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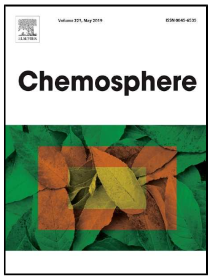


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# A review on biochar modulated soil condition improvements and nutrient dynamics concerning crop yields: pathways to climate change mitigation and global food security

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**Contents**

**ABSTRACT**

The beneficial role of biochar on improvement of soil quality, C sequestration, and enhancing crop yield is widely reported. As such we could not find a compiled source of information linking biochar modulated soil condition improvement and soil nutrient availability on crop yields. The present review paper addresses the above issues by compilation of world literatures on biochar and a new dimension is introduced in this review by performing a meta-analysis of published data by using multivariate statistical analysis. Hence this review is a new in its kind and is useful to the broad spectrum of readers. Generally, alkalinity in biochar increases with increase in pyrolysis temperature and majority of the biochar is alkaline in nature except a few which are acidic. The N content in many biochar was reported to be more than 4% as well as less than 0.5%. Poultry litter biochar is a rich in P (3.12%) and K (7.40%), while paper mill sludge biochar is highest in Ca content (31.1%) and swine solids biochar in Zn (49810 mg $kg^{-1}$), and Fe (74800 mg $kg^{-1}$) contents. The effect of biochar on enhancing soil pH was highest in Alfisol, Ferrosol and Acrisol. Soil application of biochar could on an average increase (78%), decrease (16%), or show no effect on crop yields under different soil types. Biochar produced at a lower pyrolysis temperature could deliver greater soil nutrient availabilities than that prepared at higher temperature. Principal component analysis (PCA) of available data shows an inverse relationship between pyrolysis temperature and soil pH, and biochar application rate and soil cation exchange capacity.The PCA also suggests that the original soil properties and application rate strongly control crop yield stimulations via biochar amendments. Finally, biochar application shows net soil C gains while also serving for increased plant biomass production that strongly recommends biochar as a useful soil amendment. Therefore, the application of

biochar to soils emerges as a 'win-win strategy' for sustainable waste management, climate change mitigation and food security.

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***Keywords*****:** Biochar, Nitrogen, Phosphorus, Potassium, Micronutrients, Crop yields

## 1. Introduction

During the last decade, biochar has gained importance owing to its roles in climate change mitigation and agronomic benefits among global agriculturists, environmental experts and policy makers. The term "biochar" is referred in recent literature emphasizing its use for atmospheric carbon capture and storage, and soil application differentiating from black carbon (Kookana et al., 2011). The European Commission (Verheijen et al., 2010) comprehensively defined biochar as: "charcoal (biomass that has been pyrolyzed in a zero or low oxygen environment) for which, owing to its inherent properties, scientific consensus exists that application to soil at a specific site is expected to sustainably sequester carbon and concurrently improve soil functions (under current and future management), while avoiding short- and long-term detrimental effects to the wider environment as well as human and animal health".

Biochar is produced by heating organic materials (e.g., plant residues, manures, waste materials) in absence of oxygen or otherwise known as pyrolysis (Lehmann, 2007). During pyrolysis, one-third to half of biomass carbon is converted into biochar. The heat treatment (more often thermochemical treatment) of organic biomass used to produce biochar contributes to its large surface area and its characteristic ability to persist in soils with variable biological decay (Lehmann et al., 2006) having half-life ranging from decades (Nguyen et al., 2009) to centuries (Zimmerman, 2010). Conceptually, biochar can serve multifaceted roles in soils (Fig. 1). Biochar can act as a soil conditioner or soil amendment to improve the soil quality, enhance plant growth by supplying nutrients, and retain nutrients. In this regard, an obvious positive attribute of biochar is its nutrient value, supplied either directly by providing nutrients to plants or indirectly by improving soil environment, with consequent improvement of fertilizer use efficiency. Nutrient composition and availability from biochar depend upon both the nature of the feedstock and the pyrolysis conditions (Gaskin et al., 2009; Bera et al., 2017). It helps to reduce nutrient leaching (Parvage et al., 2013), and increases crop production. It also provides other services such as improving soil physical and biological properties (Lehmann andRondon, 2005; Mandal et al., 2016a; Purakayastha et al., 2015; Purakayastha et al., 2016; Bera et al., 2016; Bera et al., 2019). Moreover, biochar can alter the root morphology of crop plants in terms of favoring the fine root proliferation increasing the specific root length and decreasing both root diameter and root tissue density. The improved root conditions help plants to exploit more soil volume even under nutrient-starved soils directing towards biochar's role in increasing the fertilizer use efficiency (Olmo et al., 2016). It also has the capability to improve water retention properties of soil and enhance the soil's ability to retain nutrients (Rens et al., 2018). It could alter various soil properties through changes in pore size distribution, residence time of soil solution and flow paths of nutrients (Major et al., 2009). Overall, biochar can potentially add a holistic dimension for enhancing the soil quality and health which sooner or later is believed to impact crop productivity positively.

Biochar application in soil for increasing crop production and other benefits including soil carbon sequestration is increasingly being recognized as a win-win strategy. The impact of biochar on crop productivity is largely influenced by the crop type, soil and biochar properties, which in turn depend on feedstock source and pyrolysis temperature. Several recent reviews have discussed the roles of biochar in climate change mitigation (Cayuela et al., 2013; Lehman et al., 2006, Mandal et al., 2016a; Meyer et al., 2001; Minasny et al., 2017; Purakayastha et al., 2015; Purakayastha et al., 2016; Singh et al., 2010), waste management (Ahmad et al., 2014; Devi and Saroha, 2015; Kookana et al., 2011; Mandal et al., 2018a; Mohan et al., 2014), agronomic benefits (Alvarej-Camposa, 2018; Atkinson et al., 2010; Clough et al., 2103; Jeffrey et al., 2010; Kookana et al., 2011; Lehman et al., 2015; Liu et al., 2013; Mandal et al., 2016b; Spokas et al., 2000; Woolf et al., 2010), soil quality (Agegnehu et al., 2017; Barrow, 2012; Bera et al., 2016; Huang et al., 2013; Jones et al., 2012; Lehman et al., 2011; Laird et al., 2010a; Sohi et al., 2010), bioenergy production (Laird et al., 2009; Ro et al., 2010), and remediation of polluted soils (O'Connor et al., 2018a,b).

The effectiveness and application of biochar heavily relies on the biomass feedstock and the conditions under which it is produced (Tag et al., 2016; Zhang et al., 2017). Traditional biochar derived from wood or agricultural plant residues may have poor sorption capabilities (Yao et al., 2012), due to the absence of important electrostatic attractions between biochar and the negatively charged ions like phosphate (Vikrant et al., 2018). Several studies have attempted to enhance sorption capacities of anions by developing modified biochar through various coating procedures. Metal oxide-coated biochar, manufactured by bioaccumulation within the feedstock plant itself, including Mg-enriched tomato plants, has proven very successful (Yao et al., 2013). Similarly, co-precipitating metal oxides on the surface of biochar, post pyrolysis, including magnesium-coated oak wood biochar was an effective adsorbent (Takaya et al., 2016). Iron-impregnated orange peel (Chen et al., 2011), corn straw (Liu et al., 2015) and wood chip (Micháleková-Richveisová et al., 2017) biochars have also been used successfully to remove phosphate from aqueous solutions in laboratory experiments. The biochar based adsorbent production methods recommended for improving contaminant removal efficiency include surface modification (Zhu et al., 2018), chemical group embedding (Zhou et al., 2013), metallic hybridization (Li et al., 2016a,b), and nanomaterial decoration (Inyang et al., 2014). For example, graphenes (Gs) and carbon nanotubes (CNTs) have been used as nanomaterial precursors for the engineered hybrid biochar adsorbent production (Tang et al., 2015).

Compared with the pristine biochar, CNT-biochar and G-decorated biochar composites exhibited superior adsorbent properties, e.g., strong affinities for aromatic hydrocarbon and heavy metal pollutants and large specific surface area (Inyang et al., 2014; Sarkar et al., 2018; Zhang et al., 2012). Hybridization of $CeO_2$–$MoS_2$ hybrid magnetic biochar greatly improved Pb (II) and humate removal compared to magnetic biochar, with > 99% Pb(II) and humate removed within 6 h (Li et al., 2019). In a review, it has been reported that soil amendment with biochar may reduce the bioavailability of a wide range of contaminants, including heavy metal(loids), potentially reclaiming contaminated soils for agricultural use (O'Connor et al., 2018a). The results of this review indicate that biochar application can potentially reduce contaminant bioavailability in the field; for instance, a significant decrease (control normalized mean value = 0.55) in the Cd enrichment of rice crops was observed. Sulphur-modified rice husk biochar increased the biochar's $Hg^{2+}$ adsorptive capacity ($Q_{max}$) by ~73%, to 67.11 mg $g^{-1}$ (O'Connor et al., 2018b).

However, there is a dearth of recently compiled information on overall impact of biochar properties on crop productivity and soil quality (Liu et al., 2013). There are continuous array of review publications on biochar, but most of them are related to the environment, for example, environmental contamination, water treatment and pollutant remediation. Principally, information on how key parameters, such as biochar feedstock type, pyrolysis temperature, application rate to soil, feedback to soil chemical properties (e.g., pH, cation exchange capacity (CEC) and crop yields are largely inconclusive. Hence, a critical synthesis of information about the above is urgently needed. The current review attempts to reveal biochars' nutrient properties and its role in soil nutrient transformation that influence soil quality and crop productivity in the present context of global climate change. Therefore, this review examines - (i) biochar nutrient value in relation to pyrolysis condition and feedstock types, (ii) biochar roles in soil nutrient availability and transformation, (iii) the potential benefits of biochar in sustainable crop production, and (iv) meta-analysis of the up to date published data for evaluating the effect of biochar on soil condition improvements and crop yield. We believe that this compilation is a useful document highlighting the emerging research needs in this area.

## 2. Methodology

### *2.1. Literature search method*

Google Scholar was searched for keywords like “biochar”, “characteristics”, ‘’availability of nutrients”, AND “yield” within publication titles. Additional articles were found by searching key words for “biochar” AND “crop yield” with various nutrients, e.g., N, P, K, secondary nutrients and micronutrients. Various online journals, e.g., Science of the Total Environment”, “Geoderma”, “Soil and Tillage Research”, “Bioresource Technology”, “Advances in Agronomy”, “Agriculture, Ecosystems and Environment”, “European Journal of Agronomy”, “Soil Biology and Biochemistry”, “Bilogy and Fertility of Soils”, “Applied Soil Ecology” etc. were also directly consulted for relevant papers. Only the relevant publications meeting the objectives of this review paper were selected to form the basis of this review. The literature search resulted in various publications relevant to this review paper, are presented in Table 1, 2, 3 and 4.

### *2.2. Data compilation and analysis*

In this review paper, we have collected the information on nutrient contents in biochar prepared from various feedstocks at different pyrolysis temperatures, their effects on physical, physico-chemical properties of soils and dynamics of N, P, K, and secondary and micronutrient dynamics in soil. The information on the impact of biochar on crop yields was based on various soil orders having dissimilar properties like pH (acidic, neutral to alkaline), texture (silty, sandy clay loam, clay loam), CEC etc. In order to classify biochar, we gathered literature on biochar prepared from various feedstocks, e.g., crop residues, manures, wood, and waste materials. Majority of the information was collected from various peer-reviewed journals of international repute. Two principal component analyses (PCA) were performed in this study using data from published literature: one in which the objective variables were changed in soil chemical properties, e.g., pH and CEC, and the other in which the objective variable was changed in crop yield. Since variables were measured in different units, the variable values were all normalised by subtracting the mean and dividing by the standard deviation of the variable group, and the PCA was computed using the correlation matrix between the variables. All PCAs were performed using the program PAST version 3.18 (Hammer et al., 2001).

## 3. Role of biochar in mitigating climate change

Any compilation on biochar without mentioning its role in mitigating climate change is incomplete. Thus, it is imperative to briefly mention the role of biochar in negating global warming. In doing so, it is notable to mention that the Paris Climate Agreement in 2015 set a target for participating countries that 'hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels' (IPCC 2015). While conventional greenhouse gas emission mitigation strategies, such as lowering the consumption of fossil fuels, are needed to achieve the goal of the Paris Agreement, simultaneous actions on negative emissions through sustainable carbon dioxide removal (CDR) technologies and engineered enhancement of natural carbon sinks are also urgently required (Gasser et al. 2015; Rogeljet al., 2016). Recent reports suggest that the goal of holding global warming to well below 2°C is extremely unlikely unless the emissions gap is not closed by 2030 (UNEP, 2017). In order to achieve large reductions in greenhouse gas emissions, sequestering carbon in the terrestrial sink is needed (Paustian et al., 2016). The global soil has been estimated to hold the largest terrestrial organic carbon pool (~1,500 Pg C to a depth of 1 m; 2,400 Pg C to 2 m depth) (Batjes, 1996). An increase in organic matter inputs to soil, or a decrease in soil organic matter decomposition rates, or the net carbon gaining effect of the both can increase the carbon stock in soil (Paustian et al., 2016). The recently launched '4 per mille Soils for Food Security and Climate' concept also proposes to increase global soil organic matter stocks by 4 per 1000 (or 0.4 %) per year in order to compensate global greenhouse gas emissions due to anthropogenic activities (Minasny et al., 2017). In this connection, the application of biochar to soils has been shown to achieve the net carbon gain in soils while also serving for increased plant biomass production by enhancing the nutrient supply to plants and increasing nutrient and water use efficiencies (NUE and WUE) by plants (Kookana et al., 2011; Lehmann et al., 2015; Minasny et al., 2017). Thus, biochar application to soils has been recommended as an important component of the pathway to 'climate-smart soil' management practices in modern global agriculture (Paustian et al., 2016).

## 4. Carbon and nutrient contents of biochar

Biochar is enriched with C, and contains a range of plant macro, micro and secondary nutrient elements (Chan and Xu, 2009). The composition of biochar depends upon the nature of feedstock and pyrolysis conditions, and published literature suggests a wide variation in biochar compositions (Table 1). Carbon contents ranged from 81.2% in biochar prepared from bamboo chip (Mandal et al., 2017) to 19.2% in biochar prepared from paper mill sludge (Devi and

Saroha, 2015) (Table 1). Biochar prepared form crop residues and woody materials contained a higher C content than biochar prepared from manure sources. Waste material biochars had a wide range of C contents (19.2-84.0%) indicating their differential initial constituents. During the pyrolysis process, N in residues is converted to recalcitrant forms, and using nuclear magnetic resonance and near-edge X-ray adsorption fine structure spectroscopy, it was found that both C and N became enriched in aromatic and heterocyclic aromatic structures in biochar (Chen et al., 2014). Manure-derived biochar was undoubtedly the richest source of N among all feedstock types of biochar, showing N content as high as 4.45%. Contrarily, biochar prepared from woody materials was scant in N content. Thus, most of the manure derived biochars had lower C/N ratios ranging between 10-30, with few exceptions.Wood-derived biochar had a wider C/N ratio (Atkinson et al., 2010; Rajkovich et al., 2012). The very low N content (0.04%) in canola straw biochar conferred it the highest C/N ratio (160:1). The P content was recorded the highest (5.90) in swine solid biochar, while the lowest (0.017%) in yellow pine chip biochar. On the other hand, the highest (7.40% for poultry litter) and lowest (0.087% for brush) K contents were recorded in manure and waste material derived biochars, respectively (Cantrell et al., 2012; Ro et al., 2010). The paper mill biochar (Devi and Saroha, 2015) and poultry manure biochar (Enders et al., 2012) prepared at 600 $^{o}$C were reported to be rich sources of Ca (25 and 31%, respectively) and Mg (0.87 and 0.29%, respectively) (Table 1). Data on micronutrient contents in biochar is limited in the literature. Biochar prepared from swine solids contained 74800, 2240, 4981, 2446 and 27.4 mg kg$^{-1}$ of Fe, Mn, Zn, Cu, and Mo, respectively (Table 1; Cantrell et al., 2012). The majority of biochar samples were alkaline in pH with few exceptions such as sugarcane bagasse biochar, yellow pine chip biochar, hazelnut biochar and eucalyptus biochar, which were found to be acidic in solution. Increasing the pyrolysis temperature in general enhances the acid neutralising property of biochar increasing the pH (Bera et. al., 2018). The alkalinity of biochar was primarily due to the presence of inorganic alkali salts. The organic COO– and –O– groups that could modify the acid reaction of biochar surface through association with $H^+$ ions might also contribute to biochar alkalinity (Al-Wabel et al., 2013).

The pyrolysis temperature significantly influenced the pH, C, and nutrient compositions of biochar. Purakayastha et al. (2016) reported that increase in pyrolysis temperature from 400 °C to 600 °C significantly increased the C content, while it decreased the N content in all biochars except that was produced from rice hull. These findings were in agreement with the other studies which also found higher C contents in plant material based biochars, e.g., canola, soybean (Yuan et al., 2011), peanut hull, pine chips (Gaskin et al., 2008), *Eucalyptus saligna* wood and leaf (Singh et al., 2010). Contrastingly, Yuan et al. (2011) reported that the C content decreased in corn and peanut biochar with an increasing pyrolysis temperature from 300 °C to 500 °C. In general, the C/N ratio increased due to an increase in pyrolysis temperature. For example, the C/N ratio of switch grass biochar increased from 54 to 84 when pyrolysis temperature increased from 400 °C to 600 °C (Purakayastha et al., 2016). In contrast, Novak et al. (2009) reported that the C/N of sugarcane bagasse biochar decreased from 129 to 79 when pyrolysis temperature increased from 250 °C to 500 °C. The slow and fast pyrolysis process during heating could also influence the C and N contents, and C/N ratios. Consequently, the C/N ratio of biochar prepared at slow pyrolysis is expected to be greater than that prepared by fast pyrolysis process (Atkinson et al., 2010). For example, Bruun et al. (2012) reported that biochar prepared from wheat straw at slow pyrolysis contained more C (69.6%) than the biochar prepared at fast pyrolysis (49.3%).

## 5. Interaction of biochar with soils

### *5.1. Soil physico-chemical properties*

#### *5.1.1. Biochar modifying soil physical environment*

Biochar amendments were reported to improve soil bulk density, porosity, water retention, and hydraulic conductivity (Abel et al., 2013; Asai et al., 2009; Atkinson et al., 2010; Jeffery et al., 2011; Karhu et al., 2011; Laird et al., 2010a). Moreover, biochar application significantly influenced the infiltration capacity in soils (Lehmann et al., 2006; Sohi et al., 2010). Bayabil et al. (2015) reported that incorporation of woody feedstock (Acacia, Croton, and Eucalyptus) charcoals significantly decreased the soil moisture retention at lower tensions (10 and 30 kPa), resulting in an increase in relative hydraulic conductivity at these tensions in a clay soil. Akhtar et al. (2014) found higher water use efficiencies when irrigation was applied through partial root zone drying along with the application of 5% biochars prepared from rice husk or cotton seed mixture, over full irrigation. Addition of 10 Mg $ha^{-1}$ biochar in a sandy soil in Finland increased the available water content in the dry period of the year under *Phleumpratense* growth (Saarino et al., 2013). In contrast, water holding capacity of Quincy sand soil of Washington State remained unchanged in a laboratory incubation study with the application of biochars prepared from switch grass, anaerobically digested fiber, softwood bark and wood pellet (Streubel et al., 2011). Biochar prepared from black locust (*Robinia pseudoacacia*) when applied at a dose of 20 Mg $ha^{-1}$ increased the available water capacity by 97%, saturated water content by 56%, and reduced the hydraulic conductivity with increasing moisture content in a sandy soil (Uzoma et al., 2011a).

Soil aggregation is considered as another important physical property which determines the stability and support of soil, and biochar showed its beneficial impact on that as well. Soinne et al. (2014) reported that biochar had the potential to improve the aggregate stability in clay soils, and thus repeated biochar additions could reduce the deteriorating effect of tillage on soil aggregates. It could even lead to the improvement of the structural stability of cultivated clay soils (Soinne et al., 2014). A study using synchrotron-based X-ray micro-computed tomography revealed that the increased porosity of macroaggregates in biochar-amended soil was jointly contributed by the inherent porosity in the applied biochar as well as the newly formed pores out of soil-biochar interactions (Yu et al., 2016). The authors also reported that wood chip biochar and waste-water sludge biochar were more efficient in increasing the porosities of the products over straw biochar, and hence showed greater effects on soil macroaggregates (Yu et al., 2016). Thus, biochar could improve the physical properties of difficultly manageable clay and sandy soils by changing their air-water relationships through mechanisms like increased aggregate stability, water infiltration and water holding capacity (Fig. 1).

#### *5.1.2. Biochar modifying soil pH, buffering system, CEC*

In soil, availability of nutrients for plants is pH dependent. Biochar may alter soil pH, which in turn can change nutrient solubility, thereby modifying the nutrient availability. The impact of biochar addition on soil pH and CEC has been summarized in Table 2. The resultant soil pH values tended to move to the alkaline side when the soil received an increased biochar application rate, and when the biochar was produced at a high temperature (e.g., 700 °C) (Mandal et al., 2016b; 2018). Effect of wood ash or horticultural biochar in modifying soil pH has long been known, and documented by earlier reports (Clarholm, 1994; Glaser et al., 2002; Mahmood et al., 2003). Jeffery et al. (2011) found that biochar could increase soil pH by 0.1-2.0 units in a wide range of soils varying in native pH values. An insight perusal of Table 2 indicated that the magnitude of soil pH change upon biochar addition was inevitably reliant on soil types, biochar properties, and application rates. Chan et al. (2007; 2008) demonstrated that green waste biochar and poultry litter biochar could gradually increase pH by 0.6 to 2.0 units of an acidic Alfisol at successive application rates ranging from 10 to 100 t $ha^{-1}$ under radish (*Raphanus sativus*) cultivation. Similarly, van Zwieten et al. (2010) reported increased soil pH values due to sludge biochar addition in an acidic Ferrosol cropped with wheat, radish, and soybean. The plotting of biochar application rate and per cent changes in soil pH provided an interesting observation in segregating various soil types as impacted biochar applications (Fig. 2). The per cent increase in soil pH due to biochar application was the highest (> 50%) in Alfisol with biochar application rates ranging from 25-50 Mg $ha^{-1}$, while the increase was between 4–50% in Alfisol, Anthrosol, Cambisol, Mollisol, Inceptisol and Oxisolis with biochar application rates ranging from 4-72 Mg $ha^{-1}$ (Fig. 2). In Planosol, even at very high rate of biochar application (90-100 Mg $ha^{-1}$), the per cent increase in soil pH was only between 22-33%. Interestingly, in calcareous soils, and some Cambisol and Mollisol, no effect of biochar on soil pH was observed (Fig. 2). Alfisols, Ferrosols and Acrisols are inherently highly acidic in nature, and biochar being alkaline material neutralised the acidity. As there could be variations in active and potential acidity in these soils, the differential impact of biochar on enhancing the soil pH was noticed. Among the biochars, poultry litter biochar being highly alkaline in nature (pH≈10) had the highest impact on the pH of acid soils.

The associated increase in soil pH with biochar addition would result in a greater availability of primary and secondary nutrients like K, P, Ca, Mg (Asai et al., 2009; Glaser et al., 2002; Major et al., 2010). The other advantage of increased pH due to biochar addition is the reduction of Al toxicity in acidic soils. In an acidic Ferrosol, 10 t $ha^{-1}$ biochar addition reduced the ammonium acetate extractable Al from 1.93 cmol ($p^+$) $kg^{-1}$ soil to an undetectable amount (van Zwieten et al. 2010). The liming effect of biochar in acid soils, as described above, not only could improve the mineral nutrient supply for plant growth, but also could alleviate Al stress for better crop production (Liu et al. 2013; Dai et al., 2017). On the contrary, limited information is available on the effects of biochar addition in alkaline soils of arid and semiarid regions. Some studies (Karer et al., 2013; Lentz and Ippolito, 2012; van Zwieten et al., 2010) did not observe a significant change in soil pH due to biochar addition where initial values were ranging between pH 7.4-7.8. Contrarily, Streubel et al. (2011) found 0.1 to 0.9 unit pH increase of an alkaline sandy soil. Similarly, Mandal et al. (2018) reported that when biochars produced from poultry manure, green waste compost and wheat straw at various temperatures (250 – 700 °C) were applied to an alkaline soil (pH 8.01), they could modify the soil pH values by about 0.84 units in both directions ranging from pH 7.37 to 8.23. These discriminating results about pH values, as discussed above, need thorough investigation by conducting biochar application trials in alkaline soils in arid and semiarid regions of the world.

The CEC of soils is an essential property in relation to the soil fertility. A higher CEC soil can hold cationic nutrients in greater amounts and for longer time than a lower CEC soil, preventing the nutrients from leaching loss and increasing their availabilities for plant uptake. As shown in Table 2, CEC increased in all cases except one where the soil was a calcarosol (van Zwieten et al. 2010). The higher CEC of biochar-amended soils was ascribed to the dominance of negatively charged surface functional groups, increased specific surface area of the products, adsorption of highly oxidized organic matter on biochar surfaces, and the presence of residual volatile matter in the biochar matrix (Glaser et al., 2003; Lehmann et al., 2005; Liang et al., 2006). The increase in total negative charge and charge density on soil applied biochar surfaces was reported due to the biotic and abiotic oxidation of organic functional groups in long-term soil application studies (Cheng et al., 2006; Zimmerman, 2010). Yuan et al. (2011a) found a significant increase in soil CEC (15-25%) when canola, rice, soybean and peanut straw biochars (CEC of biochars ranging between 179-279 cmol ($p^+$) $kg^{-1}$ were added to a low CEC Acrisol. Similar findings were reported by previous authors (Kloss et al., 2014; Liard et al., 2010b; van Zwieten et al., 2010). The increase in CEC could affect the retention of phosphate by biochar through anion exchange reaction. However, DeLuca et al. (2009) reported that biochar application to soil increased plant P availability by lowering the activity of soluble Al and Fe. The CEC of biochar is mainly influenced by the feedstock type, pyrolysis temperature and aging time (Heitkötter et al., 2015; Bera et al., 2017). Likewise, biochars produced from non-leguminous straws had a higher CEC than those produced from leguminous straws (Jiang et al., 2014). Thus, a critical decision needs to be made concerning biochar feedstock type, pyrolysis temperature, application rate, and biochar age in order to achieve intended soil pH and CEC values suitable for crop production.

*5.2. Soil nutrient dynamics*

Fig. 3 shows the mechanisms how biochar potentially can improve the retention of macro- and micronutrients in soils, and consequently may improve their availability to plants. While biochar can interfere with the key carbon and nitrogen cycle processes by interacting with relevant microorganisms, it can also participate in the nutrient cycling processes by physico-chemical interactions, such as surface adsorption of various elements (Agegnehu et al., 2017; Bornø et al., 2018; Mandal et al., 2016b; 2018; Xu et al., 2018a).The unique porous characteristics of biochar along with its heterogeneous surface functional groups can take part in diffusion-controlled adsorption of elements, surface complexation and ligand exchange reactions, which ultimately control the plant-available nutrient dynamics in soils (Mandal et al., 2016a;Liu et al., 2013; Nielsen et al., 2018).

In most of the previous studies, total nutrient contents of biochar were reported rather than the plant available nutrient contents (Table 1). However, the entire amounts of nutrients present in biochar are not readily soluble in water. Nutrients in biochar are present either in available or in difficultly accessible forms pertaining to the complex organic and inorganic composition of the material. There is a scarcity of published reports evidencing direct nutrient availability from biochar to crops. The amount of water-soluble nutrients in biochar except K is usually low (Steiner et al., 2010). Bera et al. (2014) reported that water-soluble P, K, Ca and Mg contents in mustard stalk biochar were 13-16%, 65-70%, 14-17% and 23-26% of the individual total nutrient contents, respectively. The remaining amounts of the nutrients existed either as inorganic minerals captivated within the complex organic moiety of C, H, and O, or as an integral component of the organic moiety. Biochar needs to undergo both chemical and microbial decompositions to release these captivated nutrients and subsequently make them available for plant absorption. Gaskin et al. (2010) reported an increased concentration of mineral nutrients (K, Ca and Mg) in maize tissue and soil extracted by Mehlich-1 reagent when peanut hull and pine chip biochar were added to a loamy sand soil in Tifton, Georgia. The impact of peanut hull biochar was more pronounced than pine chip biochar due to the higher contents of K, Ca and Mg in the former, and in the first year of biochar application than the second year (Gaskin et al., 2010). Novak et al. (2009) also found a high concentration of Mehlich-1 extractable P in Norfolk loamy sand soil amended with poultry litter biochar (4 Mg $ha^{-1}$) containing high total P content (3-4.3%). In another study, soil total N, Olsen-P, exchangeable K, Ca and Mg concentrations increased with cow manure biochar application under maize production in Japan (Uzoma et al., 2011). Following a three years' trial at field conditions, Munda et al (2018) also reported the possibility of soil fertility enrichment vis-a-vis improved grain yield of rice crop via rice husk biochar application. These are all indirect evidences of enriched nutrient availabilities resulted from biochar addition to soils. Thus, future research needs to be undertaken involving isotopic tracer techniques to measure the availability of plant nutrients directly from biochar, or by comparing the relative contribution of soil and biochar sources with regards to plant-available nutrients.

*5.2.1. Effect of biochar on nitrogen dynamics*

Application of biochar significantly influences the mineralization-immobilization turnover of nutrients, which is affected by altering both microbial activities and community structure of soils. Since biochar is a C-rich substrate with a high C/N ratio, upon its application to the soil, microorganisms are triggered to decompose the native soil organic matter (SOM) to acquire N via priming effect (Blagodatskaya and Kuzyakov, 2008). Biochar being rich in surface functional groups, including aromatic moieties, can alter cation and anion exchange capacities of soils, which further influences N retention (Clough et al., 2013; Slavich et al., 2013; Mandal et al., 2018). Thus, maize biochar was reported to accelerate soil N transformations by increasing the net N mineralization (Nelissen et al., 2012, Gundale and DeLuca, 2006), accelerating nitrification (Song et al., 2013), affecting denitrification (Cayuela et al., 2013), reducing ammonia volatilization (Mandal et al., 2016b; 2018), and through adsorption of ammonia and increasing $NH_4^+$ storage in soils (Clough and Condon, 2010).

The transformation of N as impacted by various biochar materials are presented in Table 3. When biochar was added to soil, gross N mineralization, recalcitrant nitrogen fraction and labile N fraction were found to be stimulated (Table 3). This increase was higher in the biochar produced at low temperature (350$^{o}$C) than that produced at high temperature (550$^{o}$C) (Nelissen et al., 2012). Results showed accelerated soil N cycling following biochar addition, with increased gross N mineralization (185-221%), nitrification (10-69%) and ammonium ($NH_4^+$) consumption rates (333-508%) (Nelissen et al., 2012). Most of the mineralized $NH_4^+$ under biochar treatments came from the recalcitrant N in soil, while in the control soil most mineralized $NH_4^+$ originated from the labile N (Nelissen et al., 2012). This could be due to the biochar induced incresae of soil porosity/aeration that stimulates the aerobic/heterotrophic microbial population resulting in the degradation of recalcitrant SOM in the presence of biochar (Anderson et al., 2011). Pereira et al. (2015) reported that the gross N mineralization increased in response to soil-applied biochar materials with high H/C ratios (i.e., Douglas fir wood pyrolyzed at 410 and 510°C, and hog waste wood pyrolyzed at 600 and 700°C). The enhancement of N mineralization could be favourable for organic farming systems challenged by insufficient N mineralization during plant growth (Pereira et al., 2015). Studies demonstrated that at least 10% of the $^{15}N$ added to the soil as $^{15}N$ labelled pyrogenic organic material (PyOM) (obtained from *Lolium perenne* charred for 4 minutes at 350$^{o}$C) could be utilized by grasses in a Mediterranean agricultural soil within just 72 days of growth (Rosa and Knicker, 2011). This showed a direct evidence that PyOM produced at a low temperature could be easily degraded, and its N would become available to plants (Rosa and Knicker, 2011).

The plausible effects of biochar on soil biological processes can significantly influence soil N transformations. Such effects can be partially explained by biochar properties. For example, biochar could increase the mineralization of recalcitrant soil organic N (Nelissen et al., 2012). The other important mechanisms include an enhanced abundance of ammonia oxidizing microorganisms (Song et al., 2013), and promotion of denitrification by the transfer of electrons to soil denitrifying microbes (Cayuela et al., 2013). For instance, PyOM derived from rye grass pyrolyzed at 450$^{o}$C induced a strongly positive priming effect within the first 18 days, and thereafter exhibiting a negative priming effect in a forest Cambisol (Maestrini et al., 2014). The initial increase in organic matter mineralization corresponded to a higher gross N mineralization and $NH_4$ content in the PyOM-treated soil than in the untreated soil (Maestrini et al., 2014). The effect of biochar on soil denitrification might depend on temperatures at which the product is produced. Compared to the unamended soil, amendment with biochar (produced at 200$^{o}$C and 400$^{o}$C from oak wood feedstock) significantly increased $N_2O$ emissions, but biochar produced at a higher temperature (600$^{o}$C) did not show such effect on $N_2O$ emissions (Zhang et al., 2015). During the pyrolysis process, N in biomasses get converted to recalcitrant heterocyclic aromatic structures in biochar, and these structural changes may lead to a reduction in C and N mineralization rates (Chen et al., 2014). The mineralized C decreased from 32.7% of the added C of raw biomass to 0.5% in the biochar produced at temperature above 400°C (Chen et al., 2014). The N dynamics thus shifted from N mineralization in raw biomass to N immobilization in biochar at charring temperature 500°C (Chen et al., 2014). As such, soil amended with biochar produced at temperatures exceeding 400°C demonstrated a 25% decrease in dry shoot biomass of water soinach (*Ipomoea aquatica*) compared with unamended soil principally due to N limitation (Chen et al., 2014). Therefore, the C stability of leguminous green manure like *Ipomoea sp.* could be enhanced by converting the raw material into biochar, but the charring process might limit the immediate supply of N. Similarly, corn stalk biochar proved to contain recalcitrant N as indicated by lower decay rate constants (Blum et al., 2013). Application of N-limited biochar may induce microbial immobilization of available N in the soil (Lehman et al., 2006; van Zwieten et al., 2009). Soil and biochar mixtures showed evidence of both soil nutrient sorption by biochar, and biochar nutrient sorption by the soil, depending upon the biochar and soil types (Mukherjee and Zimmerman, 2013; Rens et al., 2018). For example, application of willow (*Salix viminalis* L.) branch biochar prepared at 470$^{o}$C significantly decreased the available $NH_4^+$ and $NO_3^-$ levels during 30 to 90 days in flinty clay loam soils of United Kingdom indicating a net N immobilization (Prayogo et al., 2014). Availability of resin-extractable $NH_4^+$ and $NO_3^-$ fractions in soil decreased with the addition of wheat straw biochar and olive-tree pruning biochar (Olmo et al., 2016), and this might be governed by the porous nature, high surface area and ion exchange capacity of biochar that can enhance the sorption of $NH_4^+$ (cation exchange) and $NO_3^-$ (within biochar pores) (Lehmann et al., 2003; Atkinson et al., 2010; Laird et al., 2010a; Prendergast-Miller et al., 2014). The rate of N immobilization was significantly higher in the treatment receiving both litter and 2% biochar. Nitrogen deficiency in larch (*Larixgmelinii*) cultivation resulted from the application of Japanese larch wood biochar was also reported (Makoto et al., 2011). The application of hard wood biochar, a mix of white ash (*Fraxinus americana*), oak (*Quercus* sp.), and beech (*Fragus grandifolia*) produced by fast pyrolysis at 500-600 $^{o}$C with either NPK or digested dairy manure had little effect on N dynamics in Warden silt loam soil of Washington state of USA (Bera et al., 2016).

Leaching of N from soils is a serious problem, especially in light-textured soils, causing environmental pollution and eutrophication. To limit the leaching loss of N from soil, biochars prepared from a variety of feedstocks and at different pyrolysis environments (duration, temperature, heating rate) have been extensively investigated in the recent past (Petersen, 1978;

Lehmann et al., 2003; Jones et al., 2012; Zhu et al., 2012). Yao et al. (2012) reported that sugarcane bagasse, peanut hull, Brazilian pepperwood, and bamboo biochars could adsorb 1-12% $NH_4^+$-N from aqueous solution, and Brazilian pepperwood gave the most effective biochar for $NH_4^+$ adsorption among these feedstocks. Asada et al. (2002) found a greater adsorption of ammonia ($NH_3$) by bamboo (*Bambusa* sp.) biochar prepared at 500 °C than that prepared at >700 °C. The $NH_4^+$ adsorption capacities of commercial coconut shell activated carbon prepared at 600°C and 400°C were found to be 2400 and 600 to 1800 mg $NH_3$ kg$^{-1}$ carbon, respectively (Rodrigues et al., 2007). Recently Hea et al. (2018) reported that biochar application to soil with urea increased $NH_3$ volatilization losses by 14.1% in the first rice season, primarily due to increased pH and concentrations of $NH_4^+$-N in the floodwater, and decreased $NH_3$ losses in the second rice growth season by 6.8%, probably due to its high adsorption capacity for $NH_4^+$ and increased nitrification. Application of bamboo charcoal (pyrolyzed at 600 °C) to a variety of sandy silt soils showed a cumulative 15% reduction in $NH_4^+$-N leaching loss over 70 days (Ding et al., 2010). The adsorption of $NH_4^+$ on the biochar surfaces was the result of a week van der Waals forces between positively charged $NH_4^+$ and negatively charged soil or organic matter surfaces (Hale et al., 2013). The adsorbed $NH_4^+$-N eventually become available to plants or microbes in the long run reducing the loss of mineral N in soils (Taghizadeh-Toosi et al., 2012a, 2012b).

The overall impact of biochar on N transformations in soil is also reflected (positive, negative and neutral) in the post-harvest analysis of soil samples for N contents. Poultry litter biochar and wheat straw biochar, when applied at the rate of 1.0–5.0 Mg ha$^{-1}$ to an acidic Aeronosol and a neutral Vertisol, they did not affect the post-harvest total soil N (Macdonald et al., 2014). However, application of these biochars at 5 - 10 Mg ha$^{-1}$ to an acidic Ferrasol and alkaline

Calcisol increased the total soil N content significantly (Macdonald et al., 2014). Similarly, application of rice husk biochar at 41 Mg $ha^{-1}$ was found to increase total soil N after the harvest of rice crop in an acidic Gleysols of Philippines (Haefele et al., 2011). The available N content increased in an alkaline sandy loam soil too under the influence of biochar, and the effect was more pronounced for maize stover than wheat straw biochar (Purakayastha et al., 2015). Jones et al. (2012), however, reported that commercially available biochars derived from mechanically chipped trunks and large branches *of Fraxinus excelsior* L., *Fagus sylvatica* L. and *Quercus robur* L. pyrolyzed at 450°C for 48 h did not affect the dissolved organic N (DON), $NO_3^-$- or $NH_4^+$-N contents in the soil. Similarly, biochar addition showed limited effects on the turnover of soil organic carbon, DON and no long-term effect on N mineralization, $NH_3$ volatilization, denitrification and $NH_4$ sorption (Clough et al., 2013). In contrast, biochar made from chicken manure increased the available nutrient contents in soils including N (Chan and Xu, 2009, Chan et al., 2008). Peanut shell biochar (5% w/w) promoted the urease activity in a saline soil over short-term laboratory incubation indicating the role of biochar in soil N dynamics (Bhaduri et al., 2016).

Nishio and Okano (1991) reported that biological nitrogen fixation (BNF) at the early stage of alfalfa growth and nodule development stage was 15 and 227% higher, respectively, than the control when biochar (*Eucalyptus deglupta*, 350 °C) was added to the soil. Several studies indicate that biochar serves as an excellent support material for *Rhizobium* inoculants (Pandher et al., 1993; Lal and Mishra, 1998). Rondon et al. (2007) reported that the proportion of fixed N by common bean (*Phaseolus vulgaris* L.) increased from 50% in the control to 72% with 90 g $kg^{-1}$ biochar application. While total N derived from the atmosphere (NdfA) significantly increased by 49 and 78% with 30 and 60 g $kg^{-1}$ biochar applications to the soil, respectively, NdfA decreased by 30% than the control with 90 g $kg^{-1}$ biochar application (Rondon et al., 2007). The primary reason for the higher BNF with biochar additions was the greater B and Mo availability in the amended soil than the unamended control, while a greater K, Ca, and P availability with higher soil pH and lower N availability and Al saturation might have also concurrently occurred (Rondon et al., 2007).

*5.2.3. Effect of biochar on phosphorus dynamics*

Biochar, produced from common crop residues or unconventional tree species, influences P transformation in soils directly or indirectly by three major mechanisms: (1) being a direct source of soluble P and exchangeable P, (2) modifying the soil pH and ameliorating various elements (e.g., $Al^{3+}$, $Fe^{3+}$, $Fe^{2+}$, $Ca^{2+}$, $Mg^{2+}$) that are responsible for making complex with P, and (3) acting as a source of C and energy for enhancing the microbial activities and P mineralization (DeLuca et al., 2009). Many studies reported the increase of P availability via biochar application to soils (Table 3).

Biochar produced at both low and high temperatures (350$^{o}$C and 800$^{o}$C, respectively) resulted in significant changes in the extractable P pool, with a trend of decreasing extractable P with application of high temperature biochar (Gundale and DeLuca, 2006). Increasing pyrolysis temperature also decreased the water soluble P content in rice, wheat, maize and pearlmillet residue biochars due to the formation of difficultly soluble crystalline P minerals (Bera et al., 2017). The extractable P not only depends on the pyrolysis temperature, but also on the feedstock. For example, Zhang et al. (2016) studied biochars prepared from 9 different residues, and concluded that the Bladygrass (*Imperata cylindrical*) biochar had the greatest amount of extractable P among all the biochars. Similarly, application of biochar (prepared at 400$^{o}$C) at the rate of 8.94 g $kg^{-1}$ increased the available P content in a sandy loam alluvial soil (Purakayastha et al., 2015). The application of poultry litter biochar at 20 g $kg^{-1}$ increased Mehlich 1 soil extractable P concentration by 20 to 28 folds (Novak et al., 2009). Laird et al. (2010a) reported that biochar prepared from mixed hardwood feedstock (primarily oak (*Quercus* sp.) and hickory (*Carya* sp.)) increased Mehlich III extractable P in soils (Laird et al., 2010a). The total P content ranged 16-9500 mg $kg^{-1}$ for crop residue biochar, 5-6000 mg $kg^{-1}$ for wood biochar, 2950–7.40x$10^4$ mg $kg^{-1}$ for manure biochar, and 90-23300 mg $kg^{-1}$ for waste material biochar (Table 3). Recently, Xu et al. (2018b) reported that wheat straw biochar application significantly increased (positive effects) various P fractions (except for $NaHCO_3$-extractable P and residual P) in a Haplic Luvisol. The increased soil microbial activity and reduced soil acidity or increased CEC may be accounted for enhanced P transformation in the soil. The reduced $NaHCO_3$-extractable P content may be related to P immobilization with increased soil microbial activity induced by biochar addition because the high C:P ratios of biochar (ranged from 234 to 357) suggested a net P immobilization when biochar was incorporated into the soil (Xu et al., 2018b).

Biochar having high ion exchange capacity might alter P availability by enhancing the anion exchange capacity or by influencing the activity of cations that interact with P (Liang et al., 2006). However, the amount and rate of P adsorption on the surface of ferrihydrite decreased with the presence of biochar (Hao et al., 2011).

The changes in soil P dynamics may vary over time in the presence of biochar. Haefelea et al. (2011) reported that the application of carbonized rice husk biochar increased available P in rice growing soil of International Rice Research Institute (IRRI), Philippines, in the first year, while after three years it did not influence the available P content. In the second cropping year, available P content in the biochar + pyrogallol treated plot was found to increase by 25% over the control (Lashari et al., 2013). Two years after application of biochar prepared from mixed hardwood chips (primarily oak (*Quercus* sp.), elm (*Ulmus* sp.) and hickory (*Carya*spp sp.)) in a fine loamy Hapludols decreased the extractable P at different incubation periods (Rogovska et al., 2014).

Application of 8% maize stover biochar (400 $^{o}$C) substantially increased soil Olsen-P from 3 to 46 mg kg$^{-1}$ in a Red earth, and from 13 to 137 mg kg$^{-1}$ in a Fluvo-aquic soil in China after a short-term incubation (42 days) (Zhai et al., 2015). These increases were accompnied with an subsequent increase in soil microbial biomass P from 1 to 9 mg kg$^{-1}$ in the Red earth, and from 9 to 21 mg kg$^{-1}$ in the Fluvoaquic soil (Zhai et al., 2015). Researchers indicated that the increase was mainly due to the high concentration of P in the ash fraction of the biochar (77% of total biochar P). Biochar's effect on both soil Olsen-P and microbial biomass-P was increased by higher biochar application rates ensuring lower P-sorption capacity. The maximum concentration of water-soluble P was achieved at the rate of 1% wheat residue biochar (w/w) addition to soils with different textural classes, varying the water-soluble P concentrations from 11 to 253% (Parvage et al., 2013). At higher application rates, P concentrations decreased, which coincided with an increase of soil pH by 0.3–0.7 units (Parvage et al., 2013). The wheat residue biochar can act as a source of soluble P, and low and high additions of biochar showed different effects on soil solution P concentration due to possible reactions of P with Ca and Mg added with biochar. The addition of fresh *Miscanthus* or *Salix* biochar to soil significantly increased soil P contents, but artificially weathered biochars made no such change in sandy loam soil of the Rothamsted Research experimental farm, United Kingdom (Prendergast-Miller et al., 2014). The *Miscanthus* biochar had distinctly larger extractable-P content than the *Salix* biochar (Prendergast-Miller et al., 2014). In sandy soil, addition of biochar produced from mixture of Norway spruce (*Picea abies* (L.) H. Karst) and Scots pine (*Pinus sylvestris* L.) had low P sorption affinity, and thus did not increase the sorption of P in incubated soils (Sonnie et al., 2014).

Among different feedstocks, maize biochar showed the highest available P in the soil after one year of incubation followed by rice, pearl millet and wheat biochars (Purakayastha et al., 2015). Rice straw biochar with the higher CEC and the lowest contents of $Ca^{2+}$ and $Mg^{2+}$ showed the greatest inhibition of phosphate adsorption, and thus, could likely be the best choice as an amendment to mobilize phosphate in variably-charged soils (Jiang et al., 2015). The phosphate adsorption in both control and biochar-amended soils decreased with increasing pH. Incorporation of the biochars increased the pH of the amended soils, thereby further mobilizing phosphate in the soil (Jiang et al., 2015). However, Macdonald et al. (2014) reported that both poultry litter and wheat straw biochars applied at the rate of 5 and 10 Mg $ha^{-1}$ did not affect the Olsen's P in an acidic Ferrasol and alkaline Calcisol, but could increase Olsen's P in an acidic aerosol and neutral Vertisol. The interactions between biochar, P fertilizer and P fractionations indicate shifts in potential P availability both as a result of P fertilization and biochar (prepared from green waste at 550 $^{o}$C) application after harvest of a wheat crop (Farrel et al., 2014). However, in clayey soils, biochar addition increased soil aggregate stability and reduced detachment of colloidal materials, which in turn could be beneficial for erosion control and thereby reducing particulate P losses from agricultural fields.

### *5.2.4. Effect of biochar on potassium dynamics*

Biochar itself is a huge source of K, and it can directly take part in the retention of K in the soil because of having a high CEC (Table 3). Available K contents in both Ultisol and Oxisol after first and second years' of a wheat crop were invariably greater when biochar prepared from Eucalyptus trees (*Eucalyptus camaldulensis* L.) by specialized flash carbonization process was applied to soils (Lashari et al., 2013). Two years of mixed hardwood biochar (primarily oak, elm and hickory) application in fine loamy Hapludols had almost doubled the extractable K content over the unamended soil (Rogovska et al., 2014). In the second cropping year, biochar along with pyrogallol application increased the available K content by 78% over the unamended control (Rogovska et al., 2014). Among the macronutrients (N, P, K), the maximum increase in available pool due to biochar application was observed in the case of K. Purakayastha et al. (2015) found that wheat straw biochar being rich in K contributed in increasing the soil available K. Similarly, Laird et al. (2010a) reported that mixed hardwood biochar amendment (oak and hickory) increased the Mehlich III extractable K in soils.

In contrast, application of rice husk biochar at the rate of 41 Mg $ha^{-1}$ did not affect exchangeable K content in soil after harvest of rice crp in an acidic Gleysols of IRRI, Philippines (Haefele et al., 2011). Nevertheless, evidence showed that excessive application of liming materials including biochar to a coarse-textured low buffering capacity soil might lead to an abrupt increase in soil pH resulting in deficiencies of some plant nutrients (Kamprath, 1971). For example, K deficiency in radish crop due to the application of poultry litter biochar in an acid soil was noticed (Chan et al., 2008).

*5.2.5. Effect of biochar on secondary and micronutrient dynamics*

Amongst secondary nutrients, S cycle behaves quite similarly as N cycle in the soil (Stevenson and Cole, 1999). Therefore, biochar application could potentially influence the S mineralization in soils like it influences the N transformation (Table 3). Since biochar application influences the pH of soils, S mineralization rates were reported to increase following a fire in a pine forest (biomass converted to biochar by the fire) (Binkley et al., 1992). This effect was probably due to the release of soluble $SO_4^{2-}$ following partial combustion of biomass during the fire or heating event at temperature more than 200 °C (Gray and Dighton, 2006). The maximum leaching of $SO_4^{2-}$ occurred after the application of corn biochar pyrolyzed at 450 °C (11 mg $kg^{-1}$ at the first leaching, corresponding to 29% of the total S added), while the main mechanisms involved in this process were: the abiotic release of mineral S, and the hydrolysis of ester-S mediated by soil enzymes without any observed relationship with $CO_2$ evolution (Blum et al., 2013). The role of S-forms in the feedstocks (or initial materials) also seemed to drive the S mineralization process (Blum et al., 2013).

Extractable Ca contents increased in both Ultisol and Oxisol after first and second year of wheat crops owing to application of biochar prepared from Eucalyptus tree (*Eucalyptuscamaldulensis* L.) by flash carbonization process (Butnan et al., 2015). However, it showed no impact on extractable soil Mg content when biochar prepared from the same feedstock via traditional kiln or flash carbonization process was applied to the soil (Butnan et al., 2015). Peanut straw biochar pyrolyzed at 400°C showed significantly higher water soluble Ca and Mg contents in an Oxisol than other starw derived biochars, and rice straw biochar showed the lowest values among various crop straw biochars (Jiang et al., 2015). Rogovska et al. (2014) reported that along with soil available K, soil extractable Ca and Mg also increased in a maize (*Zea mays* L.) crop due to two years application of biochar made from mixed hardwood (oak, elm and hickory) at 500-

575°C. After biochar application, Ca and Mg limiting Savana Oxisol was higly productive due to 77-320% greater Ca and Mg availability, increasing soil pH and decreasing exchangable acidity (Major et al., 2010). Slow pyrolysis biochar (550°C) failed to show any effect on exchangeable Ca content after harvest of a maize crop when applied at the rate of 15.0 g $kg^{-1}$ in a silty Fluvisol, but it became more efficient when the application rate was increased to 100 g $kg^{-1}$ (Borchard et al., 2014). However, the exchangeable Mg content in soil was not influenced by biochar application rate (Borchard et al., 2014). Rice husk biochar applied at the rate of 41 Mg $ha^{-1}$ also did not affect exchangeable Ca and Mg contents after the harvest of rice in an acidic Gleysol in Philippines (Haefele et al., 2011). Thus, increasing Ca and Mg availability in biochar amended soils would be more realistic in highly acidic Oxisol and Ultisol which are inherently defficient in basic cationic nutrients.

Among the micronutrients, soil extractable Mn and Fe decreased, while Cu and Zn increased due to the application of a mixed wood biochar (Rogovska et al., 2014). Similarly, Borchard et al. (2012) reported that composted charcoal could potentially improve plant available $Cu^{2+}$ in an acidic sandy soil with small organic matter content. Transient effects of biochar on soil pH can overrule the influence of sorption of micronutrient cations on to biochar, resulting in the variable concentrations of trace elements in the soil solution and their availability to plants (Borchard et al., 2012). Biochar prepared from Eucalyptus tree either via traditional kiln process at 350°C or by flash carbonization at 800°C significantly increased the soluble Mn concentration (1.39–4.61 mg $L^{-1}$) in an Oxisol relative to the control (1.12 mg $L^{-1}$), while they decreased the plant tissue Mn concentration (0.08–0.17 g $kg^{-1}$) compared to the control (0.41 g $kg^{-1}$) (Butnan et al., 2015).

## 6. Pyrolysis conditions, stability and nutrient supplying capacity of biochar

A handful of experimental studies unanimously revealed that the source of feedstock (either plant or animal origin) and pyrolysis environments (duration, heating rate, operating method and temperature) had been the most crucial factors to determine whether the produced biochar would be suitably applied to regulate nutrient dynamics in soils, apart from its other chemical and structural features. Hence, these would decide the applicability of biochar for enhancing crop growth and yield by moderating the soil environment. It is emphasized that temperature generated during pyrolysis define the physical and structural characteristics of biochar (Clough et al., 2013; Zhao et al., 2018). Only few studies concentrated on the characterization of biochar prepared at different ranges of pyrolysis temperatures as well as feedstock materials, and compared the biochar stability and applicability for agricultural uses (Yang and Sheng, 2012; Crombie et al., 2013; Rahman et al., 2014; Zhao et al., 2018). Pyrolysis temperature was also found to be the most influential parameter for obtaining specific characteristics of rapeseed stem biochar, demonstrating a positive relationship of temperature with pH, microporous structure, surface area, fixed C and ash content, whilst showing a negative relationship with material yield, average pore size, functional groups, volatile matter, O and H mass fractions, and the number and density of functional groups (Zhao et al., 2018).

Realising the serious gap of systematically compiled information in published literature about the above, this paper attempted to gather three sets of information after searching across a large number of publications, for: (1) pH and nutrient composition of various biochars produced at different pyrolysis temperatures (Table 1), (2) changes in soil pH and CEC due to application of biochar prepared from various feedstock types, addition rates and pyrolysis temperatures (Table

2), and (3) effects of biochar on nutrient transformations in soil produced at different pyrolysis temperatures (Table 3).

**7. Biochar as slow release fertilizer**

Fertilizers play a significant role in agricultural production. After application to soils, fertilizers can be lost due to the natural processes occurring in the soil. There has been an increasing interest in using fertilizers, which can release nutrients in soils at a slower and steadier rate over an extended period. Therefore, the use of slow-release fertilizer is a favourable strategy to reduce gaseous and leaching losses of nutrients, especially the losses of macronutrients (N, P, and K) (Wang et al., 2013). Pyrolytic conversion of biomass into biochar has shown an effective impact on reducing nutrient losses ($NH_3$ volatilization, $N_2O$ emission, $CO_2$ emission, $NO_3$ leaching, etc.) from soils, and previous studies found that biochar itself contains nutrients, which help to improve plant growth. It was observed in most studies that nutrients release quickly during the initial period of biochar addition to soils. However, if exogenous nutrients (N, P, and K) was adsorbed on biochar, it could act as a slow-release fertilizer for supplying nutrients (N, P, and K) (Zhou et al., 2015). Kim et al. (2014) observed that lignocellulosic biomass-derived biochar contained low plant nutrients but could be impregnated with additional nutrients and subsequently pelletized, and the final product could control the release of nutrients at a slower rate resulting in a reduced nutrient loss. The slow release was attributed to the physical hindrance in releasing and solubilizing the nutrients through reduced pore size instead of forming any slowly soluble chemical composite (Kim et al., 2014). Wen et al. (2017) prepared biochar based slow release fertilizers (BSRFs) through $NH_4^+$ absorption on biochar prepared from cotton stalks. Authors found that the application of BSRFs to soil could significantly improve both the water retention and water holding capacity of soils. The BSRFs were also capable of releasing N fertilizer slowly with extended N-longevity, and were more effective in improving total N use efficiency and facilitated cotton plant growth through reducing N loss and improving N retention (Wen et al., 2017). The lowest N-leaching-loss were observed with BSRFs, and the phenomenon was attributed to the fact that BSRFs had better slow-release characteristics and water holding capacity than normal biochar (Gonzalez et al., 2015; Wen et al., 2017). Yao et al. (2011) also found that the phosphate-laden biochar contained valuable nutrients that could act as a slow release fertilizer to enhance soil fertility and sequester C for a longer time in soil. Moreover, physical activation of biochar materials can also make it a slow release fertilizer. For example, Dünisch et al. (2007) found that the mixing of charcoal with ashes and impregnating wood residues with nutrients such as N, P, and K could produce slow release K and N fertilizers. Studies have shown that biochar based slow-release fertilizers with their effective nutrient retention properties can be widely used in sustainable modern agriculture. However, a full assessment of these biochar based slow-release fertilizers, composites, and pellets as slow nutrients (N, P, and K) release fertilizers are needed, for example, field tests are extremely important before the wide application of these materials in soils for supporting plant growth and development.

## 8. Effect of biochar on crop yield

Researchers observed that biochar application increased, decreased or had a neutral effect(s) on crop yield(s), depending upon soil types, variation in feedstocks and pyrolysis conditions during biochar preparation (Table 4). In majority of the cases, the yield of various crops was enhanced to the tune of 4 to 144% owing to biochar application, while for few others studies, the yield declined to the extent of 4 to 24%. Some biochars triggered improved growth with increasing pyrolysis temperatures, though opposite trend was also found (Rajkovich et al., 2012). Therefore, pyrolysis temperature remains an important variable to improve biochar performance for crop yield vis-à-vis soil fertility management. Biochars made from food waste and paper mill waste at lower pyrolysis temperature (300-400 °C) resulted in significant growth reduction of corn (Rajkovich et al., 2012). With increasing pyrolysis temperature, however, the adverse effect of biochar produced from the same feedstock nullified (Rajkovich et al., 2012). On an average, biochar produced at 500°C showed a better plant growth than those produced at 300-400°C temperature. Biochar made from poultry litter maintained better plant growth over the control irrespective of application rate and pyrolysis temperature (Macdonald et al., 2014). Across all biochar types, average total biomass production of corn (*Zea mays* L.) was at par for the application rates of 0.2%, 0.5%, and 2%, but reduced to a minimum at the rate of 7% (Rajkovich et al., 2012). Except for the larger application rate (7%), biochar made from corn stover, oak, and pine wood and animal manures exhibited either positive or neutral effect on crop growth, whereas biochar from hazelnut shells did not affect the growth (Enders et al., 2012). Studies emphasized that the positive reflection of agronomic performances under biochar application depends both on soil-biochar interaction and the elemental contents of biochar. However, not only the biochar or soil type, crop choices also can determine the response of biochar as van Zwieten et al. (2010) found that wheat biomass increased linearly up to an biochar application rate of 10 t ha$^{-1}$, and decreased with 20 and 50 t ha$^{-1}$, whereas radish growth did not decrease with high rate of biochar in an acid soil of the tropics. Followed by the increasing macro and micronutrients availbility in soil, biochar from mixed hardwood chips (oak, elm and hickory) (pyrolysis temperature: 500 – 575°C) increased the grain yield of maize by 11 to 55% during the first year (Rogovska et al., 2014), presumably because biochar mitigated adverse effects of allelochemicals released from the decomposing maize residues. However, oat (*Avena sativa* L.) yield in an acidic sandy loam soil of Denmark showed no significant response to birch wood biochar application, neither for total biomass nor grain yield (Sun et al., 2014). However, on the same occasion, the total biomass of spring barley (*Hordeum vulgare*) was increased by 11% due to biochar application, though with a non-significant response for grain yield. Maize yield showed a reduction of 22-24% at the single biochar treatment (50 Mg $ha^{-1}$) which was applied in combination with pig slurry at 21 and 42 Mg $ha^{-1}$ doses (Sun et al., 2014). In acidic sandy soils, the application of rice hull biochar (2% rate) prepared at 350-400°C increased sugarcane yield in Florida, USA, probably because biochar modulated the nutrient enrichment in the soil (Alvarez-Campos et al., 2018).

In an acidic aerosol of Australia, both poultry litter biochar and wheat straw biochar demonstrated non-linear trends of biochar application rates with wheat yields (Macdonald et al., 2014). The plant biomass was significantly lower at higher biochar application rates (5 and 10 t $ha^{-1}$), having a prominent impact on shoot production but also evident in grain yield and root biomass (Macdonald et al., 2014). However, in an acidic ferralsol, a different plant response was evident. The magnitude of plant growth stimulation was more visible by applying poultry litter biochar over wheat straw biochar (Macdonald et al., 2014). More biomass (shoot, root and grain) produced under high rate of poultry litter biochar (10 t $ha^{-1}$) as compared to wheat straw biochar (Macdonald et al., 2014). Biochar application to a neutral Vertisol had no impact on the plant growth (Macdonald et al., 2014). Besides acidic soils, biochar also proved beneficial in increasing yield of crops cultivated in alkaline soils. Purakayastha (2010) reported that application of biochar at the rate of 1.9 Mg $ha^{-1}$ prepared from wheat straw along with the recommended doses of NPK (180:80:80 kg $ha^{-1}$) increased the yield of maize in an Inceptisol. Moreover, this treatment was found to be superior for obtaining benefits related to straw reutilization like crop residue incorporation (CRI) and crop residue burning (CRB) in the open field. For both pearl millet and rice, the yields in biochar treatments were at par with those obtained with CRI or CRB treatments (Purakayastha, 2010). In another study, the application of rice straw biochar (prepared at 400 °C) at the rate of 2.25 g $kg^{-1}$ (equivalent to 5.0 t $ha^{-1}$) along with 100% NPK increased the rice yield by 24.3% in an Inceptisol, and by 31.3% in an Alfisol (Bera, 2014). The yield and yield attributing characters of lowland rice was also reported to be enhanced by the combined application of rice husk biochar and flyash supplemented with chemical fertilizers (Munda et al., 2016).

Fertilizer application along with carbonized rice husk (CRH-biochar) improved the grain yields of rice, but the improvement was not always significant and even showed a decline in yield at Nitisol of Siniloan, Philippines (Haefele et al., 2011). The application of CRH-biochar failed to produce a yield-increasing effect in both anthraquic Gleysols and humic Nitisol in the Philippines (Haefele et al., 2011). Only in a gleyic Acrisols, the application of CRH-biochar resulted in a higher yield of rice in all four seasons, although the significant increase was only observed in the third and fourth wet seasons (Haefele et al., 2011). However, Gaskin et al., (2009) found that peanut hull biochar and pine chip biochar failed to show their marks towards crop productivity, and grain yield even decreased for maize crop.

Application of 0, 8 and 20 t $ha^{-1}$ of biochar to a Colombian savanna Oxisol continuously for four years (2003–2006) under a maize-soybean rotation reported that the maize grain yield did not increase in the very first year, but increased in the 20 Mg $ha^{-1}$ plots over the control by 28, 30 and 140%, respectively, in the subsequent years (Major et al., 2010). In that particular experiment, soil pH increased, and exchangeable acidity showed a decreasing trend owing to biochar application. The greater crop yield and nutrient uptake resulted due to more available (77–320%) Ca and Mg in the soil where biochar was applied (Major et al., 2010). Rice yield was increased under biochar treatment in an acidic Anthrosol, and such increase was eventually more (9–28%) in the second cycle than in the first cycle (9–12%) of the crop (Zhang et al., 2012). However, this increment could not be correlated with the biochar amendment rates (Zhang et al., 2012). Biochar can also be composted and be applied in soils for enhancing crop productivity. Application of biochar poultry manure compost and pyroligneous solution to a salt-affected soil for consecutive two years showed an ameliorative effect, decreasing the salinity and pH, and subsequently reflected in increased yield of wheat in a tune of 38% (Lashari et al., 2013).

Biochar behaved differently to crop growth improvement when applied along with fertilizers. Farrell et al. (2014) reported no significant effect on wheat yield at a low application rate (<1.0 Mg $ha^{-1}$) of biochar in highly P-constrained calcareous soil, but a prominent effect of both biochar and fertilizer on P fractionation was observed. Similarly, applying N fertilizer proved beneficial to rice grain yield when 4.0 and 8.0 Mg $ha^{-1}$ rates of two commercial biochars prepared from wood feedstocks (e.g., teak (*Tectona grandis* L.) and rosewood (*Pterocarpus macrocarpus* Kurz)) were applied in a study reported from northern Laos, but at higher dose of biochar (16 Mg $ha^{-1}$) with N-fertilizer no positive yield response was observed (Asai et al., 2009) . Higher grain yields in biochar treated plots (4.0 and 8.0 Mg $ha^{-1}$) with N fertilizer resulted due to the combined effects of the improved soil physical properties and the alleviation of biochar induced soil N availability (Asai et al., 2009) . Biochar (prepared from 80% varied hardwood and 20% varied coniferous wood chips at 750$^{o}$C) and biochar-compost treatments induced only small, economically irrelevant and mostly non-significant effects vine productivity in a poorly fertile, alkaline, temperate soils of Switzerland (Schmidt et al., 2014). However, yield reduction at a high rate of biochar application (16 Mg $ha^{-1}$) was resonated to N limitation even with N fertilizer application (Asai et al., 2009). Contrary to this observation, Zhang et al., (2012) found maize yield increased by 15.8% and 7.3% without N fertilization, and by 8.8% and 12.1% with N fertilization under biochar amendment at 20 and 40 Mg $ha^{-1}$, respectively, in a calcareous flavor-aquic loamy soil. In an earlier study, Chan et al. (2007) also found the positive interactive effect of biochar (doses at 50 and 100 Mg $ha^{-1}$) with N fertilizer (100 Mg $ha^{-1}$) on radish yield in a hard setting Alfisol. Improvement in soil physical properties along with pH, organic carbon and content of exchangeable cations were the reasons suggested for the higher radish yield. Recently, Ain et al. (2016) reported that application of biochar prepared from a weed (*Parthenium hysterophorus* L.) at 370- 417 $^{o}$C temperature to a rice-wheat cropping system could cut down the cost of fertilizer to half although the yield obtained was just as good as with full application of recommended dose of fertilizers.

In many instances, biochar behaved as a neutral amendment as far as crop yield enhancement is concerned. The bioavailability of N in a wheat-straw biochar prepared at 400 $^{o}$C was reported to be very low, and did not increase growth of rice crop or nitrogen use efficiency from fertilizer sources during the first year after application (Xie et al., 2013). Biochar was added to an agricultural field at three different doses (0, 25 and 50 t $ha^{-1}$) and planted with maize (1$^{st}$ year) and grass (2$^{nd}$ and 3$^{rd}$ years) in an acidic sandy loam soil where the biochar addition affected plant performance in the grass crop with significant increase in foliar N (2$^{nd}$ year) and above-ground biomass (3$^{rd}$ year), but biochar treatment behaved neutral towards the maize crop yield (Jones et al., 2012). Another study reported that short-term application of biochar amendment had a positive effect on soil quality in rice cultivation across a wide range of climates and soil types in China, though no significant effect of biochar amendment on rice yield was found (Huang et al., 2013). In contrast to biochar amendment, N fertilizer proved less effective for improving soil quality, but more effective for increasing the rice yield (Huang et al., 2013). More interestingly, the same study further hinted that biochar amendment showed an additional benefit on rice yield under N fertilizer application, and there was a close relationship between the effect of biochar amendment on rice yield and agronomic N use efficiency. Another investigation dealing with large volume application of biochar (30 and 60 Mg $ha^{-1}$) on durum wheat in the Mediterranean climate showed positive effects (up to 30%) on biomass production and yield, with no significant differences in the nitrogen content of grains (Vaccari et al., 2011). Moreover, no difference between the two biochar treatments were identified, suggesting that even the very high biochar application rate promoted plant growth with a non-detrimental effect (Vaccari et al., 2011).

Biomass production of the N-fixing bean (*Phaseolus vulgaris* L.) was significantly higher than that of the non-N-fixing isoline across all levels of biochar (*Eucalyptus deglupta,* 350 $^{o}$C) additions. Biochar additions significantly increased total biomass production by 39% at a defined biochar dose of 60 g $kg^{-1}$, but decreased biomass at par with the control with a higher biochar dose (90 g $kg^{-1}$). The increase in biomass production by the N-fixing bean was mainly attributed to the greater leaf biomass. Such responses confirmed earlier results with moong bean [*Vigna radiata* (L.) R. Wilczek], soybean [*Glycine max* (L.) Merr.], and pea (*Pisum sativum* L.) (Iswaran et al., 1980), or with cowpea (*Vigna unguiculata* L.) and rice (*Oryza sativa* L.) (Nehls, 2002; Lehmann et al., 2003). Biochar additions at a rate of 15 t $ha^{-1}$ resulted a remarkable difference in plant biomass of bean (*Phaseolus vulgaris* L.) over the control showing an average of 262% increase in shoot biomass, 164% increase in root biomass, 3575% increase in nodule biomass, and 2126% increase in N derived from the atmosphere (Güereña et al., 2015).

## 9. Principal component analysis to evaluate biochar's effect on soil chemical properties and crop yields

The soil chemistry variables d_pH (change in soil pH) and d_CEC (change in soil CEC) were generated by difference of treatment and control measurements for soil pH and CEC respectively. Mean value substitution was performed on missing CEC values on some of the measurements, resulting in a total number of cases analysed at 48.The variable representing yield change was generated by difference of treatment and control measurements for crop yield, with yield inhibition represented as negative yield, resulting in a total number of cases analysed at 36.

The PCA scatterplot of points for soil chemical properties in the plane of the first two principal component axes is presented in Fig.4a. The total variance explained by the first two principal components was 74.3%. The first principal component, accounting for 39.3% of the variance in the dataset, exhibits loadings dominated by biochar application rate and change in CEC (Table 5). The second principal component, accounting for 35% of the variance in the dataset, exhibits loadings dominated by pyrolysis temperature of biochar and pH adjustment of the soil. The latter principal component shows an inverse relationship between [pyrolysis temperature and pH] and [loading rate and CEC].

The projections of the variable axes onto the plane of the first two principal components (Fig. 3a) reveals that all axes exhibit some positive correlation with each other. The highest pairwise correlations exist between (i) pyrolysis temperature and pH change in soil, and (ii) between biochar loadings and change in CEC of soil. These observations may be explained by increased temperature of biochar pyrolysis resulting in modifications of the types of chemical functional groups (acidic versus ketonic) on the biochar carbon skeletons, which would modify the basicity of the biochar and thus the resulting pH of the soil which was amended by the biochar (Mandal et al., 2016; 2018). The relationship between loading rate and CEC may be explained by noting that the more oxygen-containing functional groups in a soil, the higher the CEC, thus the greater loading of biochar containing the functional groups the greater the CEC(Schmidt and Noack, 2000).The points in Fig. 3 are grouped with respect to soil type, with convex hulls enclosing the groups of points. Points group well with respect to soil type, suggesting that the original chemistry of the soil has a strong component in pH and CEC modification of the soils when amended by biochar.

The PCA scatterplot of points for crop yields in the plane of the first two principal component axes is presented in Fig. 4b. In this case, the total variance explained by the first two principal components was 76.8%. The first principal component, accounting for 45.9% of the variance in the data, was dominated by pyrolysis temperature of biochar, but contained appreciable components of application rate and crop yield modification. The second principal component, accounting for 30.9% of the variance in the data, exhibited no appreciable dependence on pyrolysis temperature, and was instead dominated by application rate and yield, which display an inverse relationship. This suggests an explanation counter to expectations that greater application rates of biochar result in lower stimulation of crop yield. There was some structure evident in the groupings of points in this analysis by soil type, suggesting that plant yield was influenced by soil type also. There was unexplained variance of 23.2% of the dataset that was neglected from the above analysis. It is likely that the low sample numbers and high diversity within the samples is such that not much information may be derived from the temperature-application rate-yield dataset by PCA.

## 10. Conclusions and future research directions

Biochar can act as a source of nutrient(s) for plants; it has its distinct, physical, physico-chemical and cation exchange properties, which can interact with native soil nutrients and added nutrients in the forms of fertilizer and manures. Therefore, biochar may influence the supply of nutrients to the plants. From the array of published research papers, we discussed in the review, the yield response of crops and nutrient releasing behavior in soil due to biochar application largely depends on the composition of biochar (i.e., feedstock, pyrolysis temperature of biochar preparation) and specific soil type. The majority of biochar is alkaline, except a few like oak and yellow pine chipped biochar, which is acidic.

Many studies showed that biochar significantly influences the mineralization/immobilization turnover of N in soil thereby controlling the N availability without any definite conclusion. However, biochar produced from manure sources being rich in N and other essential nutrients and having narrow C: N ratio could be of higher agronomic value. The majority of the studies showed biochar application increased the P and K availability in soil, and the positive effect was achieved at lower pyrolysis temperature over higher pyrolysis temperature. The mechanism through which the positive impacts of biochars on P and K is not clear yet. Therefore, more research efforts are needed to identify the mechanistic pathway by which soil P and K transformations are being impacted. For other secondary nutrients, there was a mixed response on their availability due to biochar application.

Biochar has positive, negative as well as neutral effects on crop productivity. Biochar showed a positive impact on crop productivity when it was applied to acid soil. However, at a higher rate, biochar might decrease the yield of crops and mostly that could be somewhat complemented by application of fertilizers along with biochar. The biochar application has the potential to improve soil quality, but it is highly dependent on inherent soil properties, fertility and fertilizer management history for that specific piece of land. On the other hand, the negative behavior of biochar towards both nutrient availability and crop productivity demands further insight and thus investigations to find out the most probable reasons for such effect. Therefore, before recommending the application of biochar to a soil under specified crop management, the long-term study is needed along with the clear understanding of the outcome, out of biochar application. Therefore long-term field scale pilot experiments should be conducted to resolute the following: Impacts of specific biochar properties on crop yield and how these impacts change across soil types, environmental conditions and agronomic management practices with judicious choices of the control treatment. Judicious selection of control is utmost necessary to unify the treatment effects across differential experimental units such as temperate vs. tropical soils; grass land vs. forest soils; or Oxisol vs. Inceptisol, etc. Moreover, the potential of C sequestration benefit and other soil ecosystem services as provided by biochar should be considered while recommending for field applications.

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## Author contributions

TJP wrote the first draft of the manuscript, with contributions from TB, DB, BS and SM. BS, and PW undertook data analysis. All authors improved the subsequent drafts and contributed in the accumulation and addition of appropriate references.

## References

Ain, Q.U., Bareena, F.E., Shafiq, M., 2016. Management of the *Parthenium hysterophorus* through biochar formation and its application to rice-wheat cultivation in Pakistan. Agric. Ecosyst. Environ. 235, 265-276.

Alvarez-Camposa, O., Langa, T.A., Bhadhaa, J.H., McCrayb, J.M., Glazc, B., Darouba, S.H., 2018. Biochar and mill ash improve yields of sugarcane on a sand soil in Florida. Agric. Ecosyst. Environ. 253, 122-130.

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M.,Wessolek, G., 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma 202–203, 183–191.

Agegnehu, G., Srivastava, A.K., Bird, M.I., 2017. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. Applied Soil Ecol. 119, 156-170.

Ahmad, M., Rajapaksha, A.U., Lim, J.E., Zhang, M., Bolan, N., Mohan, D., Vithanage, M., Lee, S.S., Ok, Y.S., 2014. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere 99, 19–23.

Akhtar, S.S., Li, G., Andersen, M.N., Liu, F., 2014. Biochar enhances yield and quality of tomato under reduced irrigation. Agric. Water Manage. 138, 37–44.

Al-Wabel, M.I., Al-Omran, A., El-Naggar, A.H., Nadeem, M., Usman, A.R.A., 2013. Pyrolysis temperature induced changes in characteristics and chemical composition of biochar produced from conocarpus wastes. Bioresource Tech. 131, 374-379.

Anderson, R.A., Condron, L.M., Clough, T.J., Fiers, M., Stewart, A., Hill, R.A.& Sherlock, R.R., 2011. Biochar induced soil microbial community change: implications for biogeochemical cycling of carbon, nitrogen and phosphorus. Pedobiologia 54, 309–320.

Asada, T., Ishihara, S., Yamane, S., Toba, T., Yamada, A., Oikawa, K., 2002. Science of bamboo charcoal: study on carbonizing temperature of bamboo charcoal and removal capability of harmful gases. J. Health Sci. 48, 473–479.

Asai, H., Samson, B.K., Haefele, S.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T.Horie, T., 2009. Biochar amendment techniques for upland rice production in Northern Laos. 1. Soil physical properties, leaf SPAD and grain yield. Field Crops Res. 111, 81–84.

Atkinson, C.J., Fitzgerald, J.D. Hipps, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337, 1–18.

Bai, S.H., Reverchon, F., Xu, C.Y., Xu, Z., Blumfield, T.J., Zhao, H., Zwieten, L.V.Wallace, H.M., 2015. Wood biochar increases nitrogen retention in field settings mainly through abiotic processes. Soil Biol. Biochem. 90, 232–240.

Baronti, S., Vaccari, F.P., Miglietta, F., Calzolari, C., Lugato, E., Orlandini, S., Pini, R., Zulian, C., Genesio, L., 2014. Impact of biochar application on plant water relations in *Vitis vinifera* (L.). Eur. J. Agron. 53, 38–44.

Barrow, C.J., 2012. Biochar: potential for countering land degradation and for improving agriculture. Applied Geography 34: 21–28.

Batjes, N.H., 1996. Total carbon and nitrogen in the soils of the world. European J. Soil Sci. 47, 151–163.

Bayabil, H.K., Stoof, C.R., Lehmann, J.C., Yitaferu, B.Steenhuis, T.S., 2015. Assessing the potential of biochar and charcoal to improve soil hydraulic properties in the humid Ethiopian Highlands: The Anjeni watershed. Geoderma 243–244, 115–123.

Bera, T., Purakayastha, T.J., Patra, A.K., 2015. Spectral, chemical and physical characterisation of mustard stalk biochar as affected by temperature. Clay Res. 33, 36-45.Bera, T., Collins, H.P., Alva, A.K., Purakayastha, T.J., Patra, A.K., 2016. Biochar and manure effluent effects on soil biochemical properties under corn production. Applied Soil Ecol. 71, 360–367.

Bera, T., Purakayastha, T.J., Patra, A.K., Datta, S.C., 2017. Comparative analysis of physicochemical, nutrient, and spectral properties of agricultural residue biochars as influenced by pyrolysis temperatures. J. Material Cycles Waste Manage. 20, 1115–1127.

Bera, T., Vardanyan, L.,Inglett, K.S., Reddy, K.R., O'Connor, G.A., Erickson, J.E., Wilkie, A.C., 2019. Influence of select bioenergy by-products on soil carbon and microbial activity: A laboratory study. Science Tot. Environ. 653: 1354-1363.

Bhaduri, D., Saha, A., Desai, D.Meena, H.N., 2016. Restoration of carbon and microbial activity in salt-induced soil by application of peanut shell biochar during short-term incubation study. Chemosphere 148, 86–98.

Binkley, D., Richter, J., David, M.B.Cladwell, B., 1992. Soil chemistry in a loblolly/longleaf pine forest with interval burning. Ecol. Appl. 2, 157–164.

Blagodatskaya, E., Kuzyakov, Y., 2008. Mechanisms of real and apparent priming effects and their dependence on soil microbial biomass and community structure: critical review. Biol. Fertil. Soils 45, 115–131.

Blum, S.C., Lehmann, J., Solomon, D., Caires, E.F. Alleoni, L.R.F., 2013. Sulfur forms in organic substrates affecting S mineralization in soil. Geoderma 200-201,156–164.

Borchard, N., Prost, K., Kautz, T., Möller, A. Siemens, J., 2012a. Sorption of copper (II) and sulphate to different biochars before and after composting with farmyard manure. European J. Soil Sci. 63, 399–409.

Borchard, N., Ladd, B., Eschemann, S., Hegenberg, M., Maria, B., Amelung, W., 2014. Black carbon and soil properties at historical charcoal production sites in Germany. Geoderma, 232–234, 236–242.

Bornø, M.L., Müller-Stöver, D.S., Liu, F., 2018. Contrasting effects of biochar on phosphorus dynamics and bioavailability in different soil types. Sci. Total Environ. 627, 963-974.

Bruun, E.W., Petersen, C., Strobel, B.W., Hauggaard-Nielsen, H., 2012. Nitrogen and carbon leaching in repeacked sandy soil with added fine particulate biochar. Soil Sci. Soc. Am. J. 76, 1142–1148.

Butnan, S., Deenik, J.L., Toomsan, B., Antal, M.J.,Vityakona, P., 2015. Biochar characteristics and application rates affecting corn growth and properties of soils contrasting in texture and mineralogy. Geoderma 237–238, 105–116.

Cantrell, K.B., Hunt, P.G., Uchimiya, M., Novak, J.M.R., K.S., 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresource Technol. 107, 419-428.

Cayuela, M.L., Sanchez-Monedero, M.A., Roig, A., Hanley, K., Enders, A., Lehmann, J., 2013. Biochar and denitrification in soils: when, how much and why does biochar reduce $N_2O$ emissions? Scientific Report 3, 1732. http://dx.doi.org/ 10.1038/srep01732. Nature Publishing Group.

Chan, K.Y., Xu, Z., 2009. Biochar: nutrient properties and their enrichment. In: Lehmann, J., Joseph, S. (Eds.), Biochar for environmental management: science and technology. Earthscan, London, pp. 67–84.

Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A. Joseph, S., 2007. Agronomic values of green waste biochar as a soil amendment. Aust. J. Soil Res. 45, 629–634.

Chan, K.Y., Zwieten, V.L., Meszaros, I., Downie, A.Joseph, S., 2008. Using poultry litter biochars as soil amendments. Aust. J. Soil Res. 46, 437–444.

Chen, Chi-Peng, Cheng, Chih-Hsin, Huang, Yu-Hsuan, Chen, Chien-Ten, Lai, Chao-Ming, Menyailo, Oleg V., Fan, Liang-Jen, YangYaw-Win, 2014. Converting leguminous green manure into biochar: changes in chemical composition and C and N mineralization. Geoderma 232-234, 581–588.

Cheng, C.H., Lehmann, J., Thies, J.E., Burton, S.D., Engelhard, M.H., 2006. Oxidation of black carbon by biotic and abiotic processes. Org. Geochem. 37: 1477-1488.

Clarholm, M., 1994. Granulated wood ash and a 'N-free' fertilizer to forest soil: effects on P availability. Forest Ecol. Manage. 66, 127–136.

Clough, T., Condron, L., Kammann, C.,Müller, C., 2013. A review of biochar and soil nitrogen dynamics. Agronomy 3, 275–293.

Clough, T.J., Condron, L.M., 2010. Biochar and the nitrogen cycle: introduction. J. Environ. Qual. 39, 1218–1223.

Crombie, K., Mašek, O., Sohi, S.P., Brownsort, P.Cross, A., 2013. The effect of pyrolysis conditions on biochar stability as determined by three methods. GCB Bioenergy 5(2), 122–131.

Cui, L.Q., Pan, G.X., Li, L.Q., Yan, J.L., Zhang, A.F., Bian, R.J., Chang, A., 2012. The reduction of wheat Cd uptake in contaminated soil via biochar amendment: a two-year field experiment. Bioresources 7 (4), 5666-5676.

Dai, Z., Zhang, X., Tang, C., Muhammad, N., Wu, J., Brookes, P.C., Xu, J., 2017. Potential role of biochars in decreasing soil acidification - A critical review. Sci. Total Environ. 581-582, 601-611.

DeLuca, T.H., MacKenzie, M.D., Gundale, M.J., 2009. Biochar effects on soil nutrient transformations. In: Lehman, J., Joseph, S. (Eds.), Biochar for environmental management, Earthscan, London, UK, pp. 251–270.

Devi, P., Saroha, A.K., 2015. Effect of pyrolysis temperature on polycyclic aromatic hydrocarbons toxicity and sorption behaviour of biochars prepared by pyrolysis of paper mill effluent treatment plant sludge. Bioresource Technol. 192, 312–320.

Ding, Y., Liu, Y., Wu, W., Shi, D., Yang, M., Zhong, Z., 2010. Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. Water Air Soil Pollution 213 (1), 47–55.

Dünisch, O., Lima, V.C., Seehann, G., Donath, J., Montoia, V.R., Schwarz, T., 2007. Retention properties of wood residues and their potential for soil amelioration. Wood Sci. Technol. 41(2), 169.

Enders, A., Hanley, K., Whitman, T., Joseph, S.Lehmann, J., 2012. Characterization of biochars to evaluate recalcitrance and agronomic performance. Bioresource Technol. 114, 644–653.

Farrell, M., Macdonald, L.M., Butler, G., Chirino-Valle, I., Condron, L.M., 2014. Biochar and fertiliser applications influence phosphorus fractionation and wheat yield. Biol. Fertil. Soils 50, 169–178.

Gaskin, J.W., Das, K.C., Tassistro, A.S., Sonon, L., Harris, K. Hawkins, B., 2009. Characterization of char for agricultural use in the soils of the southeastern United States. Amazonian dark earths: Wim Sombroek's Vision 433–443.

Gaskin, J.W., Speir, R.A., Harris, K., Das, K.C., Lee, R.D., Morris, L.A.,Fisher, D.S., 2010. Effect of peanut hull and pine chip biochar on soil nutrients, corn nutrient status, and yield. Agron. J. 102 (2): 623–633.

Gaskin, J.W., Steiner, C., Harris, K., Das, K.C., Bibens, B., 2008. Effect of low- temperature pyrolysis conditions on biochar for agricultural use. Trans. ASABE 51, 2061–2069.

Gasser, T., Guivarch, C., Tachiiri, K., Jones, C.D., Ciais, P., 2015. Negative emissions physically needed to keep global warming below 2 °C. Nature Commun. 6, 7958.

Glaser, B., Guggenberger, G., Zech, W. Rulvo, M.L., 2003. Soil organic matter stability in Amazonian dark earths. In: Lehman, J., Kern, D., Glaser, B., Woods, W. (Eds.) Amazonian Dark Earths: Origin, Properties and Management. Kluwer, Netherlands, pp. 141–158.

Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal: A review. Biol. Fertil. Soils35, 219–230.

Gonzalez, M.E., Cea, M., Medina, J., Gonzalez, A., Diez, M.C., Cartes, P., Monreal, C., Navia, R., 2015. Evaluation of biodegradable polymers as encapsulating agents for thedevelopment of a urea controlled-release fertilizer using biochar as support material. Sci. Total Environ. 505, 446-453.

Gray, D.M., Dighton, J., 2006. Mineralization of forest litter nutrients by heat and combustion. Soil Biol. Biochem. 38, 1469–1477.

Güereña, D.T., Lehmann, J., Thies, J.E., Enders, A., Karanja, N., Neufeldt, H., 2015. Partitioning the contributions of biochar properties to enhanced biological nitrogen fixation in common bean (*Phaseolus vulgaris*). Biol. Fertil. Soils 51, 479–491.

Gundale, M.J., DeLuca, T.H., 2006. Temperature and substrate influence the chemical properties of charcoal in the ponderosa pine/Douglas fir ecosystem. Forest Ecol. Manage. 231, 86–93.

Haefelea, S.M., Konboonc, Y., Wongboonc,W., Amarantea, S., Maarifatb, A.A., Pfeiffer, E.M., Knoblauch, C., 2011. Effects and fate of biochar from rice residues in rice-based systems. Field Crops Res. 121, 430–440.

Hale, S.E., Jensen, J., Jakob, L., Oleszczuk, P., Hartnik, T., Henriksen, T., Okkenhaug, G., Martinsen, V., Cornelissen, G., 2013. Short-term effect of the soil amendments activated carbon, biochar, and ferric oxyhydroxide on bacteria and invertebrates. Environ. Sci. Technol. 47, 8674–8683.

Hammer, Ø., Harper, D.A.T. P. D. Ryan, 2001. PAST: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica 4(1), 9.

Hao, C., Wang, J., Kuang, M., Ming, Fu., Ci En, L., 2011. Enhancing phosphorus availability in phosphorus-fertilized zones by reducing phosphate adsorbed on ferrihydrite using rice straw derived biochar. J. Soils Sediments 11 (7), 1135–1141.

Hea, T., Liua, D., Yuana, J., Nic, K., Zamand, M., Luoe, J., Lindseye, S., Dinga, W., 2018. A two years study on the combined effects of biochar and inhibitors on ammonia volatilization in an intensively managed rice field. Agric. Ecosyst. Environ. 264, 44-53.

Heitkötter, J. Marschner, B., 2015. Interactive effects of biochar ageing in soils related to feedstock, pyrolysis temperature, and historic charcoal production. Geoderma 245-246, 56-64.

Hossain, M.K., Strezov, V., Chan, K.Y., Nelson, P.F., 2010. Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (*Lycopersicon esculentum*). Chemosphere 78, 1167-1171.

Huang, M., Yang, L., Qin, H., Jiang, L.Zou, Y., 2013. Quantifying the effect of biochar amendment on soil quality and crop productivity in Chinese rice paddies. Field Crops Res. 154, 172–177.

Iswaran, V., Jauhri, K, Sen, A., 1980. Effect of charcoal, coal and peat on the yield of moong soybean and pea. Soil Biol. Biochem. 12, 191– 192.

Jeffery, S., Martijn Bezemer T., Cornelissen, G., Kuyper, T.W., Lehmann, J., Mommer, L., Sohi, S.P., van de Voorde, T.F.J., Wardle, D.A., van Groenigen, J.W., 2013. The way forward in biochar research: targeting trade-offs between the potential wins. GCB Bioenergy 7, 1–13.

Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144, 175–187.

Jiang, J., Yuan, M., Xu, R., Bish., D.L., 2015. Mobilization of phosphate in variable-charge soils amended with biochars derived from crop straws. Soil Tillage Res. 146, 139–147.

Jiang, T.Y., Xu, R.K., Gu, T.X. Jiang, J., 2014. Effect of crop-straw derived biochars on Pb (II) adsorption in two variable charge soils. J. Integrative Agric. 13, 507–516.

Jones, D.L., Rousk, J., Edwards-Jones, G., DeLuca, T.H., Murphy, D.V., 2012. Biochar mediated changes in soil quality and plant growth in a three year field trial. Soil Biol. Biochem. 45, 113–124.

Kameyama, K., Miyamoto, T., Shiono, T., Shinogi, Y., 2012. Influence of sugarcane bagasse-derived biochar appalication on nitrate leaching in calcic dark red soil. J. Environ. Qual. 41 (4), 1131-1137.

Kamprath, E.J., 1971. Potential detrimental effects from liming highly weathered soils to neutrality. Soil Crop Sci. Soc. Florida Proceed. 31, 200–203.

Karer, J., Wimmer, B., Zehetner, F., Kloss, S., Soja, G., 2013. Biochar application to temperate soils: effects on nutrient uptake and crop yield under field conditions. Agric. Food Sci. 22: 390-403.

Karhu, K., Mattila, T., Bergstr€om, I.,Regina, K., 2011. Biochar addition to agricultural soil increased $CH_4$ uptake and water holding capacity e results from a short term pilot field study. Agric. Ecosyst. Environ.140, 309–313.

Khan, S.,C. Chao, M., Waqas, H.P.H., Arp, Zhu, Y.G., 2013. Sewage sludge biochar influenceupon rice (Oryza sativa L) yield, metal bioaccumulation and greenhouse gas emissions from acidic paddy soil. Environ. Sci. Technol. 47, 8624–8632.

Kim, P., Hensley, D.,Labbé, N., 2014. Nutrient release from switchgrass-derived biochar pellets embedded with fertilizers. Geoderma 232–234, 341–351.

Kloss, S., Zehetner, F., Wimmer, B., Buecker, J., Rempt, G., Soja, G., 2014. Biochar application to temperate soils: effects on soil fertility and crop growth under greenhouse conditions. J. Plant Nutrition Soil Sci. 177, 3–15.

Kookana, R.S., Sarmah, A.K., van Zwieten, L., Krull, E., Singh, B., 2011. Biochar application to soil: agronomic and environmental benefits and unintended consequences. Adv. Agron. 112, 103–143.

Laird, D., Fleming, P., Wang, B.Q., Horton, R., Karlen, D., 2010. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma 158, 436–442.

Laird, D.A., Brown, R.C., Amonette, J.E., Lehmann, J., 2009. Review of the pyrolysis platform for coproducing bio-oil and biochar. Biofuels Bioproducts Biorefining 3, 547–562.

Lal, J.K., Mishra, B., 1998. Flyash as a carrier for Rhizobium inoculant. J. Res. 10,191–192.

Lashari, M.S., Liu, Y., Li, L., Pan, W., Fu, J., Pan, G., Zheng, J., Zheng, J., Zhang, X., Yu, X., 2013. Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China Great Plain. Field Crops Res. 144, 113–118.

Lehmann, J., 2013. Recycle waste for nourishing soils. Nature 504, 33.

Lehmann, J., 2007. Bio-energy in the black.  Frontiers Ecol. Environ. 5, 381–387.

Lehmann, J., da Silva, J.P., Steiner, C., Nehls, T., Zech, W.,  Glaser, B., 2003. Nutrient availability and leaching in an archaeological anthrosol and a ferralsol of the central Amazon Basin: fertilizer, manure and charcoal amendments. Plant Soil 249, 343–357.

Lehmann, J., da Silva, J.P., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. Plant Soil 249, 343–357.

Lehmann, J., Gaunt, J., Rondon, M., 2006. Biochar sequestration in terrestrial ecosystems– A review. Mitigation Adaptation Strategies  Global Change 11, 403–427.

Lehmann, J., Kuzyakov, Y., Pan, G., Ok, Y.S., 2015. Biochars and the plant-soil interface. Plant Soil 395, 1-5.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota? A review. Soil Biol. Biochem. 43, 812-1836.

Lehmann, J., Rondon, M., 2005. Biochar soil management on highly-weathered soils in the humid tropics. In: Uphoff, N. (Ed.), Biological Approaches to Sustainable Soil Systems. Boca Raton, CRC Press.

Lentz, R.D., Ippolito, J.A., 2012. Biochar and manure affects calcareous soil and corn silage nutrient concentrations and uptake. J. Environ. Qual. 41, 1033–1043.

Liang, B., Lehman, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J., Neves, E.G., 2006. Black carbon increases cation exchange capacity in soils. Soil Sci. Soc. Am. J. 70, 1719–1730.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R., Li, L., Pan, G., Paz-Ferreiro, J., 2013. Biochar's effect on crop productivity and the dependence on experimental conditions-a meta-analysis of literature data. Plant Soil 373, 583–594.

Macdonald, L.M., Farrel, M., Van Zwieten, L.M., Krull, E.S., 2014. Plant growth responses to biochar addition: an Australian soils perspective. Biol. Fertil. Soils DOI 10.1007/s00374-014-0921-z.

Maestrini, B., Herrmann, A.M., Nannipieri, P., Schmidt, M.W.I., Abiven, S., 2014. Ryegrass-derived pyrogenic organic matter changes organic carbon and nitrogen mineralization in a temperate forest soil.Soil Biol. Biochem. 69, 291–301.

Mahmood, S., Finlay, R.D., Fransson, A.M., Wallander, H., 2003. Effects of hardened wood ash on microbial activity, plant growth and nutrient uptake by ectomycorrhiza spruce seedlings. FEMS Microbiol. Ecol. 43, 121–131.

Major, J., Rondon, M., Molina, D., Riha, S.J., Lehman, J., 2010. Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant Soil 333, 117–128.

Major, J., Steiner, C., Downie, A., Lehmann, J., 2009. Biochar effects on nutrient leaching. In: Lehmann, J., Joseph, S. (Eds.), Biochar for environmental management: science and technology. Earthscan, London, pp. 271–282.

Makoto, K., Choi, D., Hashidoko, Y., Koike, T., 2011. The growth of *Larixgmelinii* seedlings as affected by charcoal produced at two different temperatures. Biol. Fertil. Soils 47, 467–472.

Mandal, A., Singh, N., Purakayastha, T.J., 2017. Characterization of pesticide sorption behaviour of slow pyrolysis biochars as low cost adsorbent for atrazine and imidacloprid removal. Sci. Total Environ.577, 376–385.

Mandal, S., Donner, E., Vasileiadis, S., Skinner, W., Smith, E., Lombi, E., 2018. The effect of biochar feedstock, pyrolysis temperature, and application rate on the reduction of ammonia volatilisation from biochar-amended soil. Sci. Total Environ. 627, 942-950.

Mandal, S., Donner, E., Vasileiadis, S., Skinner, W., Smith, E., Lombi, E., 2018. The effect of biochar feedstock, pyrolysis temperature, and application rate on the reduction of ammonia volatilisation from biochar-amended soil. Sci. Total Environ. 627, 942-950.

Mandal, S., Sarkar, B., Bolan, N., Novak, J., Ok, Y.S., Van Zwieten, L., Singh, B.P., Kirkham, M.B., Choppala, G., Spokas, K., Naidu, R., 2016a. Designing advanced biochar products for maximizing greenhouse gas mitigation potential. Critical Reviews Environ. Sci. Technol. 46 (17), 1367-1401.

Mandal, S., Thangarajan, R., Bolan, N.S., Sarkar, B., Khan, N., Ok, Y.S., Naidu, R., 2016b. Biochar-induced concomitant decrease in ammonia volatilization and increase in nitrogen use efficiency by wheat. Chemosphere 142, 120-127.

Meyer, S., Glaser, B., Quicker, P., 2001. Technical, economical, and climate-related aspects of biochar production technologies: A literature review. Environ. Sci. Technol. 45, 9473–9483.

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., Field, D.J., Gimona, A., Hedley, C.B., Hong, S.Y., Mandal, B., Marchant, B.P., Martin, M., McConkey, B.G., Mulder, V.L., O'Rourke, S., Richer-de-Forges, A.C., Odeh, I., Padarian, J., Paustian, K., Pan, G., Poggio, L., Savin, I., Stolbovoy, V., Stockmann, U., Sulaeman, Y., Tsui, C.-C., Vågen, T.-G., van Wesemael, B.& Winowiecki, L., 2017. Soil carbon 4 per mille. Geoderma 292, 59-86.

Mohan, D., Sarswat, A., Ok, Y.S., Pittman, C.U., 2014. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent: A critical review. Bioresource Technol. 160,191–202.

Mukherjee, A., Lal, R., Zimmerman, A.R., 2014. Effects of biochar and other amendments on the physical properties and greenhouse gas emissions of an artificially degraded soil. Sci. Total Environ.487, 26–36.

Mukherjee, A., Zimmerman, A.R., 2013. Organic carbon and nutrient release from a range of laboratory-produced biochars and biochar–soil mixtures. Geoderma193–194, 122–130.

Munda, S., Nayak, A.K., Mishra, P.N., Bhattacharyya, P., Mohanty, S., Kumar, A., Kumar, U., Baig, M.J., Tripathi, R., Shahid, M., Adak, T., 2016. Combined application of rice husk biochar and fly ash improved the yield of lowland rice. Soil Res. 54 (4), 451–459.

Munda, S., Bhaduri, D., Mohanty, S., Chatterjee, D., Tripathi, R., Shahid, M., Kumar, U., Bhattacharyya, P., Kumar, A., Adak, T. and Jangde, H.K., Nayak, A.K., 2018. Dynamics of soil organic carbon mineralization and C fractions in paddy soil on application of rice husk biochar. Biomass Bioenergy 115, 1-9.

Nehls, T., 2002. Fertility improvement of a Terra FirmeOxisol in Central Amazonia by charcoal applications. M.Sc. Thesis, University of Bayreuth, Germany.

Nellisen, V., Rutting, T., Huygens, D., Staelens, J., Ruysschaert, G.,Boeckx, P., 2012. Maize biochar accelerate short-term nitrogen dynamics in a loamy sand soil. Soil Biol. Biochem. 55, 20–27.

Nielsen, S., Joseph, S., Ye, J., Chia, C., Munroe, P., Zwieten, L.V., Thomas, T., 2018. Crop-season and residual effects of sequentially applied mineral enhanced biochar and N fertiliser on crop yield, soil chemistry and microbial communities. Agric. Ecosyst. Environ. 255, 52-61.

Nguyen, B.T, Lehmann J., 2009. Black carbon decomposition under varying water regimes. Org. Geochem. 40 (8), 846–853.

Nishio, M., Okano, S., 1991. Stimulation of the growth of alfalfa and infection ofmycorrhizal fungi by the application of charcoal. Bull. Natl. Grassl. Res. Inst. 45, 61–71.

Novak, J.M., Busscher, W.J., Laird, D.L., Ahmedna, M., Watts, D.W., Niandou, M.A.S., 2009. Impact of biochar amendment on fertility of a south eastern coastal plain soil. Soil Sci., 174, 105–112.

O'Connor, D., Peng, T., Li, G., Wang, S., Duan, L., Mulder, J., Cornelissen, G., Cheng, Z., Yang, S., Hou, D., 2018a. Sulfur-modified rice husk biochar: a green method for the remediation of mercury contaminated soil. Sci. Total Environ. 621, 819–826.

O'Connor, D., Peng, T., Zhang, J., Tsang, D.C.W., Alessi, D.S., Shen, Z., Bolan, N.S., Hou, D., 2018b. Biochar application for the remediation of heavy metal polluted land: A review of in situ field trials. Sci. Total Environ. 619–620, 815–826.

Olmo, M., Villar, R., Salazar, P.,Alburquerque, J.A., 2016. Changes in soil nutrient availability explain biochar's impact on wheat root development. Plant Soil 399 (1-2), 333–343.

Pandher, M.S., Gupta, R.P., Bhandal, B.K., Gupta. S.K., 1993. Studies on growth and survival of Rhizobium isolates in different carriers. Indian J. Ecol. 20,141–146.

Parvage, M.M., Ulen, B., Eriksson, J., Strock, J., Kirchmann, H., 2013. Phosphorus availability in soils amended with wheat residue char. Biol. Fertil. Soils 49, 245–250.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49-57.

Peng, X., Ye, L.L., Wang, C.H., Zhou, H., Sun, B., 2011. Temperature- and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. Soil Tillage Res. 112, 159-166.

Pereira, E.I.P., Suddick, E.C., Mansour, I., Mukome, F.N.D., Parikh, S.J., Scow, K., Six, J., 2015. Biochar alters nitrogen transformations but has minimal effects on nitrous oxide emissions in an organically managed lettuce mesocosm. Biol. Fertil. Soils 51, 573–582.

Petersen, H., 1978. Some properties of two high-gradient extractors for soil microarthropods, and an attempt to evaluate their extraction efficiency. Natural Jutl 20, 95–122

Prayogo, C., Jones, J.E., Baeyens, J., Gary, D., 2014. Impact of biochar on mineralisation of C and N from soil and willow litter and its relationship with microbial community biomass and structure Bending. Biol. Fertil. Soils 50, 695–702.

Prendergast-Miller, M.T., Duvall, M., Sohi, S.P., 2014. Biochar–root interactions are mediated by biochar nutrient content and impacts on soil nutrient availability. European J. Soil Sci. 65(1), 173–185.

Purakayastha, T.J., 2010. Effect of biochar on yield of different crops. In: Annual Report, Indian Agricultural Research Institute, New Delhi, pp. 55.

Purakayastha, T.J., Das, K.C., Gaskin, J., Harris, K., Smith, J.L., Kumari, S., 2016. Effect of pyrolysis temperatures on stability and priming effects of C3 and C4 biochars applied to two different soils. Soil Tillage Res. 155, 107–115.

Purakayastha, T.J., Kumari, S., Pathak, H., 2015. Characterization, stability, and microbial effects of four biochars produced from crop residues. Geoderma 239 (240), 293–303.

Quilliam, R.S., Marsden, K.A., Gertler, C., Rousk, J., DeLuca, T.H., and Jones, D.L., 2012. Nutrient dynamics, microbial growth and weed emergence in biochar amended soil are influenced by time since application and reapplication rate. Agric.Ecosys. Environ. 158, 192-199.

Rahman, A.A., Abdullah, N., Sulaiman, F., 2014. Temperature effect on the characterization of pyrolysis products from oil palm fronds. Adv. Energy Engineering 2, 14–21.

Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A.R., Lehmann, J., 2012. Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. Biol. Fertil. Soils 48, 271–284.

Rens, H., Bera, T., Alva, A.K., 2018. Effects of biochar and biosolid on adsorption of nitrogen, phosphorus, and potassium in two soils. Water Air Soil Poll. https://doi.org/10.1007/s11270-018-3925-8.

Ro, K.S., Cantrell, K.B., Hunt, P.G., 2010. High-Temperature Pyrolysis of Blended Animal Manures for Producing Renewable Energy and Value-Added Biochar. Industrial Engineering Chemistry Res. 49(20), 10125-10131.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534, 631-639.

Rogovska, N., Laird, D.A., Rathke, S.J.,Karlen, D.L., 2014. Biochar impact on Midwestern Mollisols and maize nutrient availability. Geoderma 230–231, 340–347.

Rondon, M.A., Lehmann, J., Ramirez, J., Hurtado, M., 2007. Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. Biol. Fertil. Soils 43, 699-708.

Rosa, D.L., Knicker, J.M., 2011. Bioavailability of n released from N-rich pyrogenic organic matter: an incubation study. Soil Biol. Biochem. 43, 2368–2373.

Saarnio, S., Heimonen, K.,Kettunen, R., 2013. Biochar addition indirectly affects $N_2O$ emissions via soil moisture and plant N uptake. Soil Biol. Biochem. 58, 99–106.

Sarkar, B., Mandal, S., Tsang, Y.F., Kumar, P., Kim, K.-H., Ok, Y.S., 2018. Designer carbon nanotubes for contaminant removal in water and wastewater: A critical review. Sci. Total Environ. 612, 561-581.

Schmidt, M.W.I., Noack, A.G., 2000. Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. Global Biogeochem. Cycle 14, 777-793.

Schmidt, H.P., Kammann, C., Niggli, C., Evangelou, M.W.H., Mackie, K.A., Abiven, S., 2014. Biochar and biochar-compost as soil amendments to a vineyard soil: Influences on plant growth, nutrient uptake, plant health and grape quality. Agric. Ecosyst. Environ. 191, 117-123.

Singh, B.P., Hatton, B.J., Singh, B., Cowie, A.L.,Kathuria, A.,2010. Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils. J. Environ. Qual. 39, 1224–1235.

Slavich, P.G., Sinclair, K., Morris, S.H., Kimber, S.W.L., Downie, A.Van Zwieten, L., 2013. Contrasting effects of manure and green waste biochars on the properties of an acidic ferralsol and productivity of a subtropical pasture. Plant Soil 366, 213–227.

Sohi, S.P., Krull, E., Lopez-Capel, E.Bol, R.,2010. A review of biochar and its use and function in soil. Adv.Agron. 105, 47–82.

Soinne, H., Hovi, J., Tammeorg, P.Turtola, E.,2014. Effect of biochar on phosphorus sorption and clay soil aggregate stability. Geoderma219–220, 162–167.

Song, Y., Zhang, X., Ma, B., Chang, S.X.,Gong, J.,2013. Biochar addition affected the dynamics of ammonia oxidizers and nitrification in microcosms of a coastal alkaline soil. Biol.Fertil. Soils. DOI: 10.1007/s00374-013–0857–8.

Spokas, K.A., Cantrellb, K.B., Novak, J.M., Archerc, D.W., Ippolitod, J.A., Collinse, H.P., Boatengf, A.A., Limag, I.M., Lambh, M.C., McAloonf, A.J., Lentzd, R.D.Nicholsc, K.A., 2000. Biochar: A synthesis of its agronomic impact beyond carbon sequestration. J.Environ.l Qual. 41, 973–989.

Steiner, C., Das, K.C., Melear, N.Lakly, D., 2010. Reducing nitrogen loss during poultry litter composting using biochar. J. Environ.l Qual. 39, 1236-1242.

Stevenson, F.J., Cole, M.A.,1999. Cycles of the Soil, Second edition, John Wiley and Sons, Inc., New York, NY.

Streubel, J.D., Collins, H.P., Garcia-Perez, M., Tarara, J. Granatstein, D., Kruger, C.E.,2011. Influence of biochar on soil pH, water holding capacity, nitrogen and carbon dynamics. Soil Sci.Soc. Am. J. 75, 1402–1413.

Sun, Z., Bruun, E.W., Arthur, E., Jonge, L.W.D., Moldrup, P., Nielsen, H.H., Elsgaard, L., 2014. Effect of biochar on aerobic processes, enzyme activity, and crop yields in two sandy loam soils. Biol. Fertility Soils. 50. 10.1007/s00374-014-0928-5.

Taghizadeh-Toosi, A., Clough, T., Sherlock, R.,Condron, L., 2012a. Biochar adsorbed ammonia is bioavailable. Plant Soil, 350, 57-69.

Taghizadeh-Toosi, A., Clough, T.J., Sherlock, R.R., Condron, L.M.,2012b. A wood based low-temperature biochar captures $NH_3$-N generated from ruminant urine-N, retaining its bioavailability. Plant Soil, 353, 73-84.

Tammeorg, P.,Simojoki, A.,Mäkelä, P., Stoddard, F.,Alakukku, L.,Helenius, J., 2014. Biochar application to a fertile sandy clay loam in boreal conditions: Effects on soil properties and yield formation of wheat, turnip rape and faba bean. Plant Soil. 374.

UNEP, 2017. The Emissions Gap Report 2017. United Nations Environment Programme (UNEP), Nairobi.

Uzoma, K.C., Inoue, M., Andry, H., Zahoor, A., Nishihara, E., 2011. Influence of biochar application on sandy soil hydraulic properties and nutrient retention. J.Food Agric.l Environ. 9, 1137–1143.

Vaccari, F.P., Baronti, S., Lugato, E., Genesio, L., Castaldi S., Fornasier, F., Miglietta, F.,2011. Biochar as a strategy to sequester carbon and increase yield in durum wheat. European J.Agron. 34, 231–238.

Van Zwieten, L., Kimber, S., Morris, S., Chan, K.Y., Downie, A., Rust, J.,Joseph, S., Cowie, A. 2010. Effects of biochar from slowpyrolysis of papermill waste on agronomic performance and soil fertility. Plant Soil, 327:235–246

Van Zwieten, L., Singh, B., Joseph, S., Kimber, S., Cowie, A.,Chan, K.Y., 2009. Biochar and emissions of non-$CO_2$ greenhouse gasses from soil. In: Lehmann, J., Joseph, S. (Eds.), Biochar for environmental management: science and technology. Earthscan, London, Sterling, VA, pp. 227–249.

Verheijen, F., Jeffery, S., Bastos, A.C., van der Velde, M.Diafas, F.,2010. Biochar application to soils. A critical scientific review of effects on soil properties, processes, and functions. Luxembourg pp. 149.

Wen, P., Wu, Z., Han, Y., Cravotto, G., Wang, J., Ye, B.C., 2017. Microwave-Assisted Synthesis of a Novel Biochar-Based Slow-Release Nitrogen Fertilizer with Enhanced Water-Retention Capacity. ACS Sustain. Chem. Eng., 5, 7374-7382.

Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. Joseph, S.,2010. Sustainable biochar to mitigate global climate change. Nature Communications 1: Article number: 56 (online journal). www.nature.com/ncomms/journal/v1/n5/full/ncomms1053.html.

Wrobel-Tobiszewska, A., Boersma, M., Sargison, J., Adams, P., Jarick, S.,2015.An economic analysis of biochar production using residues from Eucalypt plantations. Biomass Bioenergy, 81, 177-82.

Xie, Z.B., Xu, Y.P., Liu, G., Liu, Q., Zhu, J.G., Tu, C., Amonette, J.E., Cadisch, G., Yong, J.W.H.Hu, S.J.,2013. Impact of biochar application on nitrogen nutrition of rice, green house gas emission and soil organic carbon dynamics in two paddy soils of China. Plant Soil, 370, 527–540.

Xu, Y., Seshadri, B., Sarkar, B., Wang, H., Rumpel, C., Sparks, D., Farrell, M., Hall, T., Yang, X.Bolan, N., 2018a. Biochar modulates heavy metal toxicity and improves microbial carbon use efficiency in soil. Sci. Total Environ.621, 148-159.

Xu, G., Saho, H., Zhang,Y. Sun J.,2018b Non-additive effects of biochar amendments on soil phosphorusfractions in two contrasting soils. Land Degrad. Dev. 29, 2720-2727.

Yang, H., Sheng, K., 2012. Characterization of biocharproperties affected by different pyrolysis temperature using visible-near-infrared spectroscopy.International Scholarly Research Network, ISRN Spectroscopy, doi:10.5402/2012/ 712837.

Yao, Y., Gao, B., Inyang, M., Zimmerman, A.R., Cao, X., Pullammanappallil, P.Yang, L., 2011. Removal of phosphate from aqueous solution by biochar derived from anaerobically digested sugar beet tailings. J. Hazardous Materials 190(1-3), 501-507.

Yao, Y., Gao, B., Zhang, M., Inyang, M., Zimmerman, A.Z., 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. Chemosphere 89(11), 1467-1471.

Yu, X., Wu, C., Fu, Y., Brookes, P.C.Lu, S.,2016. Three-dimensional pore structure and carbon distribution of macroaggregates in biochar-amended soil. European J. Soil Sci. 67(1), 109–120.

Yuan, J.H., Xu, R.K., Qian, W.Wang, R.H.,2011. Comparison of the ameliorating effects on an acidic Ultisol between four crop straws and their biochars. J. Soils Sediments11, 741–750.

Yuan, J.H., Xu, R.K.Zhang, H.,2011. The forms of alkalis in the biochar produced from crop residues at different temperatures. Bioresource Technology 102, 3488–3497.

Wang, S.P., Li, X.K., Lu, J.W., et al., 2013. Effects of combined application of urea and controlled-release urea on yield, profits of rapeseed and soil inorganic nitrogen. Chin. J. Oil Crop Sci. 35(3), 295-300

Zhai, L., Cai Ji, Z., Liu, J., Wang, H., Ren, T., Gai, X., Xi, B., Liu, H.,2015. Short-term effects of maize residue biochar on phosphorus availability in two soils with different phosphorus sorption capacities. Biol..Fertil. Soils 51, 113–122.

Zhang, A., Liu, Y., Pan, G., Hussain, Q., Li, L.Pan, G.,2012. Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain. Plant Soil, 351, 263–275.

Zhang, H., Voroney, R.P.Price, G.W.,2015. Effects of temperature and processing conditions on biochar chemical properties and their influence on soil C and N transformations. Soil Biol.Biochem. 83, 19–28.

Zhao, B., O'Connor, D., Zhang, J., et al., 2018. Effect of pyrolysis temperature, heating rate, and residence time on rapeseed stem derived biochar. J. Clean. Prod.174, 977-987.

Zheng, H., Wang, Z., Deng, X., Xing, B., 2013. Impact of pyrolysis temperature on nutrient properties of biochar, inXu, J., Wu, J., He, Y. (Eds.), Functions of Natural Organic Matter in Changing Environment. pp.975-978. 10.1007/978-94-007-5634-2_179.

Zhou, L., Cai, D., He, L., Zhong, N., Yu, M., Zhang, X., Wu, Z., 2015. Fabrication of a high-performance fertilizer to control the lossof water and nutrient using micro/nano net-works. ACS Sustain. Chem. Eng. 3, 645–653.

Zhu, K.R., Fu, H., Zhang, J.H., Lv, X.S., Tang, J. Xu, X.H.,2012. Studies on removal of NHþ 4 –N from aqueous solution by using the activated carbons derived from rice husk. Biomass Bioenergy 43, 18–25.

Zimmerman, A.R., 2010. Abiotic and microbial oxidation of laboratory produced black carbon (biochar). Environ.l Sci. Technol. 44, 1295–1301.

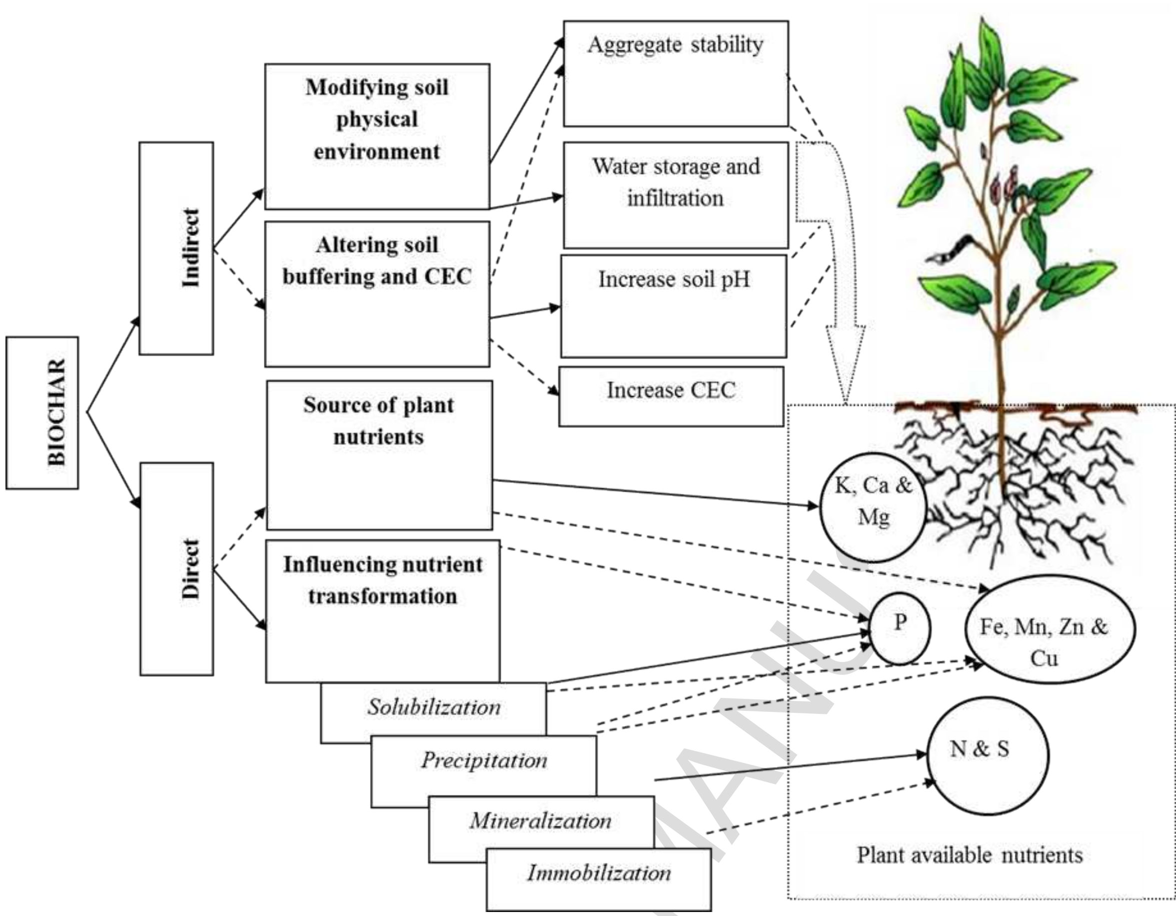


**Fig. 1.** Pathways of biochar impact in soil for better crop production. ———→ Indicate primary pathways as evident from previous literature while - - - - - -→ indicated possible pathways which needs to be validated with future research results.

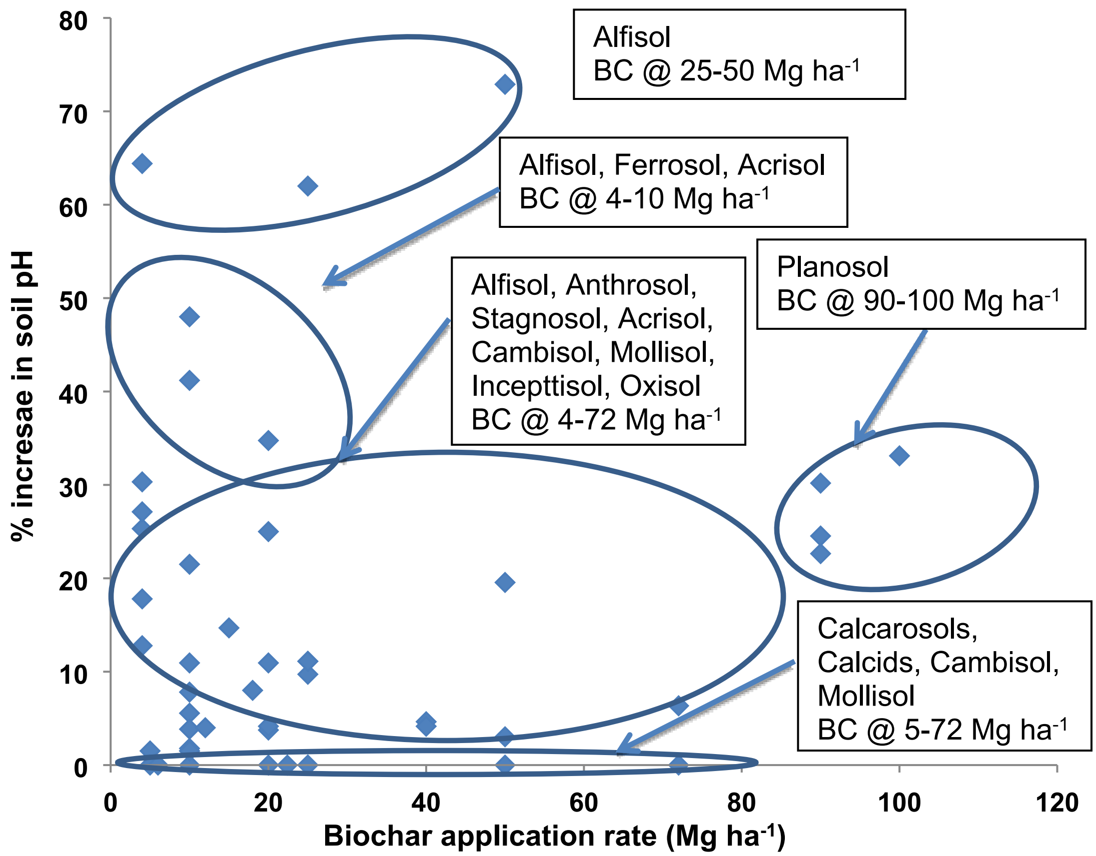


**Fig. 2.** Effect of biochar (BC) application rate on soil pH

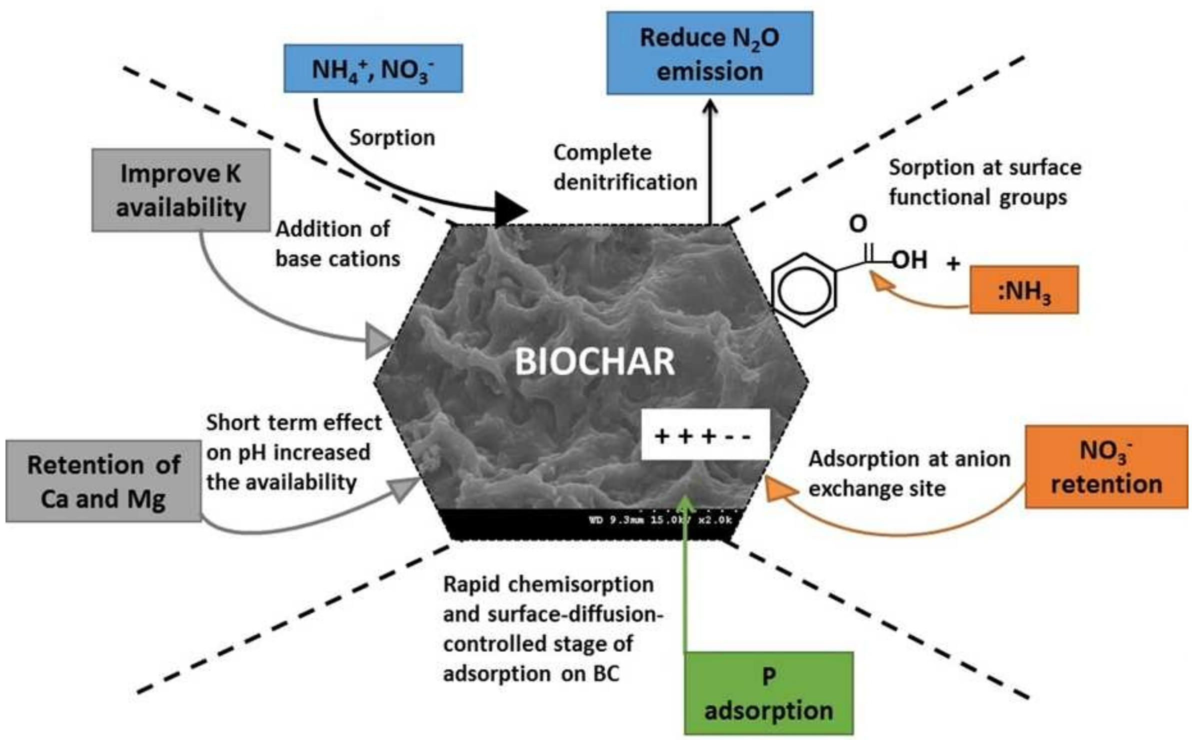


**Fig. 3.** Schematic diagram representing how biochar improves the retention of macro (N, P, and K) and micronutrients (Ca and Mg) and increases their availabilities in soils.

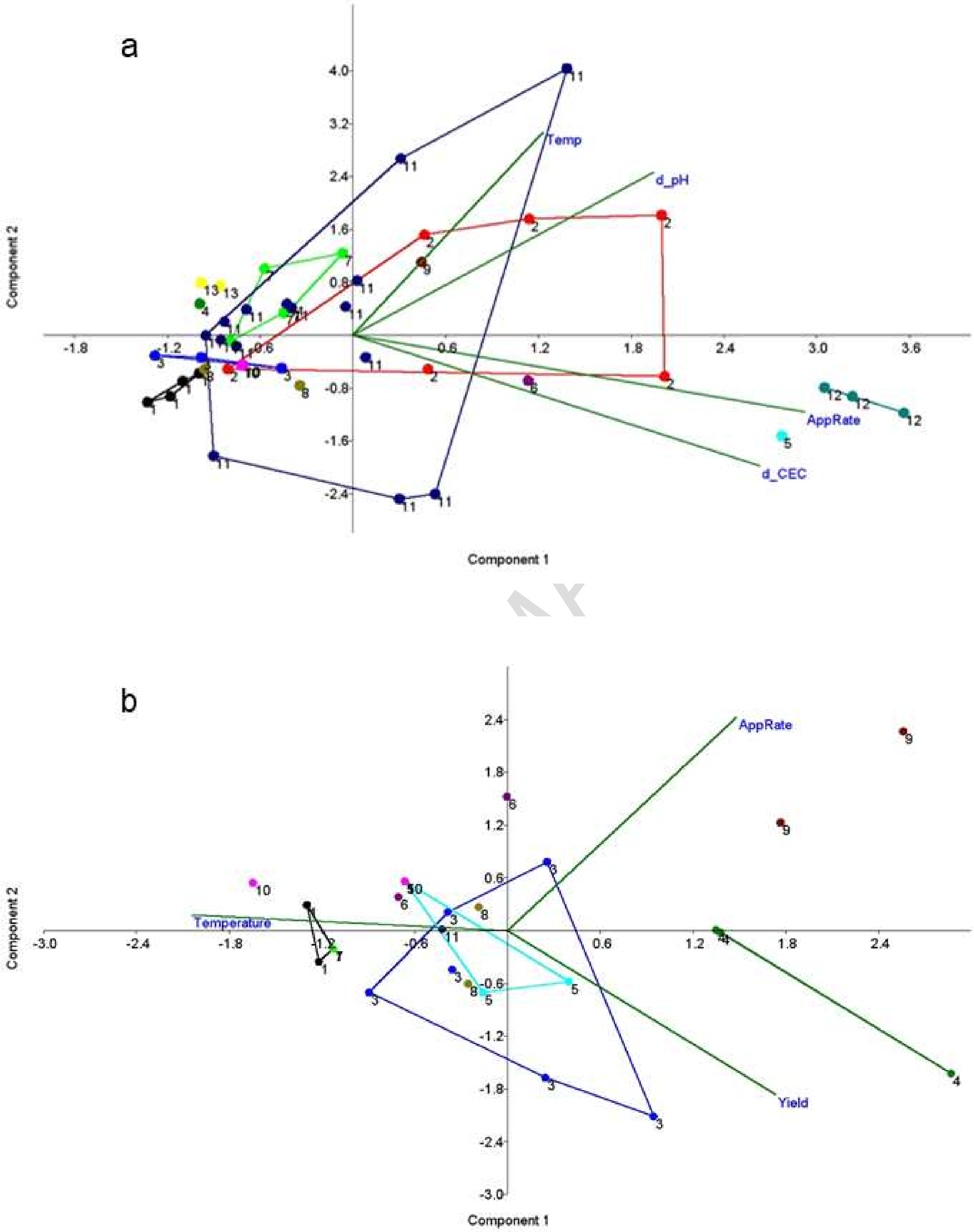
a
Temp
d_pH
AppRate
d_CEC
Component 1
Component 2
b
AppRate
Temperature
Yield
Component 1
Component 2

**Fig. 4.** Principal Component analysis with respect to soil type for effects of biochar on (a) soil chemical properties, and (b) crop yields. Point groups are enclosed by convex hulls. Numbers within the figure represent soil types.

**In Fig. 4a** 1–Acrisol; 2–Alfisol; 3–Anthrosols; 4–Calcarosol; 5–Cambisol; 6–Chernozem; 7–Entisol; 8–Eutric Cambisol; 9–Ferrosol; 10–Halpudept; 11–Haplustox; 12–Planosol; 13–Stagnosol.

**In Fig. 4b** 1–Acidic Aeronosol; 2–Acidic clay loam Ultisol; 3–Acid Ferrasol; 4–Acidic Oxisol; 5–Acidic sandy clay loam; 6–Acidic silty; 7–Alkaline Calcisol; 8–Alkaline sandy loam Inceptisol; 9–Neutral clay loam Oxisol; 10–Neutral Vertisol; 11–Slightly alkaline sandy loam Inceptisol.

**Highlights**

- Nutrient value of biochar as impacted by pyrolysis conditions and feedstock types discussed.
- Impact of biochar on improvement of soil pH, CEC and buffering system delineated.
- Role of biochar on dynamics of nitrogen, phosphorus, potassium, secondary and micronutrients in soil elucidated.
- Effect of biochar on crop yields in different soils across the globe discussed.
- Meta-analysis of the established data by Principal component analysis was done to establish the role of biochar on soil chemical properties and crop yields
- Conclusions and future directions of biochar research

**Table 1**

pH and nutrient composition of various biochar materials produced at different pyrolysis temperatures

| Biochar feedstock | Pyrolysis temp. (°C) | pH | C | N | C/N | P | K | Ca | Mg | S | Zn | Cu | Fe | Mn | Mo | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | (%) | | | (%) | | | | | (mg kg$^{-1}$) | | | | | |
| ***Crop residues*** | | | | | | | | | | | | | | | | |
| Corn cob | 600°C | 10.1 | 79.1 | 4.25 | 19 | - | - | - | - | - | - | - | - | - | - | Mandal et al. (2017) |
| *Macadamia integrifolia* | 450-480 °C | 8.76 | 78.03 | 0.43 | 182 | 0.24 | 2.19 | 0.37 | 0.17 | - | - | - | 1211 | - | - | Wrobel-Tobiszewska (2015) |
| Giant reed (*Arundodonax*) | | 9.45 | 73.4 | 0.49 | 150 | - | - | - | - | - | - | - | - | - | - | Zheng et al. (2013) |
| Switch grass | 400 °C | - | 73.1 | 1.35 | 54 | - | - | - | - | 0.32 | | | | | | Purakayastha et al. (2016) |
| Rice straw | 450 °C | | 70.6 | 0.97 | | 0.218 | 26.4 | | | | | | | | | Peng et al. (2011) |
| Wheat straw | 400 °C | - | 70.5 | 1.22 | 58 | - | - | - | - | 0.29 | - | - | - | - | - | Purakayastha et al. (2016) |
| Corn stover | 600 °C | 9.95 | 69.8 | 1.01 | 70 | 0.181 | 2.461 | 0.938 | 0.858 | 0.08 | 70 | - | 1362 | 226 | - | Enders et al. (2012) |
| Peanut hull | 400 °C | | 65.5 | 2.0 | 33 | 0.00162 | 0.00153 | 0.00044 | - | - | - | - | - | - | - | Gaskin et al. (2009) |
| Pearl millet | 400 °C | 10.6 | 64 | 1.10 | 58 | 1.60 | 2.52 | 1.47 | 1.06 | 0.22 | | | | | | Purakayastha et al. (2015) |
| Soybean straw | 500 °C | 10.9 | 62.6 | 0.37 | 171 | 0.44 | - | - | - | - | - | - | - | - | - | Yuan et al. |
| Canola straw | 500 °C | 9.39 | 61.6 | 0.04 | 1610 | 0.27 | - | - | - | - | - | - | - | - | - | (2011a) |
| Corn stover | 300 °C | 7.33 | 59.5 | 1.16 | 51 | 0.137 | 1.705 | 0.648 | 0.588 | 0.070 | 132 | - | 963 | 142 | - | Enders et al. (2012) |
| Sugarcane bagasse | 350 °C | 4.96 | 57 | 0.34 | 168 | 0.058 | 0.48 | - | - | 0.032 | - | - | - | - | - | |
| Corn stover | 400 °C | - | 55.3 | 1.30 | 43 | - | - | - | - | 0.20 | - | - | - | - | - | Purakayastha |
| Rice hull | 400 °C | - | 55 | 0.93 | 59 | - | - | - | - | 0.05 | - | - | - | - | - | et al. (2016) |
| Peanut straw | 500 °C | 10.86 | 48.5 | 1.51 | 32 | 0.95 | - | - | - | - | - | - | - | - | - | |
| Rice husk | 800°C | - | - | - | - | 0.044 | 0.670 | 0.164 | 0.084 | 0.017 | 29 | - | 29 | 22 | - | Enders et al. |
| Soybean | 500°C | - | - | - | - | 0.056 | 3.779 | 1.565 | 1.171 | 0.112 | 28 | - | 699 | 58 | - | (2012) |
| ***Woods*** | | | | | | | | | | | | | | | | |
| Bamboo chip | 600°C | 9.59 | 81.2 | 4.55 | 18 | - | - | - | - | - | - | - | - | - | - | Mandal et al. |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Eucalyptus bark | 600°C | 9.37 | 79.1 | 4.20 | 19 | - | - | - | - | - | - | - | - | - | - | (2017) |
| Spruce and pine chips | 550-600°C | 10.8 | 87.8 | 0.62 | 142 | 0.001 | 3.23 | 4.44 | 0.72 | 0.019 | 470 | 10 | 7190 | 2570 | - | Tammeorg et al., (2014) |
| Hazelnut | 400 °C | 6.38 | 87.6 | 0.17 | 510 | 0.0298 | 0.429 | 0.282 | 0.0554 | 0.016 | 10 | - | 29 | 13 | - | Enders et al. (2012) |
| *Teak and Rose wood* | 300-400 °C | 7.5 | 87.0 | 0.31 | 281 | 0.0048 | 0.12 | 0.044 | 0.036 | | | | | | | Asai et al. (2009) |
| *Eucalyptus deglupta* | | 7.0 | 82.4 | 0.573 | 144 | 0.6 | - | - | - | - | - | - | - | - | - | Rondon et al. (2007) |
| *Eucalyptus camaldulensis* L., flash carbonization | 800°C | 8.92 | 81.50 | | | 0.086 | 0.781 | 1.042 | 0.059 | | | | 0.229 | | | Butnan et al. (2015) |
| Oak | 400 °C | 4.58 | 78.8 | 0.17 | 468 | 0.0005 | 0.147 | 0.106 | 0.0061 | 0.008 | 33 | - | 169 | 15 | - | Enders et al. (2012) |
| Douglas-fir wood pellets | 500°C | 7.2 | 78.2 | 0.13 | 602 | 0.022 | 0.10 | 0.20 | 0.03 | 0.017 | 29.1 | 3.1 | 250 | 93.3 | | Streubel et al. (2011) |
| Pine | 400°C | 4.6 | 76.3 | 0.1 | 763 | 0.0035 | 0.037 | 0.225 | 0.048 | 0.010 | 66 | - | 1166 | 258 | - | |
| Wood chips | 400-450°C | 10.9 | 74.8 | 0.15 | 499 | 0.04 | 0.23 | 0.59 | 0.13 | 0.03 | - | - | 4200 | - | - | Saarnio et al., (2013) |
| Cooking wood | 500-700°C | 9.20 | 72.9 | 0.76 | 121 | 0.0030 | 0.046 | 0.033 | 0.0048 | - | - | - | - | - | - | Major et al. (2012) |
| Douglas-fir wood bark | 500°C | 7.6 | 72.7 | 0.35 | 208 | 0.047 | 0.10 | 1.07 | 0.048 | 0.023 | 40.9 | 6.8 | 700 | 266 | | Streubel et al. 2011 |
| Yellow pine chipped | 400 °C | 5.96 | 71 | 0.1 | 710 | 0.017 | 0.18 | - | - | 0.01 | - | - | - | - | - | White Jr. et al. (2015) |
| Hardwood | | | 70.3 | 0.30 | 234 | 0.0278 | 0.000241 | 0.00027 | - | - | - | - | - | - | - | Gaskin et al. (2009) |
| Pine chips | | | 67.0 | 0.14 | 479 | 0.0235 | 0.000197 | 0.00017 | - | - | - | - | - | - | - | Gaskin et al. (2009) |
| *Eucalyptus camaldulensis* L., traditional kiln | 300 °C | 6.52 | 61.86 | - | - | 0.05 | 0.51 | 0.541 | 0.043 | - | - | - | 0.05 | - | - | Butnan et al. (2015) |
| *Sesbaniaroxburghii* | 400 oC | 9.0 | 57.7 | 3.50 | 17 | - | - | - | - | - | - | - | - | - | - | Chen et al. (2014) |
| ***Manure*** | | | | | | | | | | | | | | | | |
| Bull manure | 600 °C | 9.5* | 76.0 | 0.8 | 95 | 0.295 | 3.582 | 0.938 | 0.507 | 0.102 | 193 | - | 311 | 165 | - | Enders et al. (2012) |
| Anaerobic digested fibre | 500°C | 9.3 | 65.8 | 2.23 | 30 | 0.76 | 1.17 | 2.40 | 0.70 | 0.30 | 230 | 163 | 1280 | 184 | - | Streubel et al. (2011) |
| Bull manure | 300 °C | 8.2* | 60.6 | 1.3 | 47 | 0.301 | 2.002 | 0.941 | 0.395 | 0.110 | 162 | - | 376 | 137 | - | Enders et al. (2012) |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Digested dairy manure | 600°C | 9.94 | 59.4 | 0.225 | 28 | 0.827 | 1.494 | 2.65 | 0.850 | 0.286 | 200 | - | 2356 | 191 | - | Enders et al. (2012) |
| Digested dairy manure | 400°C | 9.22 | 57.7 | 0.242 | 26 | 0.645 | 1.66 | 2.2552 | 0.973 | 0.272 | 131 | - | 1656 | 145 | - | Enders et al. (2012) |
| Dairy manure | 700°C | 9.9 | 56.7 | 1.51 | 38 | 1.69 | 2.31 | 4.48 | 2.06 | 0.15 | 423 | 163 | 44800 | 867 | 10.0 | Cantrell et al. (2012) |
| Dairy manure | 350°C | 9.2 | 55.8 | 2.60 | 22 | 1.00 | 1.43 | 2.67 | 1.22 | 0.11 | 361 | 99.0 | 26700 | 525 | 7.8 | Cantrell et al. (2012) |
| Paved-feedlot | 350°C | 9.1 | 53.3 | 3.64 | 15 | 1.14 | 3.20 | 2.27 | 0.76 | 0.45 | 359 | 91.7 | 22600 | 259 | 6.2 | Cantrell et al. (2012) |
| Paved-feedlot | 700°C | 10.3 | 52.4 | 1.70 | 31 | 1.76 | 4.91 | 3.50 | 1.22 | 0.44 | 448 | 136 | 34500 | 388 | 6.3 | Cantrell et al. (2012) |
| Swine solids | 350°C | 8.4 | 51.5 | 3.54 | 15 | 3.89 | 1.78 | 3.91 | 2.44 | 0.80 | 3181 | 1538 | 48400 | 1453 | 18.3 | Cantrell et al. (2012) |
| Poultry litter | 350°C | 8.7 | 51.1 | 4.45 | 12 | 2.08 | 4.85 | 2.66 | 0.94 | 0.61 | 712 | 213 | 13200 | 640 | 11.0 | Cantrell et al. (2012) |
| Turkey litter | 350°C | 8.0 | 49.3 | 4.07 | 12 | 2.62 | 4.01 | 4.04 | 0.85 | 0.55 | 690 | 535 | 27800 | 710 | 7.16 | Cantrell et al. (2012) |
| Poultry litter | 700°C | 10.3 | 45.9 | 2.07 | 22 | 3.12 | 7.40 | 4.02 | 1.45 | 0.63 | 1010 | 310 | 18900 | 948 | 13.0 | Cantrell et al. (2012) |
| Turkey litter | 700°C | 9.9 | 44.8 | 1.94 | 23 | 3.63 | 5.59 | 5.61 | 1.24 | 0.41 | 909 | 762 | 36500 | 986 | 10.1 | Cantrell et al. (2012) |
| Swine solids | 700°C | 9.5 | 44.1 | 2.61 | 17 | 5.90 | 2.57 | 6.15 | 3.69 | 0.85 | 4981 | 2446 | 74800 | 2240 | 27.4 | Cantrell et al. (2012) |
| Poultry litter | 400 °C | 7.7 | 38.3 | 2.0 | 19 | 0.9 | 1.0 | 2.5 | 0.3 | - | 238 | 57 | 2695 | 265 | 5 | Macdonald et al. (2014) |
| Cow manure | 500°C | 9.20 | 33.6 | 0.15 | 22 | 0.814 | 0.005 | 0.042 | 0.034 | - | - | - | - | - | - | Uzoma et al. (2011) |
| Poultry manure | 500 °C | 10.57 | 25.4 | 1.41 | 18 | 3.055 | 2.811 | 20.42 | 1.044 | 0.459 | 601 | - | 2034 | 566 | - | Enders et al. (2012) |
| Poultry manure | 600 °C | 10.65 | 23.6 | 0.94 | 28 | 2.359 | 2.74 | 24.28 | 0.877 | 0.349 | 595 | - | 1522 | 466 | - | Enders et al., (2012) |
| ***Waste materials*** | | | | | | | | | | | | | | | | |
| Brush | 500°C | 8.4 | 84 | 0.1 | 840 | 0.013 | 0.087 | 0.756 | 0.044 | 0.011 | 59 | - | 94 | 142 | - | Enders et al. (2012) |
| Whole tree residue | 600°C | 7.5** | 78 | 0.14 | 557 | 0.009 | 0.055 | 0.140 | 0.040 | 0.004 | 25 | 3.1 | 2600 | 56 | <1.2 | Van Zwieten et al. (2010) |
| Orchard pruning biomass | 500°C | 9.8 | 77.8 | 0.91 | 63.5 | 2.33 | 1.39 | 2.5 | 2.87 | 0.048 | .010 | .009 | .033 | .008 | - | Baronti et al. (2014) |
| Leave waste | 500°C | 9.0 | 60.7 | 1.1 | 55 | 0.207 | 1.084 | 5.455 | 0.361 | 0.103 | 70 | - | 1504 | 555 | - | Enders et al. (2012) |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Switchgrass | 500°C | 9.4 | 59.2 | 1.99 | 30 | 0.47 | 3.28 | 0.87 | 0.46 | 0.11 | 33.7 | 7.7 | 620 | 109 | | Streubel et al. (2011) |
| Grass waste | 500°C | 9.6 | 53.5 | 4.9 | 11 | 1.197 | 6.129 | 2.062 | 0.618 | 0.629 | 150 | - | 1557 | 360 | - | Enders et al. (2012) |
| Food waste | 400 °C | 8.27 | 52.4 | 3.65 | 14 | 0.5007 | 1.456 | 5.174 | 0.534 | 0.083 | 39 | - | 4431 | 179 | - | Enders et al., 2012 |
| Paper mill waste | 550°C | 8.2 | 50.5 | 0.31 | 104 | 0.009 | 0.029 | - | - | - | - | - | - | - | - | Van Zwieten et al. (2010) |
| Green waste | 450°C | 9.4 | 36 | 0.18 | 200 | 0.040 | 0.819 | 0.008 | 0.013 | | | | | | | Chan et al. (2007) |
| Paper mill sludge | 300 °C | - | 23.4 | 0.22 | 106.2 | - | - | - | - | 0.32 | - | - | - | - | - | Devi and Saroha (2015) |
| Paper mill sludge | 300°C | 7.8 | 21.2 | 0.3 | 71 | 0.083 | 0.278 | 25.81 | 0.243 | 0.031 | 26 | - | 4274 | 136 | - | |
| Paper mill sludge | 600°C | 11.5 | 19.2 | 0.1 | 192 | 0.094 | 0.385 | 31.12 | 0.294 | 0.031 | 51 | - | 6037 | 160 | - | |
| Waste water sludge | 550°C | 8.2 | - | 2.3 | | 0.110 | 0.009 | 0.66 | 0.043 | - | - | - | - | - | - | Hossain et al. (2010) |

*pH measured in 1 N KCl instead of water. ** pH measured in $CaCl_2$

**Table 2**

Soil pH and CEC as influenced by feedstock types, temperature and addition rates of biochar

| Feedstock | Temperature ($^{o}C$) | Application rate ($Mg\ ha^{-1}$) | Soil type | pH | | CEC ($cmol^{(+)}\ kg^{-1}$) | | References |
|---|---|---|---|---|---|---|---|---|
| | | | | Control | Treatment | Control | Treatment | |
| Greenwaste | 450 | 10 | Alfisol | 4.5 | 4.75 | | | Chan et al. (2007) |
| | | 50 | | | 5.38 | | | |
| | | 100 | | | 5.99 | | | |
| Poultry litter | 550 | 10 | Alfisol | 4.5 | 6.66 | | | Chan et al. (2008) |
| | | 25 | | | 7.29 | | | |
| | | 50 | | | 7.78 | | | |
| Sludge + wood chip | 550 | 10 | Ferrosol | 4.2 | 5.93 | 4.03 | 10.5 | van Zwieten at al. (2010) |
| | | | Calcarosol | 7.67 | 7.67 | 31.0 | 29.3 | |
| Wheat straw | 350-550 | 10 | Anthrosols | 5.6 | 5.70 | | | Cui et al. (2012) |
| | | 20 | | | 5.81 | | | |
| | | 40 | | | 5.86 | | | |
| Spruce + pine chips | 550-600 | 5 | Stagnosol | 6.6 | 6.7 | | | Tammeorg et al. (2014) |
| | | 10 | | | 6.7 | | | |
| Switch grass | 500 | 10-40 | Entisol | 7.2 | 7.9 | | | Streubel et al. (2011) |
| Wood bark | | 10-40 | | | 8.0 | | | |
| Digested fibre | | 10-40 | | | 8.0 | | | |
| Wood pellet | | 10-40 | | | 7.2 | | | |
| Sludge | 550 | 10 | | 4.0 | 4.86 | | | Khan et al. (2013) |
| | | 20 | | | 5.39 | | | |
| Hardwood | 500 | 22.4 | Haplocalcids | 7.7 | 7.7 | | | Lentz and Ippolito (2012) |
| Wood chip | 450 | 25 | Eutric Cambisol | 6.8 | 6.8 | | | Quilliam et al.(2013) |
| | | 50 | | | 6.8 | | | |
| Mix wood chips | 525 | 90 | Planosol | 5.3 | 6.9 | 75.1 | 101.1 | Kloss et al. (2014) |
| Wheat straw | | | | | 6.5 | | 94.0 | |
| Vineyard pruning | | | | | 6.6 | | 96.5 | |
| Canola straw | 350 | 4 | Acrisol | 3.99 | 4.7 | 9.1 | 11.4 | Yuan et al. (2011b) |
| Rice straw | | | | | 4.5 | | 10.7 | |
| Soybean straw | | | | | 5.2 | | 10.6 | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Pea straw | | | | | 5.0 | | 10.5 | |
| Wood chip | <550 | 72 | Chernozem | 7.4 | 7.4 | 201 | 208 | Karer et al. (2013) |
| | | | Cambisol | 6.3 | 6.7 | 187 | 214 | |
| Oak + Hickory | | 5 | Hapludolls | 6.4 | 6.4 | 17.1 | 19.8 | Laird et al. (2010b) |
| | | 10 | | | 6.9 | | 20.7 | |
| | | 20 | | | 7.1 | | 20.8 | |
| Cow manure | 500 | 10 | | 6.40 | 7.1 | 0.8 | 0.9 | Uzoma et al. (2011) |
| | | 15 | | | 7.34 | | 1.2 | |
| | | 20 | | | 8.0 | | 1.3 | |
| Poultry litter | 700 | 4 | | 5.9 | 9.7 | | | Novak et al. (2009) |
| Pecan shell | 700 | 4 | | | 7.5 | | | |
| Wheat Straw | 350-550 | 10 | Halpudept | 6.5 | 6.75 | | | Zhang et al. (2012) |
| | | 20 | | | 6.77 | | | |
| | | 40 | | | 6.77 | | | |
| Birch wood | 500 | 10 | Hapludalf | 6.6 | 6.7 | | | Sun et al. (2014) |
| | | 20 | | | 6.6 | | | |
| | | 50 | | | 6.8 | | | |
| Eucalyptus | 350 | 6 | Haplustox | 5.0 | 5.0 | 108.2 | 118.5 | Rondon et al. (2007) |
| | | 12 | | | 5.2 | | 131.7 | |
| | | 18 | | | 5.4 | | 131.5 | |

**Table 3**

Effect of biochar on nutrient contents and nitrogen transformations in soil at different pyrolysis temperatures

| Biochar | Pyrolysis temperature | Soil | Rate | Nitrogen* | | | | | | | P | K | Ca | Mg | S | Zn | Cu | Fe | Mn | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | TSN | AN | MN | IM | N/D | $NO_3^-$ | $NH_4^+$ | | | | | | | | | | |
| Maize | 350°C | Arable | - | ↑ | - | ↑ | - | ↑(N) | ↑ | ↓ | - | - | - | - | - | - | - | - | - | Nelissen et al. (2012) |
| | 550 °C | | - | ↑ | - | - | - | - | ↓ | ↑ | - | - | - | - | - | - | - | - | - | |
| Cotton stalks | 650 °C | Sandy loam | - | - | - | - | - | ↑(N) | - | ↑ | - | - | - | - | - | - | - | - | - | Song et al. (2013) |
| Corn stalk | 450 °C | Clayey Oxisol | - | - | - | ↑ | ↑ | - | - | - | | | | | ↑ | | | | | Blum et al. (2013) |
| Rye grass | 450 °C | Forest Cambisol | - | ↑ | - | ↑ | | ↑(N) | ↓ | ↓ | | | | | | | | | | Maestrini et al. (2014) |
| Poultry manure | 400 °C | Vertisol and Alfisol | | - | - | - | - | ↑ (D) | - | ↓ | - | - | - | - | - | - | - | - | - | Clough and Condon (2010) |
| Douglas fir wood | 410 °C | - | - | - | - | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | - | Pereira et al. (2015) |
| | 510 °C | - | - | - | - | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| Hog waste wood | 600 °C | - | - | - | - | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| | 700 °C | - | - | - | - | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | - | |
| *Loliumperenne* | 350°C | - | - | - | - | - | - | ↑ (N) | - | - | - | - | - | - | - | - | - | - | - | Rosa and Knicker (2011) |
| Oak wood | 200 °C | - | - | - | - | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | - | Zhang et al. (2015) |
| | 400 °C | - | - | - | - | ↑ | - | ↑ (N) | - | - | - | - | - | - | - | - | - | - | - | |
| | 600°C | - | - | - | | No effect | - | ↑ (D) | - | - | - | - | - | - | - | - | - | - | - | |
| Willow (*Salix viminalo*) | 470 °C | Flinty clay loam | - | - | - | - | ↑ | - | ↓ | ↓ | - | - | - | - | - | - | - | - | - | Prayogo et al. (2014) |
| Japanese larch wood (*Larixgmelinii*) | | | | - | - | - | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | Makoto et al. (2011) |

| | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Bamboo (*Bambusa* sp.) | 500ºC | | - | - | - | - | - | - | - | ↑ | - | - | - | - | - | - | - | - | - | Asada et al. (2002) |
| | 700ºC | - | - | - | - | - | - | - | - | ↓ | - | - | - | - | - | - | - | - | - | |
| Bamboo (*Bambusa*sp.) | 600 ºC | Sandy silt soils | - | - | - | - | - | - | - | ↓ | - | - | - | - | - | - | - | - | - | Ding et al. (2010) |
| Pine chips (*Pinus*sp.) wood | - | - | - | - | - | - | - | - | ↑ | ↓ | - | - | - | - | - | - | - | - | - | Bai et al. (2015) |
| Eucalyptus | 600 ºC | Acidic Grey OrthicTenosol | 5-25 Mg ha$^{-1}$ | - | - | ↓ | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | |
| Sugarcane bagasse | 400 ºC | - | - | - | ↓ | - | - | - | ↓ | - | - | - | - | - | - | - | - | - | - | Kameyama et al. (2012) |
| | 800 ºC | - | - | - | ↓ | - | - | - | ↓ | - | - | - | - | - | - | - | - | - | - | |
| Poultry litter and wheat straw | - | Acidic ferrasol and alkaline calcisol | 5 & 10 Mg ha$^{-1}$ | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | Macdonald et al. (2014) |
| Rice husk | - | Acidic Gleysols | 41 Mg ha$^{-1}$ | ↑ | - | - | - | - | - | - | ↑ | - | - | - | - | - | - | - | - | Haefele et al. (2011) |
| Lump biochar | - | Loamy soils | | ↑ | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | Laird et al. (2010a) |
| Maize stover and wheat straw | 400ºC | Sandy loam alluvial soil | - | - | ↑ | - | - | - | - | - | ↑ | ↑ | - | - | - | - | - | - | - | Purakayastha et al. (2015) |
| Charcoal | - | Base rich soils | - | - | - | - | - | - | ↑ | - | - | - | - | - | - | - | - | - | - | Borchard et al. (2014) |
| | | Extremely acidic soils | - | - | - | - | - | - | ↓ | - | - | - | - | - | - | - | - | - | - | |
| Chicken manure | - | - | - | - | ↑ | - | - | - | - | - | ↑ | ↑ | - | - | - | - | - | - | - | Chan and Xu (2009) |
| Peanut straw | 400 ºC | Oxisol | - | - | - | - | - | - | - | - | - | - | ↑ | ↑ | - | - | - | - | - | Jiang et al. (2015) |
| Rice straw | | | - | - | - | - | - | - | - | - | - | - | ↓ | ↓ | - | - | - | - | - | |
| Mixed hardwood | 500 ºC – 575 ºC | - | - | - | - | - | - | - | - | - | - | - | ↑ | ↑ | - | ↑ | ↑ | ↓ | ↓ | Rogovska et al. (2014) |

*TSN: total soil nitrogen; AN: available nitrogen; MN: mineralization; IM: immobilization; N: nitrification; and D: denitrification.

**Table 4**

Effect of biochar on crop yield

| Biochar feedstock | Application rate (t ha$^{-1}$) | Soil Type | Test crop | Yield increase/decrease* (%) | Country | Reference |
|---|---|---|---|---|---|---|
| | 30 | Acidic silty | Wheat | +28.2 | Italy | Vaccari et al. (2011) |
| | 60 | | | +28.6 | | |
| Poultry manure | 12 | Alkaline alluvial | Wheat | +38 | China | Lashari et al. (2013) |
| Wheat straw | 10 – 40 | Fine loamy Gleysols | Rice | Neutral | China | Huang et al. (2013) |
| Wheat straw 450 $^{o}$C | 1 | Acid Ferrasol | | +19 | Germany | Macdonald et al. (2014) |
| | 5 | | | +79 | | |
| | 10 | | | +51 | | |
| Wheat (*Triticum aestivum* L.) straw (1 yr + Pyrogallol) | 12 | | | +60 | | |
| Wheat straw, 350-500 $^{o}$C | 10 | | Rice | +28 | China | Zhang et al. (2012) |
| | 20 | | | +9 | | |
| | 40 | | | +22 | | |
| Biochar 450 $^{o}$C 1$^{st}$yr | 25 | Acidic sandy clay loam, Cambisol | Maize | Neutral | UK | Jones et al. (2012) |
| 2$^{nd}$yr | | | | Neutral | | |
| 3$^{rd}$yr | | | | +78 | | |
| Wood 300 $^{o}$C, 1$^{st}$yr | | Acidic Oxisol | Maize | +28 | Colombia | Major et al. (2010) |
| 2nd yr | | | | +30 | | |
| 3rd yr | | | | +140 | | |
| Birch wood (*Hordeumvulgare* L.) | 20 | Acidic sandy loam soil | Oat | Neutral | Denmark | Sun et al. (2014) |
| | | | Spring barley | +6 | | |
| | 50 | | Maize | -22-24 | | |
| Poultry litter 450 $^{o}$C | 1 | Acid Ferrasol | | +24 | Germany | Macdonald et al. (2014) |
| | 5 | | | +101 | | |
| | 10 | | | +144 | | |
| | 1 | Acidic Aeronosol | | Neutral | | |
| | 5 | | | Neutral | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | 10 | | | -21 | | |
| | 1, 5, 10 | Alkaline Calcisol | | Neutral | | |
| | | Neutral Vertisol | | Neutral | | |
| Domestic green waste biochar 550 $^{o}$C | 25 | | Wheat | +7.54 | Australia | Farrel et al. (2014) |
| Wheat straw, 400 $^{o}$C | 12 | Slightly alkaline sandy loam Inceptisol | Rice | Neutral | China | Xie et al. (2013) |
| Corn stover 400 $^{o}$C | 12 | Acidic clay loam Ultisol | | | | |
| Maize biochar 400 $^{o}$C | 20 | Alkaline sandy loam Inceptisol | Maize | +3.68 | India | Purakayastha (2010) |
| Rice biochar 400 $^{o}$C | 5 | Alkaline sandy loam Inceptisol | Rice | +24.3 | India | Bera (2014) |
| | 5 | Acidic sandy loam Alfisol | Rice | +31.3 | | |
| *Eucalyptus deglupta* 350 $^{o}$C | 90‡ | Neutral clay loam Oxisol | Bean | +46 | Colombia | Rondon et al. (2007) |
| | 60‡ | | Bean | +39 | | |

*Values of yield indicated by '+' and '-' represent yield increase and decrease, respectively.

‡Biochar application rate in g $kg^{-1}$ soil

**Table 5**

Eigenvalues, percentage of variation explained by the principal components, and Eigenvectors of Principal Component Analysis (PCA)

| **Eigenvalues and percentage of variations** | | | | | | |
|---|---|---|---|---|---|---|
| Principal component | Soil chemical properties | | | Crop yields | | |
| | Eigenvalue | % variance | % variance (cumulative) | Eigenvalue | % variance | % variance (cumulative) |
| 1 | 1.57 | 39.3 | 39.3 | 1.38 | 45.9 | 45.9 |
| 2 | 1.40 | 35.0 | 74.3 | 0.93 | 30.9 | 76.8 |
| 3 | 0.62 | 15.5 | 89.8 | 0.70 | 23.2 | 100 |
| 4 | 0.41 | 10.2 | 100 | - | - | - |

| **Eigenvectors** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Principal component | Soil chemical properties | | | | Crop yields | | |
| | Temp | AppRate | d_pH | d_CEC | Temp | AppRate | Yield |
| 1 | 0.27 | 0.64 | 0.43 | 0.58 | -0.67 | 0.48 | 0.57 |
| 2 | 0.67 | -0.25 | 0.54 | -0.43 | 0.06 | 0.79 | -0.61 |
| 3 | 0.51 | 0.48 | -0.65 | -0.29 | 0.74 | 0.37 | 0.56 |
| 4 | 0.46 | -0.54 | -0.32 | 0.63 | - | - | - |