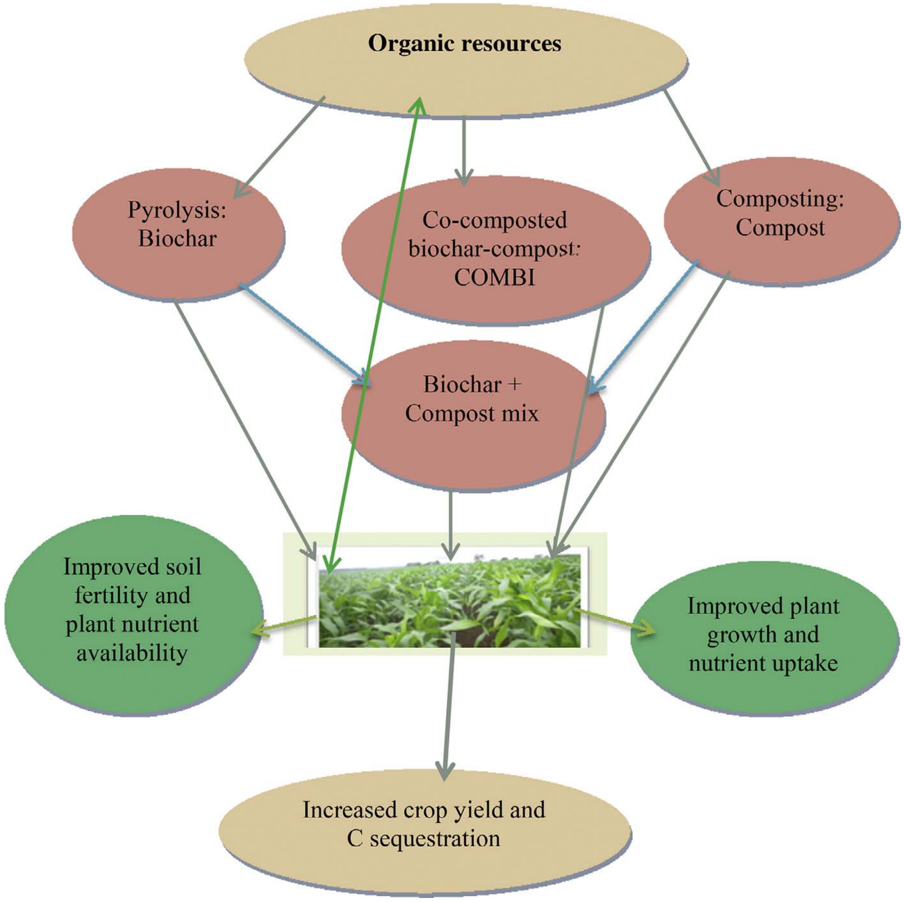

Fig. 2. Conceptual framework for organic amendments and plant – soil relationships.

practical application of organic fertilizers. Thus, in addition to repeated application at high dose and cost of application of organic materials, their rapid decomposition and mineralization may make a significant contribution to global warming (Kaur et al., 2008; Srivastava et al., 2014; Zech et al., 1997). Realizing such environmental and soil degradation problems, biochar research has progressed considerably with important key findings on agronomic benefits, carbon sequestration, greenhouse gas emissions, soil quality, soil acidity, soil fertility, soil salinity, etc. (Lehmann et al., 2003a; Van Zwieten et al., 2014), along with research into biochar-compost mixes and co-composted-biochar-compost as soil amendments (Agegnehu et al., 2015a; Schulz et al., 2013).

In spite of the application of mulches, composts, and manures having positive effect in enhancing soil fertility, organic matter is usually mineralized very rapidly under tropical conditions (Tiessen et al., 1994), and thus, only a small portion of the applied organic compounds will be stabilized in the soil in the long term, with most released back to the atmosphere as CO_2 (Bol et al., 2000; Fearnside, 2000). An alternative to organic amendments is the use of more stable carbon compounds such as carbonized materials or their extracts. Glaser et al. (2001) showed that carbonized materials from the incomplete combustion of organic material (black C, pyrogenic C, charcoal) are responsible for maintaining high levels of SOM and available nutrients in anthropogenic soils of the Brazilian Amazon basin. Global analysis further revealed that up to 12% of the total anthropogenic C emissions by land use change (0.21 petagram, Pg C) can be off-set annually in soil, if slash- and- burn is replaced by slash- and-char (Lehmann et al., 2006). Some recent studies have indicated that the simultaneous application of biochar and compost resulted in enhanced soil fertility, water holding capacity, crop yield and C sequestration benefit (Agegnehu et al., 2016a; Schulz and Glaser, 2012).

Soil quality is a strong determinant of agronomic yield. Although food and nutritional insecurity are global issues, they are particularly critical in developing countries due to population growth and declining availability of land, water and other farm resources (Lal, 2015b; Ray et al., 2015). Sustainability of agronomic practices and increases in production are, thus, essential to meeting the goals of increasing food supply. The challenge is especially overwhelming owing to the changing and uncertain climate (Lobell and Field, 2007) and the associated increase in the potential for further soil degradation (Bai et al., 2008). Soil organic matter and bulk density are two parameters and indicators of potential soil productivity and can be improved upon addition of organic wastes. Soil organic carbon (SOC) is vital for sustainable yields as it is able to retain water and nutrients, provide a habitat for soil biota and improve soil structure (Lal, 2009; Lorenz et al., 2007). Globally the SOC pool contains more than twice the total carbon present in the atmosphere (Taghizadeh-Toosi et al., 2016). Land use change and farming practices have already led to a marked reduction in SOC, and with the increased temperatures expected with climate change SOC is likely to fall further (Raich et al., 2002), reducing soil fertility and exacerbating climate change. While analyzing the heterogeneous global crop yield response to biochar through a meta-regression analysis, Crane-Droesch et al. (2013) suggested no biochar physical parameters including pH, carbon content or temperature of pyrolysis were significant predictors of yield impacts. While soil cation exchange capacity and organic carbon were two strong predictors of yield response. In the recent past, many reviews touching various issues related to biochar have been published (Atkinson et al., 2010; Biederman and Harpole, 2013; Jeffery et al., 2011; Lehmann et al., 2011; Lone et al., 2015; Mahar et al., 2015; Sohi et al., 2010; Solaiman and Anawar, 2015; Spokas et al., 2012; Wiszniewska et al., 2016), but reviews focusing on crop response using the nexus between biochar and compost are lacking. Above all, the available studies also demonstrate, why short term biochar application has low magnitude of crop response (Jay

Table 1
Global frequency distribution of experimental conditions and targeted crops for biochar and biochar-compost related studies.

Experiment condition	Cereal crop	Horticultural crops	Legumes	Grasses/ pasture
Experiment type				
Field	121	63	19	11
Greenhouse/pot	112	82	61	13
Production system				
Commercial production	112	61	23	14
Experimental production	76	39	31	11
Traditional	20	5	3	3
Unspecified	49	35	23	14
Feedstock				
Wood	135	68	41	16
Crop residue	122	53	16	12
Manure	33	27	18	15
Grasses and weeds	12	10	11	7
Sludge and municipal organic waste	34	21	14	12

et al., 2015; Vaccari et al., 2015). This review examines the impact of biochar, biochar-compost and co-composted-biochar-compost on crop yield, soil biophysical and chemical properties, outlined through a new conceptual framework (Fig. 2).

2. Literature search and data processing

The International Biochar Initiative (IBI) worked with interested parties around the world to develop a definition of biochar. They agreed on the following definition: Biochar is a solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment.

A literature search and data collection was conducted through the Web of Science (apps.webofknowledge.com), Elsevier Science Direct (www.sciencedirect.com), IBI (www.biochar-international.org) and Google Scholar (scholar.google.com). We searched the literature published up to 2016, using the keywords "biochar" and "biochar-compost". Although 1053 papers were retrieved; we focus on those reporting empirical results. A total of 634 publications were used to develop a data archive (Table 1); altogether including 273 field; 258 greenhouse pot and 103 laboratory studies. Of these; nine publications researched the use of biochar-compost mixture and co-composted biochar-compost (COMBI).

Individual articles from the collected literature were grouped with respect to research objective, experiment type, feedstock and biochar production method. Research objectives were further sub-categorized into articles focusing on crop yield, pollutant remediation and greenhouse gasses emission, after which the experiments were then grouped into experiment type as laboratory (incubation), pot or field experiments; biomass feedstock for biochar production were organized into 6 classes: wood residue, crop residue, grass, manure, sludge and municipal organic waste. Biochar production systems were categorized as those using a laboratory muffle furnace, stove/oven and other experimentally designed pyrolyzer, traditional production technology (conventional retort and kiln), and commercial-scale engineered production systems. The crop or plant tested in the field and pot experiments were classified into four groups: cereal crop (grain crops such as wheat, maize and rice), horticultural crops (such as tomato, cabbage, lettuce, etc.), legumes and grass/pasture. A study was assigned as "unspecified" when relevant information for a given category was not provided.

All the information gleaned from the published literature was organized into an archived database. Statistical analysis was performed using SAS-STAT software and graphical presentation was performed in Microsoft Excel 2016.

3. Characterization of biochar

When biochar is applied to soil, it has generally been shown to be beneficial for growing crops. Moreover, biochar contains stable C and after its application to soil, this C remains sequestered for much longer periods than it would in its original organic carbon form. Thus, Biochar can be used as a product by itself or as an ingredient within a blended product, with a range of applications as an agent for soil improvement, improved resource use efficiency, remediation and/or protection against particular environmental pollution, and as an avenue for greenhouse gas mitigation (IBI, 2014).

The physicochemical properties of different biochar types can be characterized and used as a guide to where and how they are applied to soil. Physical characteristics include particle density, surface area and pore-size distributions whereas the main chemical characteristics, include pH, total C and total N, conductivity, P, acid neutralizing capacity, exchangeable cations, cation exchange capacity, and selected nutrient and contaminant trace elements. Characteristics of biochar materials will vary depending on the biochar feedstock and pyrolysis conditions, (Bird, 2015). Variation in the pH, ash content, surface area, and other characteristics of biochar provides the basis for the concept of "designer biochar" (Major, 2010; Novak et al., 2009), where the characteristics of a biochar are matched to the specific needs of a soil and/or soil management method. For instance, some high-pH biochars may be best for applying to acidic soils, while others with elevated contents of highly recalcitrant C, but which are amorphous in structure, may be suitable to situations where C sequestration is the main goal.

Thus far, actual field data is lacking from which to determine the measurable characteristics of biochars that are the most relevant to soil improvement and soil C sequestration, in a range of soil environments and management systems. There is a strong need for a biochar characterization system, to allow testing of biochar products to ensure quality and effectiveness. Currently, the International Biochar Imitative (IBI) is working with a range of groups to determine the most appropriate suite of characteristics that should be measured in biochar materials, and on adapting analytical methods for carrying out the measurements (IBI, 2014). Users of biochar should be aware that biochar contains ash (mineral matter, including salts) and water. Since biochar can hold a great deal of moisture, users should enquire about moisture content when purchasing biochar by weight. Ash can provide plant nutrients but biochar with a high proportion of ash, such as biochar made from animal manure, will contain a correspondingly lower amount of recalcitrant carbon (Major, 2010).

As the market for biochar develops, producers of biochar will be required to document and understand differences in these materials, and to work with farmers to provide them with the most appropriate biochar for their conditions. Co-composted biochar-compost can also be characterized using similar procedures to those used for biochar (Agegnehu et al., 2015a). Overall, although the potential for improving crop production and environmental management with biochar is clear, more research and development is required to determine best management practices for biochar application in a variety of systems, taking into consideration the specific characteristics of each biochar material and the proposed end use.

4. Biochar-compost and soil health

Soil health refers to the capacity of soil to perform a number of agronomic and environmental functions. Important among these functions are: agronomic/biomass productivity, response to management and inputs and resistance to biotic and abiotic stresses (Doran and Zeiss, 2000; Srivastava and Ngullie, 2009). With reference to agricultural land use, soil health refers to the capacity of the soil to sustain and support the growth of crops and animals while also maintaining or improving the quality of the environment (Doran and Zeiss, 2000).

Maintaining an appropriate level of soil organic matter and biological cycling of nutrients is crucial to the success of any soil management regime. The decline in SOM contributes to several soil degradation processes including erosion, compaction, salinization, nutrient deficiency, loss of biodiversity and desertification, all of which are accompanied by a reduction in soil fertility (Lal, 2015b). Hence, the application of biochar and its impact on the quality of soil function is worthy of an exhaustive assessment. Tillage methods and soil surface management affect sustainable use of soil resources through their influence on soil stability, soil resilience and soil quality. Soil stability refers to the susceptibility of soil to change under natural or anthropogenic perturbations. In comparison, soil resilience refers to the ability of the soil to recover its quality in response to any natural or anthropogenic perturbations (Lal, 2015a). The term soil quality refers to the soil's capacity to perform its three principal functions, namely economic productivity, environment regulation and the provision of aesthetic and cultural values. Soil quality and resilience have a profound impact on productivity and environmental quality, and soil quality is directly affected by crop residue management and tillage methods (Lal, 2008; Powlson et al., 2011).

Soil quality indicators are a composite set of measurable physical, chemical and biological attributes which relate to functional soil processes and can be used to evaluate soil health status, as affected by management and climate change drivers (Allen et al., 2011). Several indicators have been suggested reflecting changes over various spatial and temporal scales. Soil depth, soil organic matter content and electrical conductivity have been suggested as properties most affected by soil degradation processes (Allen et al., 2011; Dalal et al., 2011). For evaluation of soil quality, the selection of indicators that are sensitive to management practices is desirable. Several biological attributes including microbial biomass, respiration, amino acids, soil enzymes and earthworm activity have been suggested as soil quality indicators (Mele, 2011; Powlson et al., 2011). Earthworms can affect infiltration, water transport and plant root development by creating macro-pores. Physical conditions such as water-filled pore space which influences biological activity have also been identified as important indicators. Although water-filled pore space and many of the biological indicators are much more temporally, and perhaps spatially, dependent than physical indicators such as bulk density or chemical indicators such as CEC, they can be very responsive to soil and crop management practices (Doran and Zeiss, 2000). Aggregate stability and size distribution are indicators for evaluating effects of soil and crop management practices on soil quality, as they reflect resistance of soil to erosion. Soil carbon content has been suggested as a soil quality indicator because decreases in this parameter can be directly related to decreased water stability of both macro- and micro-aggregates (Allen et al., 2011).

Microbial biomass, respiration and ergo-sterol concentrations are biological measurements that have been suggested as indicators for assessing long-term soil and crop management effects on soil quality. Periodic reassessment of soil properties has also been suggested as essential for evaluating the chemical aspects of soil quality. These may be especially important when no-till practices are used, because increased concentrations of nutrients, organic matter and hydrogen ions (decreased pH) in surface soils (typically 5 cm) and significant stratification of P and K have been reported by researchers (Allen et al., 2011; Mele, 2011).

4.1. Soil physical properties

Biochar as a soil amendment may improve the physicochemical properties of degraded or nutrient-depleted soils. The ability of biochar to retain soil water is a function of the combination of its porosity and surface functionality (Suliman et al., 2017). Biochar increases porosity due to its particularly porous internal structure and increased soil porosity increases the surface area of soil so that water is better able to penetrate. Previous studies showed that application of biochar to infertile soils decreases soil bulk density, increases total pore volume and water holding capacity (Abel et al., 2013; Chan et al., 2007). According to Oguntunde et al. (2008) bulk density on charcoal-site soils was reduced by 9% compared to adjacent field soils. Total porosity increased from 45.7% on adjacent field soils to 50.6% on earth kilns. The saturated hydraulic conductivity of soils under charcoal kilns increased from 6.1–11.4 cm h^{-1}, representing a relative increase of 88%. Soil color became darkened under charcoal kilns, with hue, value and chroma decreasing by 8, 20 and 20%, respectively. Surface albedo reduced by 37% on charcoal-site soils while soil surface temperature increased up to 4 °C on average due to the dark color of the biochar. Higher infiltration rates were measured on charcoal site soils, which suggest a possible decrease in overland flow and less erosion on those kiln sites. This is the main attribute of Terra Preta soil, as evidenced by several research findings (Glaser et al., 2001; Sombroek et al., 2003).

4.2. Soil chemical properties

Biochar has potential benefits in improving the chemical properties of soils. Research findings indicate significant changes in soil quality including increases in pH, organic carbon, exchangeable cations, and N fertilizer use efficiency as well as a reduction in tensile strength at higher biochar rates > 50 t ha^{-1} (Chan et al., 2008; Bera et al., 2016; Glaser et al., 2002; Laird et al., 2010b). For example, application of paper-mill biochar at the rate of 10 t ha^{-1} in a Ferrosol significantly increased pH, CEC, exchangeable Ca and total C, and reduced Al availability, while in a Calcarosol it increased C and exchangeable K (Van Zwieten et al., 2010).

Application of biochar to soil may improve nutrient supply to plants. Soil reaction (pH) is an important characteristic of soils in terms of nutrient availability and plant growth. Most plants have a preferred pH range where maximum growth and production can be attained. Plant growth, fertilizer application and crop harvesting acidify soils depending on the source of fertilizer, the differential uptake and distribution of positively and negatively charged ions (Fageria and Baligar, 2008). It is usual practice to amend acidic soils by adding agricultural lime to raise the pH, which allows plants to grow at their maximum potential when other requirements such as water and nutrient availability are met. Previous studies have indicated that high-pH biochar raised soil pH at about one-third the rate of lime, increased calcium levels and reduce aluminum toxicity on red ferralitic soils (Glaser et al., 2002; Lehmann et al., 2003a; Steiner et al., 2007) (Table 2). Granatstein et al. (2009) reported varying pH effects when different types of biochar were applied to soils. This study showed that soil pH increased from 7.1 to 8.1 when 39 t ha^{-1} herbaceous feed-stock derived biochar was added to a sandy soil. The pH of the biochars used in this study ranged from 6.0-9.6 depending on the pyrolysis temperature and feedstock type. The increase in pH was less pronounced for biochars from woody feedstock. A smaller overall pH increment was observed when the biochars used in this study were applied to silt loam soils at rates up to 39 t ha^{-1}. The authors suggested that the smaller pH increases in silt loam soils was due to the high initial CEC and hence, a high buffering capacity. In contrast, a recent study on soil salinity indicated that amendment of a saline soil with biochar and poultry manure co-composted together and pyroligneous solution resulted in significant decreases in soil salinity by 3.6 g kg^{-1}, accompanied by a soil pH increase of 0.3 and soil bulk density increase of 0.1 g cm^{-3}. Increases were also observed in SOC and available P by 2.6 g kg^{-1} and 27 mg kg^{-1}, respectively (Lashari et al., 2013).

Soil with a high CEC has the ability to hold or bind plant nutrient cations to the surface of biochar particles, humus and clay, so nutrients are retained rather than leached and therefore more available for uptake by plants (Glaser et al., 2002; Laird et al., 2010a; Lehmann et al., 2003a). High soil CEC translates into a soil with high buffering capacity, signifying that addition of acidic or basic components has a smaller

Table 2
Summarized response of biochar application on soil biophysical and chemical properties.

Biochar source	Soil type	Effect on soil properties/soil quality changes	References
Different feedstock types	Different soil types	Increase in soil pH, CEC, available K, Ca and Mg, total N and available P; decrease in Al saturation of acid soils.	(Glaser et al., 2002; Schulz and Glaser, 2012)
Wood charcoal	Anthrosol and Ferralsol	Increase in soil C content, pH value and available P; reduction in leaching of applied fertilizer N, Ca and Mg and lower Al contents.	(Chan et al., 2007; ; Lehmann et al., 2003a)
Eucalyptus logs, maize stover	Clay-loam Oxisol; silt loam	Increase in total N derived from the atmosphere by up to 78%; higher total soil N recovery with biochar addition.	(Güereña et al., 2012, 2015; Rondon et al., 2007)
Charcoal site Soil	Haplic Acrisols	Increase in total porosity from 46% to 51% and saturated soil hydraulic conductivity by 88% and reduction in bulk density by 9%.	Oguntunde et al. (2008)
Peanut hulls, pecan shells, poultry litter	Loamy sand	Biochars produced at higher pyrolysis temperature increased soil pH, while biochar made from poultry litter increased available P and Na.	Novak et al. (2009)
Wood and peanut shell − Chicken manure − wheat chaff	Sandy soils	Increase in P availability from 163 to 208%, but decreased AMF abundances in soils from 43 to 77%.	(Madiba et al., 2016; Warnock et al., 2010)
Wood and manure-derived biochars	Different soil types	Increase the soil's saturated hydraulic conductivity and plant's water accessibility, as well as boost the soil's total N concentration and CEC, improving soil field capacity, and reduce NH_4-N leaching.	(Abel et al., 2013; Ajayi et al., 2016; Atkinson et al., 2010; Stavi, 2012)
Manure, corn stover, woods, food waste	Alfisol	Tissue N concentration and uptake decreased with increasing pyrolysis temperature and application rate, but increased K and Na content.	Rajkovich et al. (2012)
Different biochar sources	Different soil types	Increased crop yield, improved microbial habitat and soil microbial biomass, rhizobia nodulation, plant K tissue concentration, soil pH, soil P, soil K, total soil N, and total soil C compared with control conditions.	(Biederman and Harpole, 2013; Thies et al., 2015)
Peanut hull	Ultisols	Increased K, Ca, and Mg in the surface soil (0–15 cm). Increased K was reflected in the plant tissue analysis.	Gaskin et al. (2010)
Simoca, activated wundowie	Loamy sand − clay	Increased soil microbial activity more in clay than loamy soil	Jaafar et al. (2015b)
Acacia whole tree green waste	Planosol	Increase in porosity either direct pore contribution, creation of accommodation pores or improved aggregate stability	Hardie et al. (2014)
Wheat straw	Fimi-Orthic Anthrosols	Increase in soil pH, organic carbon, total nitrogen and reduction in yield scaled N_2O emissions	Li et al. (2015)

effect on soil pH at least up until a certain point (Granatstein et al., 2009). For instance, a high CEC soil will take a longer time to develop into an acidic soil compared with a lower CEC soil. Conversely an acidic soil with a high CEC will need application of more lime to correct the soil pH compared with an acidic soil with a lower CEC. Once fresh biochar is exposed to oxygen and water in the soil environment, spontaneous surface oxidation reactions occur in the biochar, resulting in an increase in the net negative charge and hence an increase in CEC. Aged biochar particles are associated with high negative charge, potentially promoting soil aggregation and increasing nutrient availability to plants (Joseph et al., 2009). However, Granatstein et al. (2009) reported that in spite of an increasing trend in CEC when added to soils with a low initial CEC, biochar application did not change CEC significantly. Inyang et al. (2010) also found that bagasse biochar addition significantly enhanced the exchange capacity of cations and anions of soils and improved their nutrient holding capacities (Table 2).

High reactivity of the surfaces of the biochar particles is partly attributed to the presence of a range of reactive functional groups (siloxane, OH, COOH, C=O, C−O, N), some of which are pH – dependent (Cheng and Lehmann, 2009). These functional groups are major sites for pH – dependent charges, thereby, translating the actual CEC of biochar, depending upon the nature of feedstock and temperature of pyrolysis. Biochar ageing causes an increase in hydroxyl groups and carboxyl groups (Lehmann and Joseph, 2015), while aging of biochar in soils causes development of quinine functional groups (Mukome et al., 2014). Thus, biochar aging creates oxygen − containing functional groups on the surface. While describing these properties, aromaticity on account of H:C ratio and oxidation state on account of O:C ratios are considered very important. Specific surface area is one of the important physical properties of biochar that affects the sorption capacity (Rajapaksha et al., 2016), water holding capacity and habitat for microbes (Ng et al., 2014). Naturally aged biochars have shown much higher negative charge compared to either fresh or artificially aged biochar (Cheng et al., 2008). Fresh biochar showed very low surface negative charge in the pH range of 7.0–11.0, with a positive charge only below pH 7.0 (Li et al., 2014b) and surface negative charge increased until pH 3.5 following artificial oxidation of biochar (Silber et al., 2010). However, naturally aged biochar showed comparatively higher negative surface charge than either fresh biochar or artificially aged biochar (Cheng et al., 2008). The ion exchange capacity of biochar varied widely ranging from CEC of 250 to an anion exchange capacity of 120 mol kg^{-1}, depending on production conditions and feedstock used for pyrolysis (Cheng et al., 2014; Yuan et al., 2011). However, CEC of biochar treated soils is reported much higher than the soil alone (Zhao et al., 2015). Studies carried out by Silber et al. (2010) on kinetics of element release was characterized by rapid H^+ consumption and mineral dissolution reaction.

The pyrolysis conditions and biomass type affect both the composition and structure of biochar (Crombie et al., 2013; Ippolito et al., 2015; Ronsse et al., 2013; Subedi et al., 2016), resulting in significant differences in the characteristics of the biochar correlated with changes in nutrient content and retention (Agegnehu et al., 2015b; DeLuca et al., 2009; Granatstein et al., 2009). Moreover, the variation in the physicochemical characteristics of biochars causes variability in the availability of nutrients within each biochar to plants. Biochars derived from manure and animal-product feedstock are relatively rich in nutrients when compared with those derived from plant materials and especially those derived from wood (Singh et al., 2010; Alburquerque et al., 2014). However, biochars in general may be more important for use as a soil amendment and driver of nutrient transformation than as a primary source of nutrients (DeLuca et al., 2009).

4.3. Stability and nutrient retention

Biochar addition to soil is currently being considered as a means to sequester carbon, while simultaneously improving soil health, soil fertility and agronomic benefits (Solaiman and Anawar, 2015). Several researchers have indicated that biochar in soil should persist longer and retain cations better than other forms of soil organic matter (Glaser et al., 2002; Lone et al., 2015; Sohi et al., 2010). The precise residence time of biochar in soil is still disputed and this has important implications for the value of the technology in terms of carbon trading (Lehmann, 2007). Both rapid and slow decomposition of biomass-derived biochars have been reported (Lehmann et al., 2006). In addition, the cation retention of fresh biochar is relatively low compared to aged biochar in soil and it is not clear after what period of time and under which conditions biochar attains its optimal adsorbing properties (Abiven et al., 2011; Cheng and Lehmann, 2009). Biochar and other more aromatic black carbons persist in the environment longer than any other form of organic carbon, where finely divided biochar has even remained in soils for thousands of years under humid tropical climates such as the Amazon, producing a distinct black color and did not show the rapid rates of mineralization common to organic matter in these environments. Such biochar is typically older than any other form of carbon in soils as demonstrated by radiocarbon dating (Kuzyakov et al., 2009; Sombroek et al., 2003).

Charred biomass does not only consist of recalcitrant aromatic ring structures but also of more easily degradable aliphatic and oxidized carbon structures (Abiven et al., 2011; Zimmerman, 2010). The range of carbon forms within a biochar particle may depend on the properties of the plant cell structure, charring conditions and the formation process by either condensation of volatiles or by direct charring of plant cells. One consequence of this heterogeneity is an indication that some portions of biochar may be rapidly mineralized as shown for aliphatic carbon forms. Thus, an extrapolation from relatively easily mineralizable carbon forms liberated during the first few years of degradation to the entire biochar may lead to erroneous projections of stability. Biochar exists as particulates and biotic or abiotic decomposition can take place on its surface. Such surface oxidation may start rapidly within a few months (Cheng et al., 2006), but it was found to be limited to the outer areas of particles even after several hundred years in soils (Zimmerman, 2010). Thus, quantification of the decomposition of fresh biochar based on short-term experimental results may lead to an overestimation of long term decay. Abiven et al. (2011) showed that 40–55 times more condensed structures were released from the aged char than from the fresh char, indicating that the soluble fraction of the char is small at first, and tends to increase with the residence time in the soil.

Nutrients are retained and remain plant available in soils mainly by adsorption to minerals and organic matter. The ability of soils to retain cations in an exchangeable and plant-available form is called CEC, which normally increases in proportion to the amounts of SOM and this also holds for biochar (Glaser et al., 2002). However, biochar has an even greater ability than other SOM to adsorb cations per unit carbon due to its greater surface area (Sombroek et al., 2003), greater negative surface charge and greater charge density (Jaafar et al., 2015a). Compared to other organic matter in soil, biochar also appears to be able to strongly adsorb phosphate despite being an anion, but the mechanism is not entirely clear. Such properties make biochar a unique substance to retain exchangeable and hence plant-available nutrients in the soil, improve crop yields while decreasing environmental pollution by nutrients (Lehmann, 2007).

Leaching of nutrients from soils can deplete soil fertility, hasten soil acidification, rise cost of fertilizer for farmers, reduce yield of crops and most notably cause a threat to environmental health. An option to reduce nutrient leaching may be the application of biochar to soils. The application of Brazilian pepperwood biochar significantly reduced the total amount of nitrate, ammonium and phosphate in the leachates by 34%, 34.7%, and 20.6%, respectively, relative to the soil alone. Similarly, peanut hull biochar also reduced the leaching of nitrate and ammonium by 34% and 14%, respectively (Yao et al., 2012). Other studies also indicated that addition of biochar to a typical Midwestern agricultural soil substantially reduced leaching of N, P and Mg (Laird et al., 2010a) and Ca and Mg (Major et al., 2012). Agegnehu et al. (2015b) also reported that willow and acacia biomass derived biochars and their mixture with compost significantly reduced leaching of NO_3-N, P, K, Ca, Mg and Na.

4.4. Soil biological properties

Biochar as a soil amendment is confronted with the challenge that it must benefit soil health as it can by no means be separated from soils once it is added (Lone et al., 2015). Soils can be viewed as complex communities of organisms that are continually changing in response to soil characteristics, climatic and management factors and especially in response to the addition of organic matter (Chen et al., 2013; Thies and Rillig, 2009). However, the application of biochar to soils is likely to have different effects on soil biota compared with the addition of fresh organic matter and this may affect the abundance, activity and diversity of soil biotic communities (Lehmann et al., 2011). The differences arise as a result of the relative stability of biochar and the general lack of biologically available carbon in biochar in comparison with fresh organic matter. Application of biochar has been demonstrated to modify the biological functionality by providing a habitat for microorganisms due to its highly porous nature or by altering substrate availability and enzyme activity on, or around, biochar particles (Gomez et al., 2014). Rather than supplying microorganisms with a primary source of nutrients, biochar is thought to improve the physical and chemical environment in soils, providing microbes with a more favorable habitat (Lehmann et al., 2011). Using slow pyrolyzed wood biochar and phosphorous solubilizing microbes (PSM) in different soil conditions in three different countries (India, Thailand, and the United Kingdom), soil characteristics and crop type are more likely to determine the impact of biochar on specific crop output than could the feedstock species. These observations explained the ineffectiveness of biochar to enhance PSM activity for P mobilization in phosphate rich soils, but significantly improved the crop yield in P deficient soils (Deb et al., 2016).

Biochar has the potential to affect microbial biomass and composition and the microbes are also able to change the properties of biochar (Lehmann et al., 2011; Thies et al., 2015). Because of the porous nature of biochar, its high surface area and its ability to adsorb soluble organic matter and inorganic nutrients, biochar provides a suitable habitat for microbes (Thies and Rillig, 2009). This is true for bacteria, actinomycetes and arbuscular mycorrhizal fungi from amongst which some types may preferentially colonize biochar depending on its physical and chemical properties. Abujabhah et al. (2016) reported that microbial abundance was improved after the addition of biochar. Application of 2% and 4% w/w pine biochar led to a significant decline in arbuscular mycorrhizal fungal (AMF) abundance in roots of 58 and 73%, respectively, but not in soils, which were accompanied by significant decline of 28 and 34% in soil P availability (Warnock et al., 2010). In contrast, application of a peanut shell biochar increased P by 101% while AMF root colonization and extra-radical hyphal lengths deceased by 74 and 95%, respectively. Similarly, application of mango wood biochar at rates of 23.2 and 116.1 t C ha^{-1} increased P availabilities by 163% and 208% respectively, but decreased AMF abundances in soils by 43 and 77% (Warnock et al., 2010). On the other hand, addition of biochar, mycorrhizal fungi and high N decreased aboveground plant biomass by 42% relative to the mycorrhizae and high N treatment, while simultaneously promoting mycorrhizal root colonization. This is evidence for an induced parasitism of the mycorrhizal fungus in the presence of N and biochar. Biochar in soils with mycorrhizae but without sufficient N showed more surface oxidation (LeCroy et al., 2013).

Biochar pores may provide physical protection for soil microorganisms. Microbial abundance, diversity and activity are strongly influenced by pH (Rousk et al., 2010). The buffering capacity, that is, the ability of the soil solution to resist changes in pH imparted by biochar CEC may also help maintain appropriate pH conditions and minimize pH fluctuations in the microhabitats within biochar particles (Rousk et al., 2010; Sparkes and Stoutjesdijk, 2011). Biochar is relatively stable and has a long soil residence time in the soil, suggesting that biochar is not a good source of substrate metabolism by soil biota. The very low values of water soluble C and N are an indication of the low degradability of biochar in soil (Wang et al., 2016). However, biochars freshly added to soils may contain suitable substrates to support microbial growth. Depending on feedstock type and production conditions, some biochars may contain bio-oils or re-condensed organic compounds which could support the growth and reproduction of certain microbial groups over others. The implications of this possibility are that microbial communities in biochar will change over time once it has been added to the soil and ecosystem services, which are beneficial for agriculture, such as nutrient cycling or mineralization of organic matter may develop over time following biochar addition (Lehmann et al., 2011; Rousk et al., 2010; Wang et al., 2016).

Biochar also promotes the production of ethylene (C_2H_4), which is the only hydrocarbon and an important plant hormone with a pronounced effect on plants (Spokas et al., 2010). The study further indicated that a greater ethylene production was obtained from non-sterile soil than sterile soil (by 215%), implying a role for soil microbes in the ethylene production, with rates of production varying with different biomass sources and biochar production conditions. This observation may provide an insight into a potential mechanism behind the biochar effects observed on plant growth, particularly in light of the important role ethylene plays in plant and microbial processes (Spokas et al., 2010).

Biological nitrogen fixation (BNF) significantly decreases if available nitrate concentrations in soils are high, and if available Ca, P and micronutrient concentrations are low (Giller, 2001). However, as evident from Amazonian Dark Earths, soils with appreciable concentrations of biochar, available nitrate concentrations are usually low and available Ca, P and micronutrient concentrations are high, which is ideal for maximum BNF (Lehmann et al., 2003b). Studies have shown that biochar and fertilizer application increased microbial biomass compared to mineral fertilizer (Birk et al., 2009; Burger and Jackson, 2003). Microbial immobilization is an important mechanism to retain N in soils affected by leaching (Burger and Jackson, 2003). Increased C availability stimulates microbial activity resulting in greater N demand, promoting immobilization and recycling of NO_3^-. Microbial reproduction rate increased after glucose addition in soils amended with biochar despite no indication of higher soil respiration rate, denoting low-biodegradable SOM content but sufficient soil nutrient contents to support microbial population growth (Birk et al., 2009). Biochar addition has also increased crop yield, soil microbial biomass, plant tissue K concentration, total soil C and N, soil P and K (Biederman and Harpole, 2013; Galvez et al., 2012), nodulation and BNF by common beans (Rondon et al., 2007), red clover (Mia et al., 2014), soybean (Mete et al., 2015) and faba bean (Van Zwieten et al., 2015).

5. Biochar and biochar-compost in relation to crop yield

In many cases, the application of biochar and biochar + compost improves the biophysical and chemical properties of the soil, as well as nutrient supply to plants. Biochar can also be used to reclaim marginal or depleted soils, making more agricultural land available, while increasing crop yields so that the need for expansion of agricultural land area decreases (Barrow, 2012). Biochar soil amendment significantly increased plant growth and nutrition and improved the efficiency of N fertilizers (Steiner et al., 2008). Moreover, significant increases in root biomass, crop growth and yield have been observed following application of biochar to soil (Abiven et al., 2015; Agegnehu et al., 2015b).

Both positive (Blackwell et al., 2015; Chan et al., 2007; Yamato et al., 2006) and negative (Deenik et al., 2010) yield responses have been reported for a wide variety of crops as a result of biochar application to soils (Table 3). For example, maize yield increased by 98–150% and water use efficiency by 91–139% as a result of manure biochar addition (Uzoma et al., 2011), wheat grain yield increased by 18% from the use of oil mallee biochar (Solaiman et al., 2010) and peanut yield increased by 23% and 24% from the applications of biochar and co-composted biochar-compost (Agegnehu et al., 2015a). Overall, averaged across many published scientific studies, biochar increases crop yields about 20% with application rates often exceeding 10 t ha^{-1}. It has also been reported that applications of less than 5 t ha^{-1} can increase crop yields by over 50% in certain types of soils. Even highly productive agricultural lands contain patches of degraded soils that would benefit from biochar application.

However, there have been few studies reporting the influence of biochar on early stages of plant growth such as on seed germination and seedling growth (Solaiman et al., 2012; Van Zwieten et al., 2010). For instance, maize seed germination and early growth were not significantly affected by biochars produced from a range of feedstock sources (Free et al., 2010). The application of biochar and compost to soil can alter the organic matter status (Fischer and Glaser, 2012; Schulz and Glaser, 2012) which is linked to the release of nutrients such as N (Sanchez et al., 2001). The resultant change in nutrient status of the soil may affect both seed germination and seedling growth. Responses will likely depend on the type and rate of amendment applied to soil as well as on soil characteristics such as soil C, pH, CEC and other components of soil fertility. It is expected that different soil fertility treatments in relation to amendment type may differ in their effects on soil biophysical and chemical properties and early crop growth and development (Lehmann et al., 2003a; Schulz et al., 2013).

Plant growth and yield increases with biochar additions have, in most cases, been attributed to optimization of the availability of plant nutrients (Agegnehu et al., 2016a; Gaskin et al., 2010; Lehmann et al., 2003a), increase in soil microbial biomass and activity (Lehmann et al., 2011; Wang et al., 2016) and reduction of exchangeable Al^{3+} (Glaser et al., 2002; Qian et al., 2013). Likewise, wood biochar addition increased wheat yield by up to 30%, with no differences in grain N content and sustained yield for two consecutive seasons without biochar addition in the second year (Vaccari et al., 2011). Major et al. (2010) found that maize grain yield did not increase significantly in the first year following addition of 20 t biochar ha^{-1}, but increased by 28%, 30% and 140% relative to the control over the following 3 years, implying a longer term beneficial impact of biochar on yield and soil fertility (Table 3). Yield responses of maize, cowpea and peanut to the applications of charred bark of *Acacia mangium* at the rate of 37 t ha^{-1} were only recorded at sites with less fertile soil, but a 200% increase was recorded on the less fertile soil when applied with fertilizer, which could be due to the increase in N and P availability, mycorrhizal fungi colonization and reduction of exchangeable Al^{3+} (Yamato et al., 2006). Solaiman et al. (2012) indicated that the application of Oil Mallee biochar at the rate of 10 t ha^{-1} increased wheat seed germination from 93% to 98% in soil-less Petri dish bioassay and by 9% on soil-based glasshouse bioassay, but decreased the germination of subterranean clover and mung bean. Application of biochar at the rate of 25 t ha^{-1} and FYM at the rate of 5 t ha^{-1} also resulted in improved maize growth and a reduced weed population at 30 and 60 days after sowing (Arif et al., 2012).

Addition of biochar also significantly increased N uptake in wheat grown in fertilizer amended Ferrosol, resulting in a concomitant increase of 250% in biomass production compared to the control attributable to improved fertilizer use efficiency. Similarly, a Ferrosol amended with biochar and fertilizer significantly increased soybean and radish biomass. However, the effects of biochar on wheat and soybean were not significant in the absence of fertilizer, despite a significant increase in radish biomass (Van Zwieten et al., 2010). In contrast, a Calcarosol amended with fertilizer and biochar increased soybean biomass, but reduced wheat and radish biomass (Van Zwieten et al., 2010). Yield increases relative to a control have frequently been reported to be directly attributable to the addition of biochar (Lehmann et al., 2003a; Major et al., 2010), biochar-compost mix and co-composted biochar-compost (Agegnehu et al., 2015a; Schulz et al., 2013). Nutrient-poor soil amended with low C algal biochars, without and with mineral fertilizer increased sorghum growth rate between 15 and 32 times, respectively, relative to the control without biochar, and smaller but significant effect on relatively fertile soil (Bird et al., 2012).

Table 3
Summaries of responses of crops to different sources of biochar applications.

Biochar source and application rate	Crop type	Crop response details	References
		Field crops	
Mango wood (0, 8, 16 t ha^{-1}), corn stover (2.6–91 t ha^{-1})	Maize	Increase in biomass from 30–43% and yield by 22% due to improvements in soil pH, CEC, nutrient availability and water retention.	(Rajkovich et al., 2012; Rondon et al., 2006)
Acacia bark (10 L m^{-2})	Maize and Peanut	Twofold increase in maize and peanut yields due to higher N and exchangeable bases and low Al.	Yamato et al. (2006)
Teak and rose wood biochars (4–16 t ha^{-1})	Rice and Sorghum	Improved plant growth and 2–3 times yield increment as biochar improved crop response to NP fertilizer.	(Asai et al., 2009; Steiner et al., 2007)
Oil palm fruit bunch biochar (0,10, 20 and 40 t ha^{-1}) green waste compost	Rice	Increase in grain yield under organic system of rice intensification by 141–472%	Bakar et al. (2015)
Macadamia nut shell (0, 5, 10, 20%)	Maize, Lettuce	Biochar with high volatile matter (225 g kg^{-1}) decreased plant growth and soil NH_4^+–N compared to low-VM (63.0 g kg^{-1}).	Deenik et al. (2010)
Paper-mill biochar (10 t ha^{-1})	Wheat and Radish	Increase in biomass by 250% attributable to improved fertilizer use efficiency on Ferrosol, but reduced biomass on Calcarosol.	Van Zwieten et al. (2010)
Wood, cow manure (0, 10, 15, 20 t ha^{-1})	Maize	Increase in yield from 14 to 150% due to increases in water use efficiency, pH and available Ca and Mg, and decrease in exchangeable acidity	(Major et al., 2010; Uzoma et al., 2011)
Coppiced trees (30, 60 t ha^{-1}), wood, wheat chaff (10 t ha^{-1})	Wheat	Increase in seed germination by 4–9%; yield improvement by 30% and sustained yield for two consecutive seasons.	(Solaiman et al., 2012; Vaccari et al., 2011)
Cassava stem, farm-yard manure, maize cob.	Maize, cassava	Increase in yield due to improvements in soil organic C, N, P, CEC, K and water availability.	(Abiven et al., 2015; Islami et al., 2011)
		Horticultural crops	
Green waste, poultry litter (0, 10, 25, 50, 100 t ha^{-1})	Radish	Increases yield (42–96%) due to improved soil physicochemical properties, N-availability and use efficiency, and decrease in exchangeable Al.	Chan et al. (2007, 2008)
Waste water sludge biochar (10 t ha^{-1})	Cherry and Tomato	Increment in yield by 64% over the control due to increased NP availability.	Hossain et al. (2010)
Biochar- pine sawdust (0,5,10,15 t ha^{-1})	Tomato	Increase in plant growth, yield and quality over pine sawdust alone	Dunlop et al. (2015)
Biochar from whole tree green waste of acacia green fowl manure (10 t ha^{-1})	Apple	Increase in tree trunk girth without any effect on yield or quality	Eyles et al. (2015)
Citrus wood biochar (1,3 or 5% by volume in pots)	Pepper and Tomato	Increase in leaf area, canopy dry weight, number of nodes and yield	Graber et al. (2010)
Rice bran pellets (14 t ha $^{-1}$)	Tomato	Increase in soil cation exchange capacity, organic carbon and available N, P and K without affecting fruit yield	Vaccari et al. (2015)
Rice husk char (25,50, and 150 g kg^{-1})	Lettuce and Cabbage	Increase in biomass by 903% with biochar treatment, besides increase in soil Ca, Mg, and K	Carter et al. (2013)
Maize straw (20,30 and 40 t ha^{-1})	Choy Sum and Amaranth	Increase in yield by 28–48%, besides reduction in N_2O and CH_4 emissions	Jia et al. (2012)

However, the effect of biochar and biochar-compost on plant growth and yield have been reported minimal or absent in a number of studies conducted in temperate regions (Borchard et al., 2014; Schmidt et al., 2014).

Biochar and biochar-compost mixture can improve crop yields by a variety of mechanisms, including direct supply of nutrients, improving soil pH, improving nutrient use efficiency and thus nutrient uptake for a given fertilizer application rate by increasing the soil CEC and improving soil water holding capacity in light or sandy soils or drainage in clayey soils (Agegnehu et al., 2015a; Jeffery et al., 2011). The immediate beneficial effects of biochar applications on nutrient availability are largely due to the availability of higher K, P and Zn, and to a lesser extent, Ca and Cu in biochar (Lehmann et al., 2003a; Steiner et al., 2007). The long-term benefits for nutrient availability include greater stabilization of organic matter, slower nutrient release from added organic matter and improved retention of cations due to enhanced CEC (Lehmann, 2007; Liang et al., 2006). Applications of biochar to soil have shown obvious increases in total SOC and N concentrations, the availability of major cations and P (Biederman and Harpole, 2013; Steiner et al., 2007), CEC and pH (Agegnehu et al., 2016a; Peng et al., 2011; Yuan and Xu, 2011). Higher nutrient availability for plants is the result of the direct nutrient addition by biochar as well as enhanced nutrient retention (Lehmann et al., 2003a) and possible changes in soil microbial dynamics (Lehmann et al., 2011). Thus, biochar addition to soil can have a significant effect on retention of cations due to its proven longevity, restoration of degraded lands, enhancing agricultural productivity, drawing CO_2-C from the atmosphere and abating environmental pollution.

The effect of biochar on the productivity of crops partly depends on the rate of application. Despite plant growth and yield increases due to soil biochar application, clover seed germination and growth (Solaiman et al., 2012) and common bean yield (Rondon et al., 2007) were decreased at both very low and high biochar application rates. Progressive growth improvement with higher biochar rate is seen with comparatively low levels of biochar, with significant improvements ranging from 20 to 220% observed in productivity over the control at low rates of 0.4–8 t C ha^{-1} (Lehmann and Rondon, 2006). Overall, the positive responses of crops to different biochars could be due to the improvement in soil pH and availability of macro- and micronutrients (Glaser et al., 2002; Lehmann et al., 2003a), improvement in soil physical properties and water holding capacity (Abel et al., 2013; Novak et al., 2012; Tammeorg et al., 2014) and soil biological properties (Lehmann et al., 2011; Steiner et al., 2007), while the negative responses of crops to biochar application could be due to changes in soil properties and pH induced micronutrient deficiency (Agegnehu et al., 2015a; Xu et al., 2015). Nitrogen limitation may be the reason for declining yields at high biochar rates since the availability of N decreases through immobilization by microbial biomass at high C:N ratios, although other growth-limiting factors may be responsible as well (Lehmann et al., 2003b; Sigua et al., 2016).

Biochar and biochar-compost additions directly influenced the availability of native or applied nutrients. Agegnehu et al. (2015b) reported that application of compost with fertilizer significantly increased plant growth, soil nutrient status and plant nutrient content, with plant biomass (as a ratio of control value) decreasing in the order biochar + compost (3.6) > biochar (3.3) co-composted biochar-compost (3.1) > fertilizer (2.9) > control (1.0). Enhanced plant growth in the biochar + compost treated soil has largely been attributed to improved

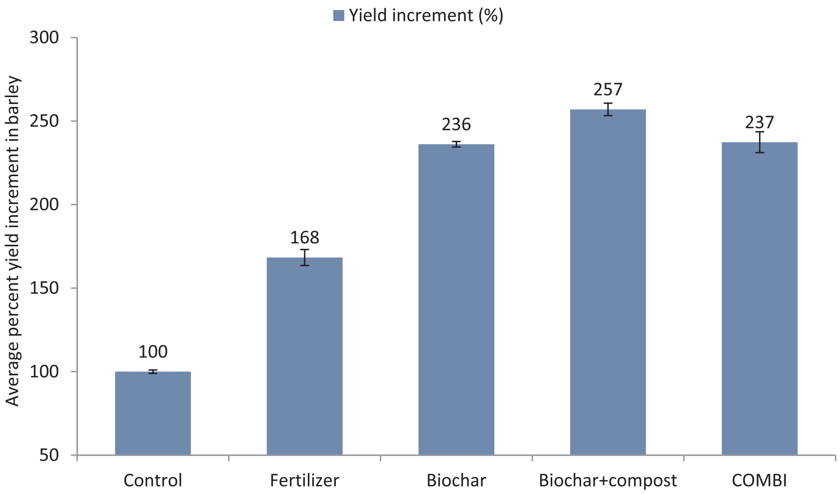

Fig. 3. Relative performance of the amendments on average yield of barley (Agegnehu et al., 2016b).

nutrient availability and uptake compared to biochar alone (Agegnehu et al., 2016b; Schulz et al., 2014). Addition of biochar with compost resulted in better plant growth and C sequestration than biochar with mineral fertilizer. With biochar and biochar + compost, a significant part of the initial total C content remained after the second harvest, whereas only 58% remained in the biochar treatment. Nevertheless Schulz and Glaser (2012) indicated that in contrast to total C, black C contents remained almost constant during two crop growth periods without further biochar additions, but the mineral fertilizer only reduced the black C content to 75% of the original amount. Schulz et al. (2013) found that addition of 100 t ha^{-1} co-composted biochar-compost to sandy and loamy soil increased growth of oat plants. Fig. 3 shows the relative performance of the treatments on barley yields.

6. Biochar and the environment

6.1. Biochar and composting

Research on co-composting of biochar with organic waste is in its infancy. However, biochar has a potential role in composting in that incorporation of biochar into composting material has been shown significantly lessen the total N loss during sludge composting. Available literature suggests that biochar addition during composting leads to higher N retention in the final compost product (Steiner et al., 2010) as well as heavy metal stabilization (Hua et al., 2009a, 2009b), more rapid volume reductions through higher carbon mineralization rates, and changes in microbial community structure (Jindo et al., 2012). The combined co-composted product has potential in terms of improving soil fertility and crop yields (Agegnehu et al., 2016b; Dias et al., 2010; Glaser et al., 2015; Lashari et al., 2013; Schulz and Glaser, 2012). Exposure of fresh biochar to the oxidizing conditions during composting will accelerate the functional oxidation or ageing of the biochar surfaces (Prost et al., 2013; Wiedner et al., 2015), accelerating the development of positive plant-soil interactions. In addition, recent research has suggested that co-composting of biochar led to significant uptake of nitrogen from the compost matrix and reduction of potentially phytotoxic PAH compounds initially present in the biochar (Borchard, 2014).

Biochar might be an ideal bulking agent for composting nitrogen rich materials. Emissions from organic wastes and crop residues may be avoided by preventing its natural decomposition in soil. For instance, Hua et al. (2009a,b) reported that with 9% biochar amendment, total N loss at the end of composting decreased by 64.1% relative to no biochar amendment, and mobility of Cu and Zn in the sludge composting material could also be reduced by 44.4 and 19.3% respectively by biochar addition. Dias et al. (2010) also reported that application of biochar to poultry manure reduced the losses of N in the mature composts, although the use of sawdust would be more efficient in preserving the organic matter and N in the mature compost. Steiner et al. (2010) reported that biochar has been shown to act as an absorber of NH_3 and water-soluble NH_4^+, and thus reduce losses of N during composting of manure. Ammonia concentrations in the emissions were lower by up to 64% if poultry litter was mixed with biochar (20%), and total N losses were reduced by up to 52%. Therefore, a co-composted biochar-compost product potentially represents a new higher-value product derived from organic waste streams, capable of providing multiple benefits to soil fertility, carbon sequestration, GHG abatement and food security.

6.2. Biochar and carbon sequestration

According to FAO (2016), agriculture generates around a fifth of the world's greenhouse gas emissions. The adoption of climate-smart practices would enhance productivity and incomes of farmers while contributing to overcome the negative effects of climate change. The application of biochar is proposed as a novel approach to establish a significant, long term, sink for atmospheric carbon dioxide (CO_2) in terrestrial ecosystems. Conversion of biomass C to biochar leads to sequestration of about 50% of the initial C compared to the low amounts retained after burning (3%) and biological decomposition (< 10–20% after 5–10 years), therefore yielding more stable soil C than burning or direct land application of biomass (Lehmann et al., 2006). Biochar addresses two important sources of environmental problems, by sequestering CO_2 into the soil and by reducing water pollution through enhancing soil nutrient retention (Lehmann et al., 2006; Shackley et al., 2010). The incorporation of the biochar into the soil is the crucial step in making biomass pyrolysis sustainable and carbon negative, rather than relying on biomass combustion for energy. The durability of biochar carbon in soil is such that net carbon emissions for the process are negative for centuries to millennia (Lehmann et al., 2006; Wang et al., 2016). Soil emissions in the form of CO_2, methane (CH_4), and nitrous oxide (N_2O) can be reduced by 1.8 Pg CO_2-C equivalent per year (12% of current anthropogenic CO_2-C equivalent emissions) and total net emissions over the course of a century by 130 Pg CO_2-C equivalent, which would create a meaningful sink in comparison to current fossil fuel emissions of 8.7 Pg C per year (Woolf et al., 2010).

Biochar applications to soils have also shown enormous potential to reduce greenhouse gasses on a large scale, increase agricultural production while at the same time delivering carbon-negative biofuels based on feedstock that require less fertilizer and water. Emissions of greenhouse gasses such as CO_2 and N_2O, which is more than 300 times as potent as CO_2, were significantly reduced from soils (Felber et al., 2012; Lentz et al., 2014; Martin et al., 2015; Mukherjee et al., 2014). Woolf et al. (2016) indicate that biochar could play an important role in removal of carbon from the atmosphere, which is increasingly recognized as essential to meeting global climate targets. Biochar-bioenergy systems can play an important role in a global strategy to actively remove carbon from the atmosphere to avert precarious climate change. Biochar-bioenergy competes favorably with carbon capture and storage at lower carbon prices, and where biochar addition to soils delivers significant increases in crop yields. Hence, effective use of biochar as a carbon removal strategy depends on identifying those sites that are most responsive to biochar application. This requires similar knowledge systems as those commonly in place around the world to guide fertilizer application.

Biochar helps reduce the leaching of nitrogen into groundwater, while reducing the need for fertilizers that are the source of excess nitrogen (Glaser et al., 2015; Lehmann, 2007; Zhang et al., 2016). One of the factors holding back the adoption of organic means of fertilization is the high labor and transport costs. However, increasing chemical fertilizer costs combined with the reduced need for frequent application on biochar enhanced soils, will help inspire the conversion to sustainable integrated soil fertility and plant nutrient management approach (Glaser et al., 2015). Healthy, biochar-enriched soils may also give farmers more options for crop selection. The increased fertility of the soil will also help farmer adapt to the changing climate, while widespread use of biochar will reduce the intensity of climate change (Lehmann et al., 2006; Zhang et al., 2016). The findings of Agegnehu et al. (2015b) have indicated that application of biochar and biochar-compost mixture significantly reduced the cumulative leaching of NO_3-N, P, exchangeable K, Ca and Mg through increased SWC and decreased leachate volume (Fig. 4). Moreover, on-site pyrolysis may reduce mass by 20 to 30% of the wet waste mass, minimizing transportation costs and wastes to landfill, which would otherwise be transported (McHenry, 2009).

7. Sustainable availability and competing uses of biomass-feedstock

Organic amendments such as animal manures and crop residues are largely used for competing uses, especially for household energy and animal feed rather than being recycled to maintain soil fertility. Burning of dung cake is common in developing countries due to serious shortages of fuel wood or other alternative energy sources. For example, Zelleke et al. (2010) reported that the use of dung cake accounts for about 50% of the total fuel supply of households especially in the highland cereal zones of the north and central Ethiopian highlands. The practice deprives the soils of important sources of organic matter and nutrients.

More than one-half of all dry matter in the global harvest is in the form of crop residues, and in most developing countries the amounts of nutrients in the crop residues are higher than the quantities applied as fertilizers (IAEA, 2003). Crop residues are used for different purposes in developing countries. For example, Zelleke et al. (2010) reported that 63, 20, 10 and 7% of cereal residues are used for feed, fuel, construction and bedding purposes, respectively in Ethiopia. One of the options to address this issue is to rehabilitate and make better use of degraded and communal grazing lands for improved biomass production for livestock feed. In general, efficient management and utilization of crop residues may contribute to the sustainability of the integrated farming system. Different practices can be developed as sources of organic materials, such as the planting of multipurpose trees (Zelleke et al., 2010). However, the potential of such approaches may be limited in labor and water scarce areas. In areas where population density is high small farm size may limit more extensive practices, such as planting trees. Although planting on boundaries and bunds may create problems since the trees compete with crops for water and light on fields, planting of trees may be most feasible in particular niches, such as in the homestead plot, on bunds and on plot boundaries in land scarce settings to provide a source for biochar and compost production. We also suggest that biomass can be produced on abandoned, degraded agricultural soils as this may not adversely affect food security and can improve biodiversity.

In terms of fertility benefits from incorporation of biochars, manure and legume-derived biochars are far superior to wood derived biochars. Feed-stock types for biochar production and pyrolysis conditions can influence soil physical and chemical properties in different ways (Alburquerque et al., 2014; Novak et al., 2009). Singh et al. (2010) indicated that wood biochars had higher total C and lower ash content, lower contents of total N, P, K, S, Ca, Mg, Al, Na and Cu, lower potential CEC and exchangeable cations than manure-based biochars, with leaf biochars intermediate. Differences were also observed in amendment effects of biochars generated from various crop residues on an acidic soil. In general, biochar from leguminous plants results in increased pH and liming effect on acid soils as a result of its higher alkalinity in comparison with biochar from non-leguminous plants (Yuan and Xu, 2011).

8. Conclusions

Our review has presented evidence that while a large number of research studies have been conducted, there is still a scarcity of field based evidences emerging for its applicability in developing countries facing gradual reduction in nutrient density of crops as a result of multiple soil fertility constraints. The production of biochar and its incorporation into soils, particularly in tropical agricultural soils is a novel approach for improving soil health and establishing a long-term sink for atmospheric CO_2. In addition to utilization of key waste sources

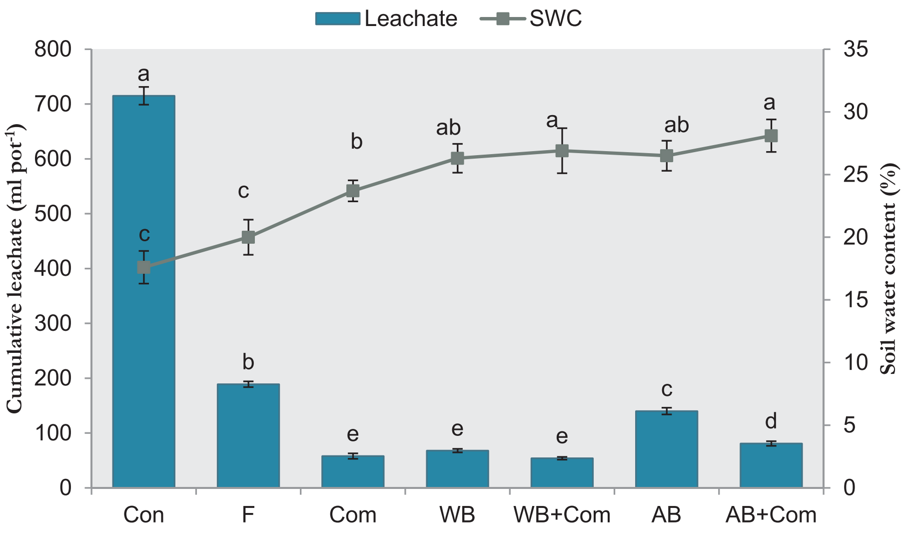

Fig. 4. Cumulative leachate and soil water content (SWC) as influenced by biochar, compost and biochar-compost (Agegnehu et al., 2015b). Columns with the same letter are not significantly different at $p = 0.05$. Error bars represent ± 1 SE. Con: control; F: fertilizer; Com: compost; WB: willow biochar; AB: acacia biochar.

and avoiding landfill and environmental contamination, biochar has considerable potential in improving soil nutrient availability by reducing leaching and promotion of soil quality. Biochar applications can also have considerable potential to improve the water holding capacity of soils and to reclaim landscapes and soils that have been degraded. These are key components in the development of improved agricultural efficiency which will rely at minimum on sustaining, if not increasing, land-use-efficiency to meet changes in climate and securing food for an increasing world population.

Although, the potential agricultural benefits of biochar have been identified in tropical regions, their uses in temperate regions have not been studied in sufficient critical detail. Some studies show that incorporation of biochar influences soil physicochemical and biological properties of soils. Porosity of biochars provides habitat for beneficial soil microorganisms, including bacteria and mycorrhiza. These features can improve soil quality by enhancing processes like soil nitrification, with the added benefits of catalyzing N_2O reduction and reducing GHG emissions (Atkinson et al., 2010; O'neill et al., 2009). Other benefits reported from biochar incorporation into soils, include reductions in environmental pollution; reductions in fertilizer applications and increasing efficacy of water and fertilizer usage.

Application of biochar-compost will have substantial effects on poor soil fertility and immediate economic value on yields of crops as compost in biochar-compost mixture has the potential to replenish deficiency of nutrients in soils. On the other hand, biochar application can be effective in soils of medium fertility in terms of nutrient and water retention, crop productivity and carbon sequestration.

Future work is anticipated on field investigations of biochars for long term sink for sequestering atmospheric CO_2, role of microbes in oxidizing biochar surfaces and release of nutrients, surface properties of carbonized material in the soil environment, comparison of biochar-nutrient against biochar-compost, type and rate of biochar application, in addition to optimization of feedstock properties and pyrolysis conditions suitable at farm condition for better commercialization of biochar usage. Short term and long term evaluation of biochar must complement each other to unravel the possible effect of age on biochar. It may also be important to evaluate biochar and compost both developed from same feedstock as a part of future line of research.

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