

1 **Biochar and its Importance on Nutrient Dynamics in Soil and Plant: A Review**

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54 **Highlights**

- 55 • Biochar's role as a potential source of plant macro- and micro-nutrients reviewed.
- 56 • Biochar increases plant nutrient availability in soils.
- 57 • Biochar influences soil physical, chemical and biological properties.
- 58 • Biochar enhances nutrient use efficiency and uptake by plants by decreasing nutrient loss.

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84 **Abstract**

85 Biochar, an environmentally friendly soil conditioner, is produced using several thermochemical processes. It has
86 unique characteristics like high surface area, porosity, and surface charges. This paper reviews the fertilizer value
87 of biochar, and its effects on soil properties, and nutrient use efficiency of crops. Biochar serves as an important
88 source of plant nutrients, especially nitrogen in biochar produced from manures and wastes at low temperature (\leq
89 $400\text{ }^{\circ}\text{C}$). The phosphorus, potassium, and other nutrient contents are higher in manure/waste biochars than those
90 in crop residues and woody biochars. The nutrient contents and pH of biochar are positively correlated with
91 pyrolysis temperature, except for nitrogen content. Biochar improves the nutrient retention capacity of soil, which
92 depends on porosity and surface charge of biochar. Biochar increases nitrogen retention in soil by reducing
93 leaching and gaseous loss, and also increases phosphorus availability by decreasing the leaching process in soil.
94 However, for potassium and other nutrients, biochar shows inconsistent (positive and negative) impacts on soil.
95 After addition of biochar, porosity, aggregate stability, and amount of water held in soil increase and bulk density
96 decreases. Mostly, biochar increases soil pH and, thus, influences nutrient availability for plants. Biochar also
97 alters soil biological properties by increasing microbial populations, enzyme activity, soil respiration, and
98 microbial biomass. Finally, nutrient use efficiency and nutrient uptake improve with application of biochar to soil.
99 Thus, biochar can be a potential nutrient reservoir for plants and a good amendment to improve soil properties.

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102 **Keywords:** Biochar, Nutrients, Manure, Soil properties, Nutrient use efficiency

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114 **1. Introduction**

115 In recent decades, application of biochar to soil has drawn attention from the scientific community. Research has
116 focused on its cost-effectiveness and environmentally friendly features, such as enhancing carbon sequestration
117 and remediating contaminated soil. Biochar can influence nutrients in soil in several ways: (i) as a source of
118 nutrients for plants and soil microorganisms (Li et al. 2017b); (ii) as a nutrient sink, thereby impacting the mobility
119 and bioavailability of nutrients (Gul and Whalen 2016); and (iii) as a soil conditioner, thereby altering soil
120 properties that influence the reactions and cycling of nutrients in the soil (Lusiba et al. 2017). As a source, biochar
121 can supply nutrients such as nitrogen (N), phosphorus (P), potassium (K), and other trace elements inherently
122 present in the original feedstock used for biochar production (Purakayastha et al. 2019). While some nitrogen and
123 sulfur in the feedstock materials are lost through gaseous emission during pyrolysis (Al-Wabel et al. 2013; Leng
124 et al. 2020), most nutrients are released during the weathering of biochar in soil, and they become available for
125 plant uptake (Zhao et al. 2018). The nutrient content of biochar depends on the nature of the feedstock materials
126 and the pyrolytic conditions. Biochars derived from manure- and biosolid-based feedstock materials generally
127 contain higher levels of N and P than those derived from wood- and straw-based feedstock materials (El-Naggar
128 et al. 2019a; Purakayastha et al. 2019). While the N content decreases with increasing pyrolytic temperature
129 through gaseous emission (Leng et al. 2020), the P and K contents increase due to an increase in ash content
130 (Christel et al. 2016; Tomczyk et al. 2020; Wang et al. 2013). As a nutrient sink, biochar can retain nutrients,
131 thereby reducing their losses through leaching and gaseous emission. The nutrient retention capacity of biochar
132 depends on its porosity and surface charge (cation and anion exchange capacity) (Yu et al. 2018). Biochar
133 application reduces the loss of N, P, and K through leaching, and N through nitrous oxide emission (Beusch et al.
134 2019; Yao et al. 2012; Yuan et al. 2016). However, the loss of N through ammonia emission depends mainly on
135 the pH of the biochar; biochar with a slightly acidic or near-neutral pH reduce ammonia volatilization from soil
136 (Mandal et al. 2019; Mandal et al. 2018).

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138 Biochar application influences various soil properties including pH, bulk density, cation exchange capacity, water
139 retention, and biological activity. These changes in soil properties are likely to impact nutrient reactions on soil
140 particles and microbial transformation of nutrients (Mandal et al. 2018). Upon application to the soil, biochar
141 improves soil fertility and crop productivity by increasing the soil nutrient contents and the mobility of nutrients.
142 It enhances microbial activity (Meier et al. 2019), improves aeration, and water retention (Kambo and Dutta 2015;
143 Razzaghi et al. 2020), buffers soil reactions (Laghari et al. 2016), reduces bulk density (Yan et al. 2019a), and

144 maintains soil aggregate structure (Zhang et al. 2020). Moreover, biochar reduces nutrient leaching and loss of
145 nutrients by volatilization through altering the soil pH and by enhancing the ion exchange capacity (DeLuca et al.
146 2015). Biochar can change the soil microbial community composition (Ducey et al. 2013), and thus it impacts
147 nutrient cycling and uptake by plants (Lehmann et al. 2011). Biochar decreases nitrification in soil resulting in
148 reduced nitrate leaching (Igalavithana et al. 2016). Fig. 1 shows a conceptual framework depicting various impacts
149 of biochar on soil and plants.

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151 Many reviews have been published about the importance of biochar for soil health, crop production, and problem
152 soils (Agegnehu et al. 2017; Al-Wabel et al. 2018; Dai et al. 2017; Ding et al. 2017; Ding et al. 2016; El-Naggar
153 et al. 2019b; Juriga and Šimanský 2018; Laghari et al. 2016; Lone et al. 2015; Muhammad et al. 2018; Munoz et
154 al. 2016; Palansooriya et al. 2019; Shaaban et al. 2018; Yu et al. 2019), soil carbon sequestration (Sarfraz et al.
155 2019), availability of N, P, and K (Liu et al. 2019a), and decreasing drought and salinity stress in plants (Ali et al.
156 2017). Reviews and meta-analyses also have been published focussing on soil N dynamics such as available N
157 (Nguyen et al. 2017b), leaching and gaseous emissions of N (Borchard et al. 2019; Cai and Akiyama 2017), and
158 the overall soil-N cycle (Liu et al. 2018). However, there is no review concerning the ability of biochar to retain
159 multiple nutrients in soil through reducing gaseous and leaching losses and, thus, enhance plant growth. This
160 paper focusses on: (i) effect of biochar on soil properties, (ii) biochar as a nutrient source, and (iii) impact of
161 biochar on nutrient reactions in soil and uptake by plants.

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163 **2. Production and characteristics of biochar**

164 The term *char* means output from disintegration of organic and inorganic materials. Biochar and charcoal have
165 been synonymously used but can be differentiated by their use, because charcoal is used for energy, whereas
166 biochar is considered for carbon sequestration and environmental applications. Biochar is also called as
167 ‘pyrochar,’ because it is produced by the pyrolysis of biomass (Ralebitso-Senior and Orr 2016). The typical
168 definition of biochar, as stated by the International Biochar Initiative (IBI), is ‘a solid material obtained from the
169 thermochemical conversion of biomass in an oxygen-limited environment’ (IBI 2015). The production and soil
170 application of biochar are related to the ‘*terra-preta*’ (black earth) soils of Amazon region, which are important
171 because of their high productivity. After the characterization of these soils, the scientific community recognized
172 that biochar has properties similar to the *terra-preta* soils. Thereafter, much work was done related to biochar and
173 its application in the soil. Generally, biochar is produced from a range of biomasses (e.g., manure, wood, crop,

174 and industrial residues) at temperatures less than 900 °C and under oxygen-limited pyrolytic conditions (Zhang
175 et al. 2019e). However, recent studies have shown that biochar can also be produced by other thermochemical
176 processes, e.g., hydrothermal carbonization, gasification, torrefaction, and microwave-assisted pyrolysis (Kambo
177 and Dutta 2015; Vithanage et al. 2017; Yuan et al. 2017).

178

179 The characteristics of biochar are influenced by the feedstock and heating conditions (Joseph and Taylor 2014;
180 Laghari et al. 2016; Li et al. 2017b; Ralebitso-Senior and Orr 2016; Yuan et al. 2017). The physical and chemical
181 properties also depend on other factors such as heating rate, kiln pressure, the composition of the atmosphere (N
182 or CO₂ atmosphere in the kiln), and the type of pre- or post-treatment of biochar (Joseph and Taylor 2014). The
183 important properties of biochar are presented in Fig. 2. Based on the ash composition and its properties, biochar
184 can be divided into the following three main groups (Joseph and Taylor 2014).

185 i) Biochar produced from biomass with minimum ash content (<3–5%), such as wood, nut shells,
186 bamboo, and some seeds (e.g., apricots). These hard biochars have large porosity, surface area (SA),
187 and hold more water than biochars in other groups.

188 ii) Biochar produced from biomasses containing medium ash content between 5 to 13%, which include
189 most agricultural wastes, bark, and high-quality green waste (i.e., with low contamination of plastics,
190 soil, and metals).

191 iii) Biochar produced from biomasses with high ash contents (>13%), such as manures, sludges,
192 wastepaper, municipal waste, and rice husks.

193

194 The physical characteristics of biochar, especially the surface area and pore size/volume/distribution, are
195 controlled by the pyrolytic conditions and the nature of feedstock. For example, under high-temperature pyrolytic
196 conditions (>550° C), biochar is characterised by having a large surface area and a high aromaticity (Ralebitso-
197 Senior and Orr 2016). However, at pyrolysis under low temperatures (200–400°C), biochar is characterised by
198 having more oxygen-containing functional groups, such as –COOH, –OH, C=O, phenolic –OH and –CHO groups,
199 which stimulate nutrient exchange and, thus, improve soil fertility (Mandal et al. 2020; Ralebitso-Senior and Orr
200 2016). The characteristics of biochar are important for its uses. For example, biochar with a low surface area is
201 less suitable for soil health improvement than that with a high surface area.

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204 **3. Effect of biochar on soil properties**

205 The changes in soil properties resulting from biochar application are likely to impact nutrient reactions and
206 microbial transformation of nutrients. Fig. 3 summarizes these processes.

207

208 **3.1 Physical properties**

209 Owing to special characters (such as high surface area and porosity), biochar application influences soil physical
210 properties (Fu et al. 2019; Greenberg et al. 2019; Horák et al. 2019; Oladele 2019; Zhang et al. 2020). The effect
211 of biochar on various soil physical properties that are likely to impact nutrient interactions in soil are summarized
212 in Table 1. For example, in a 4-year field study, peanut-shell biochar altered soil properties by increasing water-
213 stable aggregates (WSA) (Du et al. 2018), and rice straw biochar increased aggregate stability from 1 to 17%
214 (Peng et al. 2011). In addition, biochar rate is positively correlated with WSA. For instance, Oladele (2019)
215 reported that addition of rice husk biochar increased WSA at various soil depths over three years. The author
216 found that with 3, 6, and 12 t ha⁻¹ of biochar application, WSA increased by 10, 18, and 23%, respectively, at the
217 0-10 cm depth, and by 16, 20, and 26%, respectively, at the 10–20 cm soil depth compared to no biochar
218 application in the first year. After three years, WSA increased by 22 and 24% at the 0–10 and 10–20 cm depths,
219 respectively. Moreover, the application of rice husk biochar (10 t ha⁻¹) increased soil porosity by decreasing bulk
220 density and increased available water in a sandy clay loam soil (Laghari et al. 2016). Li et al. (2018) said that
221 maize straw biochar reduced soil bulk density and improved soil porosity in a semi-arid region. In a pot study,
222 Prapagdee and Tawinteung (2017) concluded that cassava stem biochar increased soil porosity, which was in line
223 with Fu et al. (2019) who found in a field trial that biochar dose was positively correlated with soil porosity. Li et
224 al. (2018) conducted a study on the impact of maize straw biochar on soil properties in a tomato field in a semi-
225 arid region of China. The authors found that application of biochar at 10, 20, 40, and 60 t ha⁻¹ increased the soil
226 porosity from 42.5% to 48, 50, 55, and 56%, respectively, and reduced the bulk density of a sandy loam soil. The
227 application of biochar reduces bulk density of soil regardless of soil types, study environments, biochar application
228 rate, or production conditions (Table 1).

229

230 Addition of biochar has been shown to increase the ability of soil to hold water (Yadav et al. 2018). Razzaghi et
231 al. (2020) did a meta-analysis on the effect of biochar on soil water retention and found that the ability of soil to
232 hold water increased, especially in coarse-textured soils, Peake et al. (2014) reported that biochar had a positive
233 impact on the ability of loamy sand and sandy loam soils to hold water. The ability of soil to hold water has

234 increased with increasing biochar application rates (Greenberg et al. 2019; Oladele 2019). Biochar reduced the
235 tensile strength and cracks of a surface soil (Mandal et al. 2020), and suppressed soil shrinkage by increasing the
236 ability of the soil to hold water; thus, soil structure was improved (Fu et al. 2019). Nair et al. (2017) observed that
237 biochar improved soil water retention, reduced bulk density, and stabilized soil organic matter. Additionally, it
238 was confirmed that there were hydrophilic functional groups on the surface and pores of biochar with a high
239 affinity for water; biochar application was shown to increase soil water retention more in a sandy soil than a loamy
240 soil or a clay soil (Mandal et al. 2020). Biochar also showed a positive impact on surface area of soil (Anawar et
241 al. 2015), which varied with biochar types (Tomczyk et al. 2020). For example, biochar (10%) amended soil had
242 3 times higher surface area than untreated soil (Tomczyk et al. 2019). Therefore, irrespective of soil types,
243 experimental conditions, biochar types, pyrolytic temperatures, and application rates, biochar has positive impacts
244 on soil physical properties. Moreover, the above discussion shows that the soil physical properties are interlinked
245 and influence each other.

246

247 **3.2 Chemical properties**

248 Biochar application has been shown to impact soil chemical properties such as pH, electrical conductivity (EC),
249 and cation exchange capacity (CEC). These soil chemical properties influence nutrient interactions in soil. The
250 impacts of biochar on selected chemical properties of soils are summarised in Table 2. Soil pH can be altered by
251 incorporation of biochar into soil, thereby contributing to alterations in nutrient availability. The pH of biochar is
252 an important character for its use in agriculture as a soil conditioner. Biochar pH is dependent on the rate of the
253 carbonization process, pyrolytic temperature, and feedstock type (Weber and Quicker 2018). Biochar also
254 generates organic acids during pyrolysis of biomasses that influence the pH of the final product (Cheng et al.
255 2018). Biochars generally have a pH range of 6.52–12.64 (Table 4), and the pH values positively correlate with
256 the pyrolytic temperature (Fig. 4). Biochar has an alkaline nature due to the presence of alkali and alkaline metals
257 in feedstocks that are not volatilized during pyrolysis (Yang et al. 2018). Application of alkaline biochar tends to
258 increase the pH of acidic and neutral soils (Buss et al. 2016). The alkalinity of biochar depends on three important
259 factors: a) organic functional groups; b) carbonate content, and c) inorganic alkali content (Lee et al. 2013). The
260 concentration of base cations in biochar is strongly correlated with biochar alkalinity, which is not a simple
261 function of biochar's soluble ash content (Fidel et al. 2017). Alkaline biochar can be used as a liming material for
262 neutralizing acid soils (Taskin et al. 2019). However, the soil liming potential of biochar is not consistent across
263 soil and biochar types. For example, application of biochar (at 1% and 2% rate) generated from various types of

264 crop straws (pH value of biochar ranging from 7.69–10.26) in a three-month incubation study decreased the pH
265 of an acidic Ultisol (pH = 4.31) over time (Laghari et al. 2016). However, in a field study, application of a paddy
266 straw-derived biochar (biochar pH was 10.50) to a sandy soil (soil pH = 5.24) increased the pH of the soil by 4.5
267 units compared to the control (El-Naggar et al. 2018b). Moreover, a high dose (50 and 100 t ha⁻¹) of biochar (pH
268 = 9.40) increased the pH of an Alfisol and, consequently, reduced exchangeable Al concentration in the soil
269 (Tomczyk et al. 2020). Li et al. (2018) observed that application of biochar (10, 20, 40, and 60 t ha⁻¹) had no
270 impact on soil pH in a semi-arid region, which was consistent with the results reported by Werner et al. (2018)
271 who found that the pH of a sandy loam soil was not changed with addition of biochar. Therefore, biochar
272 application to soil could either increase or decrease soil pH based upon the original soil properties (e.g., pH,
273 texture) and biochar pH and alkalinity, as well as the species of crop grown in the biochar-amended soil (Table
274 2).

275

276 Most biochars contain high amounts of soluble salts, and, hence, the EC of biochar is generally higher than most
277 agricultural soils (Igalavithana et al. 2018). Availability of soluble nutrient ions such as NO³⁻, K⁺, and Ca²⁺ could
278 be directly related to the soluble salt content and, hence, the EC of biochar when applied to soil. Excess salts or
279 high EC in soil is harmful for plants, because of a decrease in osmotic potential. Therefore, the EC of the soil must
280 be maintained low for desirable nutrient availability and plant growth. Nevertheless, the EC of soil was reported
281 to increase with increasing application rates of biochar (Li et al. (2018). Prapagdee and Tawinteung (2017) found
282 that the EC of soil increased when cassava stem-derived biochar was applied at a rate of 10% (w/w). In a sandy
283 soil (EC = 0.07 dS m⁻¹), the EC was increased by 385, 100, and 71% with the addition of paddy straw, silver grass
284 residue, and umbrella tree residue biochar (30 t ha⁻¹), respectively (El-Naggar et al. 2018b). However, rice husk
285 biochar (EC = 2.56 dS m⁻¹) had no impact on increasing the EC in the soil (Jatav et al. 2018).

286

287 The CEC of most biochars is higher than that of typical agricultural soils (Sohi et al. 2009; Sohi et al. 2010). The
288 CEC of biochar is attributed to the generation of various functional groups, such as carboxyl and hydroxyl groups,
289 during the pyrolysis of biomass (Tomczyk et al. 2020). Biochar CEC is governed by two important factors: (a)
290 surface oxidation, and (b) adsorption of highly oxidized organic matter onto the biochar surface (Tomczyk et al.
291 2020). Like pH, CEC of soil can also be altered by biochar application. For instance, in a short-term (11 d)
292 incubation study using an Ultisol, the addition of rice straw-derived biochar at 2.4 t ha⁻¹ increased the CEC of soil
293 (Peng et al. 2011). In another study, El-Naggar et al. (2018b) showed that the CEC of a sandy soil (CEC = 0.5

294 cmol kg⁻¹) increased by 3.00, 1.00, and 0.75 cmol kg⁻¹ with the application of biochars (at 30 t ha⁻¹ rate) derived
295 from paddy straw, silvergrass residue, and umbrella tree residue, respectively. However, in a sandy loam soil
296 (initial CEC = 10 cmol kg⁻¹), the paddy straw-biochar (at 30 t ha⁻¹ rate) increased the CEC by 1.0 cmol kg⁻¹ only.
297 In another study, biochar derived from wood was found to increase the CEC by as much as 190% in an Anthrosol
298 (initial CEC = 2.81 cmol kg⁻¹) compared to the control treatment (Tomczyk et al. 2020). Therefore, various types
299 of biochars produced from various feedstocks change the CEC of soils to a different extent (Table 2), and the CEC
300 affects nutrient availability and water retention of soil (Yadav et al. 2018). Moreover, biochar is known to increase
301 the organic carbon content in soil (Table 2) and stimulate C sequestration by suppressing the long-term turnover
302 of soil organic matter (Schofield et al. 2019). The increased organic carbon content, together with improved
303 chemical properties due to biochar application, positively affect the nutrient status in soil.

304

305 **3.3 Biological properties**

306 Effects of biochar on various soil biological properties, such as soil respiration, microbial biomass carbon,
307 microbial activity and functions, and soil enzymatic activity, are presented in Table 3. Owing to its porous system,
308 biochar can be a favourable habitat for soil microorganisms including bacteria, mycorrhizal fungi, and
309 actinomycetes (Compant et al. 2010; Prapagdee and Tawinteung 2017). Du et al. (2018) found that peanut-shell
310 biochar (1%) increased microbial populations, microbial biomass, and actinomycetes. However, Wang et al.
311 (2020) reported that a high dose of biochar could show a negative impact and a low dose could have a positive
312 impact on soil microbial communities. The authors suggested that such variation of biochar's effects was due to
313 the toxic effect (chemical stress) of biochar on soil microorganisms when applied at a high rate. However, in
314 numerous studies biochar application exhibited positive effects on soil microbial activities. For example, in a
315 coastal wetland soil, biochar application boosted the soil microbial biomass C and resulted in a low metabolic
316 quotient (Zheng et al. 2018). Zheng et al. (2018) also found a shift of the bacterial community towards low C
317 turnover bacterial taxa (e.g., Actinobacteria and Deltaproteobacteria), which stabilised soil aggregates. In another
318 study over 90 d by growing tobacco plants with biochar application, Cheng et al. (2017) reported that, as the result
319 of biochar application to soil with tobacco, the average populations of Sphingomonadaceae and
320 Pseudomonadaceae bacteria were increased by 18 and 63%, respectively. In the same study, when tobacco plants
321 were not grown, populations of the two bacterial groups in the soil were increased by 46 and 110%, respectively.
322 Moreover, biochar was reported to increase microbial biomass N by 12% (Liu et al. 2018). The effects of biochar
323 on soil microbial community structure and N-cycling bacteria depends on several factors, such as soil type, C/N

324 ratio, nutrients, pH, and biochar addition rates (Abujabhah et al. 2018). Biochar application increased biological
325 N fixation by 63% (Lu et al. 2018). Schofield et al. (2019) tested horticultural green waste biochar to retain N in
326 a sandy loam soil. They found that biochar increased the microbial activity by 73, 84, 214% when applied at rates
327 of 2, 5 and 10%, respectively.

328

329 Biochar showed positive impacts on soil enzymatic activities (Mierzwa-Hersztek et al. 2016; Ouyang et al. 2014).
330 For instance, addition of biochar (5 and 10 t ha⁻¹) in an Inceptisol increased the dehydrogenase and urease activity
331 by 19 and 44%, respectively (Ameloot et al. 2013; Mierzwa-Hersztek et al. 2016). Similarly, a greenhouse study
332 concluded that biochar improved soil enzymatic properties with the application rate up to 6% (Yadav et al. 2018).
333 Biochar also increased P-solubilizing bacterial populations such as *Burkholderia-Paraburkholderia*,
334 *Planctomyces*, *Sphingomonas*, and *Singulisphaera*, which contributed to improving P availability in a forest soil
335 (mountain acidic red loam soil) (Zhou et al. 2020). However, Haefele et al. (2011) found a negative effect on
336 earthworm populations with the addition of rice residue biochar (41.3 Mg ha⁻¹). Similarly, Weyers and Spokas
337 (2011) observed a negative effect (short-term) or no effect (long-term) of poultry litter biochar on earthworm
338 activity in soil, which was attributed to a rapid pH change or high ammonia concentration in the soil due to the
339 addition of the biochar (Liesch 2010). Earthworms are highly sensitive to soil pH and ammonia concentration
340 (Saleh et al. 1970).

341

342 **4. Biochar as a source of nutrients**

343 Biochar can be a nutrient source for crop plants. The nutrient content of biochar depends mainly on the nature of
344 the feedstock materials and the pyrolytic conditions (pyrolytic temperature, residence time, gaseous environment)
345 (El-Naggar et al. 2019a). Feedstock materials containing high nutrient contents result in nutrient-enriched
346 biochars. For example, manure and sewage sludge produce nutrient-rich biochars (Table 4).

347

348 **4.1 Primary nutrients**

349 **4.1.1 Nitrogen**

350 Nitrogen is one of the most limiting nutrients in soils for plant growth and productivity due to high crop demand
351 for it and to chances of losses by leaching, runoff, and volatilization (Nguyen et al. 2017b). A continuous
352 application of N in available forms is essential for many agricultural soils to maintain production in cropping
353 seasons (Fageria and Baligar 2005). Biochar can be a potential source of N for plants. In addition to organic forms

354 of N (e.g., hydrolyzable-N, water-soluble-N, and nonhydrolyzable-N), biochar also contains inorganic N forms
355 such as NH_4^+ -N, NO_3^- -N, and N_2O -N (Liu et al. (2019a). Although N content is low in most biomasses, the N
356 content is mostly increased after pyrolysis due to reducing the mass (mainly the moisture) of the biomass. In the
357 case of N, there could be some losses also during the pyrolysis of biomass due to gaseous emissions of the element.
358 Hence not all forms of N present in the feedstock can be found in the biochar. For example, some amino acids,
359 such as arginine containing amide groups, are mostly converted to ammonia or other gaseous forms of N during
360 biomass pyrolysis, and, consequently, they are lost (Leng et al. 2020). Nitrogen conversion pathways from
361 feedstock-N to biochar-N through the process of pyrolysis are presented in Fig. 4. The existence of metal elements
362 in feedstock can influence the conversion of N-containing compounds and, thus, the amount and forms of N
363 species in final biochar products (Xiao et al. 2018). Table 4 shows that the N content of biochar can be of a wide
364 range (0.24 to 6.8 %). Although, most biochars have low N content (below 1.5 %) (Table 4), the N content is high
365 in a few biochars such as those derived from sewage sludge (6.8%), poultry litter (5.85%), grass waste (4.9%),
366 and microalgae (14.12%) (Chang et al. 2015). Biochar produced from sewage sludge (at 350 °C) had more N
367 (3.17%) than that produced from sugarcane and eucalyptus wastes (1.4 and 0.4%, respectively) (Figueredo et al.
368 2017). Furthermore, N content of biochar decreases with an increase in the pyrolytic temperature (Fig. 5), due to
369 conversion of parts of amino acids into pyridine-N and pyrrolic-N (Leng et al. 2020). Ultimately, the loss of NH_4^+ -
370 N as NH_3 occurs through volatilization during pyrolysis (El-Naggar et al. 2019a). For instance, N contents of
371 chicken manure biochar were found to be 2.79, 2.45, and 1.81% when the material was produced at 250, 350 and
372 550 °C, respectively (Xiao et al. 2018). Similarly, N content of maize-straw biochar decreased from 1.25% (300
373 °C) to 1.20% (500 °C) (Song et al. 2018), and that of elephant-grass biochar decreased from 3.87% (400 °C) to
374 2.15% (600 °C) (Ferreira et al. 2018), due to a rise of the pyrolytic temperature. Acidified biochar (pre-pyrolysis)
375 decreased the total N content, which was attributed to volatilization loss of N during pyrolysis (Sahin et al. 2017).
376 However, salt impregnated (chicken manure with CaCl_2 and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) biochar slightly increased the total and
377 available NH_4^+ -N contents when pyrolyzed at a low temperature (250°C), but at 350 and 550°C, the NH_4^+ -N
378 content decreased (Xiao et al. 2018). Xiao et al. (2018) found 0.48, 0.30, and 0.17 g kg^{-1} available NH_4^+ -N (KCl
379 extractable) in chicken manure biochar following pre-pyrolysis impregnation of the biomass with CaCl_2 ,
380 $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ mineral salts, respectively. Chang et al. (2015) found that N content in a *Chlorella*-
381 based algal residue biochar increased from 10.23 to 14.12% when the residence time of pyrolysis was increased
382 from 20–60 min at 500 °C. However, the effect of rising pyrolytic temperature ranging from 300 to 700 °C on the
383 N content of algal biochar was not consistent (Chang et al. 2015). The N-containing components of biochar can

384 be present on the biochar surfaces and/or inside the pores as nitrates, ammonium salts, or heterocyclic compounds
385 (Grierson et al. 2011). These N components of algal biochar were much higher than other common biochars such
386 as manure and biosolid/sewage sludge derived biochars. Among the inorganic forms of N, NO_3^- -N and N_2O -N
387 were increased at a high temperature (800 °C) for pyrolysis, NH_4^+ -N and NO_3^- -N were decreased drastically at
388 300 °C, and all inorganic N remained stable at 600 °C (Zhu et al. 2016). Therefore, when producing N-enriched
389 biochar, special care should be taken to decide the pyrolytic temperature and feedstock type.

390

391 **4.1.2 Phosphorus**

392 Like the N content in different biochars, the P content varies over a wide range (0.005–5.9 %) (Table 4). While
393 the N content decreases with pyrolytic temperature, the P content is positively correlated with the pyrolytic
394 temperature (Fig. 5). The increased P content in biochar with increasing pyrolytic temperature can be attributed
395 to the ‘concentration effect’ resulting from decreased biochar yield with increasing temperature. For example,
396 Xiao et al. (2018) produced biochar from chicken manure at 250, 350, and 550 °C and found corresponding P
397 contents of 1.91, 2.15 and 2.96%, respectively (Table 4). Moreover, the P content also depends on the type of
398 biomass. For instance, P contents in biochar derived from swine solid (5.9%) (Cantrell et al. 2012), chicken
399 manure (2.96%) (Xiao et al. 2018), and poultry litter (2.57%) (Brantley et al. 2016) were greater than those derived
400 from rice husks (0.15%) (Bu et al. 2017) and apple branches (0.18%) (Li and Shangguan 2018). Thus, feedstock
401 selection is an important aspect for producing P-enriched biochar. In addition, the P content of chicken manure
402 biochar increased from 1.91 to 2.96% by increasing the pyrolytic temperature from 250 to 550 °C (Table 4).
403 Biochar with a high ash content contained a high P content (Laghari et al. (2016). In a review on the mineral
404 contents of biochar, Xu et al. (2017) stated that biochar from sewage sludge and poultry litter had higher P contents
405 than biochar from crop residues, animal manures, and woody biochar. They also found that available P (i.e., Olsen-
406 P) in biochar increased from 280 to 676 mg kg^{-1} when the pyrolytic temperature increased from 300 to 600 °C.
407 Li et al. (2020) found that Olsen-P increased in both pristine and P-laden biochar by 43 and 15%, respectively,
408 when the pyrolytic temperature increased from 350 to 600 °C. The authors also observed that the amount of Olsen-
409 P increased in KH_2PO_4 biochars with increase in temperature. In addition, Xiao et al. (2018) found that water-
410 extractable P was negatively correlated with the pyrolytic temperature for both pristine and modified biochars,
411 while the Olsen-P was positively correlated with increasing temperature. The authors also observed that the Olsen-
412 P decreased when pre-treatment of chicken manure was conducted with different types of salts, because of the
413 formation of insoluble phosphate compounds such as $(\text{CaMg})_3(\text{PO}_4)_2$ and $\text{Fe}_4(\text{PO}_4)_2\text{O}$. Zhang et al. (2019d) found

414 that Olsen-P and water soluble-P contents were 775.45 and 495.21 mg kg⁻¹, respectively, in an acidified biochar
415 (700 °C) derived from maize straw.

416

417 **4.1.3 Potassium**

418 The K content in biochar also varies both with the feedstock type and temperature of pyrolysis (Table 4). For
419 example, poultry litter, chicken manure, rice straw, and bamboo biochar contained more K than biochars made
420 from rice husks, corn stalks, and apple branches. As in the case of P, K content of biochar also increases with
421 increasing pyrolytic temperature (Fig. 5), which can be attributed to the ‘concentration effect’. Xiao et al. (2018)
422 found that the K content in chicken manure biochar was increased from 4.16–5.93% when the pyrolytic
423 temperature was increased from 250 to 550 °C (Table 4). Poultry litter-derived biochar contained 3.88 and 5.88%
424 K at pyrolytic temperatures of 400 and 600 °C, respectively (Subedi et al. 2016). Similarly, Vaughn et al. (2018)
425 produced biosolid-biochar at 300, 400, 500, 700, and 900 °C, and the K contents were 3.89, 3.98, 4.06, 4.02, 8.12,
426 and 9.83%, respectively. Karim et al. (2017) evaluated the K-enrichment of banana peduncle biochar produced in
427 the presence of different gases (Ar and O₂) and plasma with processing times of 3, 5, 7, and 9 min. They found
428 that plasma processing for up to 7 min enriched the biochar with K in both Ar and O₂ environments. For instance,
429 due to Ar gas loading for 7 min, K increased from 8.6 to 28.6% for available K, 3.5 to 11.2% for water soluble K,
430 and 5.1 to 14.7% for exchangeable K. Amin (2016) reported that soluble-K content was 6.05 g kg⁻¹ in corn cob
431 biochar, and Nguyen et al. (2020) found 8.50 g kg⁻¹ exchangeable K in rice husk biochar.

432

433 **4.2 Secondary nutrients**

434 As shown in Table 4, contents of secondary nutrients including S, Ca, and Mg are high in animal manure biochar,
435 as reported by Xiao et al. (2018) and Brantley et al. (2016). The Ca contents of animal-manure biochar ranged
436 from 0.40 to 6.15% and that of industrial and municipal waste-derived biochar ranged from 0.37–6.57% (Table
437 4). Biochar derived from crop residues had concentrations of Ca ranging from 0.20–1.57% and that of woody
438 biochar was in the range of 0.05–2.42% (Table 4). However, biochar produced from apple branches had a higher
439 Ca content (2.42%) (Li and Shangguan 2018) than other feedstocks such as barley straw (0.20%) (Jatav et al.
440 2018), sugar maple sawdust (0.50%) (Noyce et al. 2017), and acacia (0.27%) (Arif et al. 2016). The Mg contents
441 of biochar produced at 250-750 °C from various types of biomasses (e.g., animal manure, woody biomass, crop
442 residue) ranged from 0.001–3.78% (Table 4). Most of the animal-manure derived biochars and grass waste biochar
443 contained higher Mg contents than crop-residue biochar and woody biochar (Table 4). Generally, the S content

444 was lowest (0.001–0.32%) in biochar produced from woody biomass followed by waste-derived biochar (0.005–
445 0.63%) and crop residue-derived biochar (0.07–0.32%) (Table 4). Animal manure biochar contained more S
446 (0.02–1.36%) than orchard-pruning-biomass-derived biochar (0.005%) (Table 4). The effects of pyrolytic
447 temperature on the S content of biochars are inconsistent (Table 4), because high temperatures can either increase
448 S content by the incorporation of S into complex structures or decrease S content due to volatilization loss (Al-
449 Wabel et al. 2013).

450

451 **4.3 Trace elements**

452 Biochar also contains a significant amount of trace element nutrients (micronutrients) such as Fe, Cu, B, Zn, Mn,
453 and Mo. Most of the published literature reports only Fe, Zn, and Cu contents of biochar; few of them mention
454 Mn content; and only few report Mo and B contents (Table 4). Table 4 shows that Fe content in biochar of animal
455 manure was higher (311–7480 mg kg⁻¹) than biochar from crop residues and woody materials. The Fe content in
456 biochars produced from waste materials was in the range of 0.009–380 mg kg⁻¹ (Table 4). Like Fe, animal manure
457 biochar contained more Zn (131–4981 mg kg⁻¹) and Cu (99–2446 mg kg⁻¹) than waste- and crop-residue derived
458 biochars (Table 4). The contents of the micronutrient elements depend on the feedstock type and biochar
459 production temperature. However, the effect of these factors is not consistent for micronutrient contents of biochar
460 products, which can be attributed mainly to the low micronutrient contents in feedstock materials. For instance,
461 eucalyptus green waste biochar produced at 650–750 °C had 7000 mg kg⁻¹ Fe (Abujabhah et al. 2016), whereas
462 willow wood waste biochar produced at 550 °C had only 0.05 mg kg⁻¹ Fe (Agegnehu et al. 2016a). Several other
463 studies (Brantley et al. 2016; Chen et al. 2018; Li and Shangguan 2018; Miranda et al. 2017; Noyce et al. 2017)
464 also reported that biochar contains a low but significant amount of micronutrients.

465

466 **5. Effect of biochar on nutrient reactions in soil and uptake by plants**

467 As a sink, biochar can retain nutrients, thereby reducing their losses through leaching and gaseous emission.
468 Biochar application influences various soil properties including pH, bulk density, CEC, water retention, and
469 biological activity (section 3), which in turn affect nutrient retention of soils.

470

471 **5.1 Nutrient Retention**

472 Biochar can contribute in improving nutrient retention capacity of soil due to its large surface area, porosity, and
473 presence of both nonpolar and polar surface sites (Ahmad et al. 2014; Hussain et al. 2017; Mukherjee et al. 2011;

474 Yu et al. 2018). The polar sites are likely to increase the soil CEC (Mukherjee et al. 2011). For example, biochar
475 with a high CEC retains more nutrients in soil by reducing nutrient loss through leaching (Tomczyk et al. 2020).
476 Application of biochar also enhances nutrient retention by increasing the soil pH and soil organic matter (Mendez
477 et al. 2012). Nutrient retention and release depend on soil pH (Fig. 6). For instance, Gao et al. (2016) reported that
478 addition of biochar increased NO_3^- -N and NH_4^+ -N retention in soil by 33 and 53%, respectively. Sorrenti et al.
479 (2016) also observed a similar effect of biochar application on soil N. Liu et al. (2017b) proposed three important
480 mechanisms for N retention after biochar application in soil: (i) adsorption of NH_4^+ -N due to the high CEC of
481 biochar, (ii) reduced leaching of NO_3^- -N due to increased ability of the soil to hold water, and (iii) increased
482 microbial immobilization of N in soil by the supply of labile C. Schofield et al. (2019) suggested that high cation
483 and anion exchange capacities of biochar and its ability to retain ions and molecules within the pores further
484 contribute to biochar's enhanced nutrient retention capacity. Hence, biochar produced at high temperature might
485 have a high ability to retain NO_3^- -N without its leaching to ground water. Sometimes biochar has reduced nutrient
486 retention due to quick decomposition of biochar C (e.g., by 51% within 16 months of application) (Beusch et al.
487 2019). The impacts of various types of biochar and nutrient availability changes in different soils are summarized
488 in Table 5.

489 Owing to porous structure and NH_4^+ -N adsorption ability, biochar can play a vital role in slowing down N release
490 from the soil. This statement was supported by Zhang *et al.* (2017) who reported that the pore space of biochar
491 can facilitate water and nutrient transfer at initial stage of biochar application. The hydrophobic nature of biochar
492 can hinder water transport and thus limit N diffusion (Dong *et al.*, 2020). Moreover, NO_3^- -N adsorption capacity
493 of biochar also influence N release in soil (Hagemann *et al.*, 2017). In recent years, several studies reported that
494 biochar can be used as a slow-release fertilizer. For example, Shi *et al.* (2020) conducted a pot study and found
495 that biochar-urea composite release N slowly than conventional urea fertilizer and thus it was more effective in
496 NH_4^+ -N retention. This agreement was supported by Sashidhar *et al.* (2020) who also reported that biochar-based
497 slow-release fertilizer (BSRF) release N slowly by 69.8% over a period of 30 d. Similarly, Hu *et al.* (2019) and
498 Liu *et al.* (2019d) reported that 59.32% N was released after 84 d and 69.8% N released within 28 d of BSRF
499 application, respectively.

500 Biochar plays a role for N availability in soil due to two main mechanisms: biotic (fixation, mineralization,
501 immobilization, denitrification, plant uptake) and abiotic (sorption, volatilization, leaching) (Clough et al. 2013;
502 Nguyen et al. 2017b). The increase of N availability in soil from biochar application is, therefore, beneficial for
503 plant growth (Esfandbod et al. 2017; Igalavithana et al. 2016). In addition, negative and neutral impacts of biochar

504 on soil N availability have been reported (Mukherjee and Lal 2014; Nguyen et al. 2017b). For example, addition
505 of rice husk biochar reduced the available N content by 21% (sole biochar) and 15% (biochar + fertilizer)
506 compared to a control soil (Arenosol), which was due to immobilization of N (Werner et al. 2018). Liu et al.
507 (2018) did a meta-analysis and concluded that biochar application decreased $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ contents in soil
508 by 6 and 12%, respectively. Therefore, the effects of biochar application on N availability in soil are not consistent
509 as the N availability is governed by rate and type of biochar as well as the soil type (Table 5). For example, under
510 field conditions, the addition of biochar (10 Mg ha^{-1}) plus organic and chemical fertilizers increased N availability
511 in a silty clay loam soil (Arif et al. 2017). In addition, modified biochar (calcium alginate impregnated) also
512 increased the nutrient (N and K) retention in soil, as reported by Wang et al. (2018). Moreover, combined
513 application of biochar and farm yard manure (FYM) improved the nutrient (N and P) retention in soil (Arif et al.
514 2017).

515

516 Biochar can be a reserve stock for P in soils (Dai et al. 2016; Zhang et al. 2016). For instance, with the
517 incorporation of sugar maple and red pine biochar, available P was found to be three times higher in a sand than
518 in sandy loam and silty sand soils (Noyce et al. 2017). Several studies showed that soil amended with biochar
519 increases P bioavailability and plant growth (Arif et al. 2017; Beheshti et al. 2017; Biederman et al. 2017; Brantley
520 et al. 2016; Efthymiou et al. 2018; Houben et al. 2017). The changes of P availability in soil, as impacted by
521 biochar application, are presented in the Table 5. Like N, the availability of P is changed with the addition of
522 biochar and it depends on the biochar and soil. The majority of the studies report that the availability of P is
523 increased with the application of biochar. However, some researchers showed decreased availability of P after
524 biochar addition (Table 5). Modified or fortified biochars increase the P retention capacity of soil. For instance,
525 Wu et al. (2019a) studied the mechanism of inorganic P adsorption under field conditions in saline-alkaline soil.
526 The authors found that MgO-biochar showed 1.46 times more phosphate adsorption than pristine biochar due to
527 electrostatic attraction, precipitation, and exchangeable anions. Thus, modified biochar increased the availability
528 of P in soil. Several studies (Atkinson et al. 2010; Glaser et al. 2002; Major et al. 2010) reported that application
529 of alkaline biochar to acidic soils increased K content in soils. This is in agreement with DeLuca et al. (2015) and
530 Lehmann et al. (2003) who reported that the bioavailability of K was increased with addition of biochar. Usually
531 the availability of K in soil is increased with the addition of biochar irrespective of the study, although some
532 negative impacts of biochar on the availability of K in soil have been reported (Table 5). The addition of biochar
533 (10 t ha^{-1}) increased the Mg content in a loamy-sand soil (Lusiba et al. 2017).

534

535 The impacts of biochar on nutrient retention in soil are mostly positive. For instance, biochar increased Ca and
536 Mg availability in soil and, thus, boosted crop yield (Hussain et al. 2017) which was previously supported by
537 Abujabhah et al. (2016) who found that woody biochar had a significant impact on exchangeable Ca, Mg, and Na
538 in black clay loam, red loam, and brown sandy loam soils. Moreover, the Ca availability increased in soil even at
539 a low rate of biochar application (1.25%); however, no change in S availability was observed (Eykelbosh et al.
540 2014). The availability of Ca, Mg, and S increased or decreased due to incorporation of biochar in soil, as shown
541 in Table 5. A few studies (Lu et al. 2014; Zhang et al. 2013) state that biochar alters the bioavailability of trace
542 elements in soils (Beesley et al. 2011). For example, woody biochar improved the availability of micronutrients
543 (B and Mo) (Hussain et al. 2017), whereas the addition of mixed hardwood-derived biochar did not influence the
544 Cu and Zn content (Cai and Chang 2016). The Fe and Al contents were decreased by biochar addition in sandy
545 soils, but biochar had no impact in silt or clay soils (El-Naggar et al. 2018c). However, addition of hardwood-
546 derived biochar increased Fe and Mn availability, but it had no effect on Zn and Cu availability (Ippolito et al.
547 2014). Noyce et al. (2017) showed a positive effect of biochar on Mn and Na contents in sand, sandy loam, and
548 silty sand soils. The availability of micronutrients is influenced by the application of biochar to soil (Table 5), and
549 feedstock and type of soil are important in determining micronutrient availability.

550

551 **5.2 Nutrient Leaching**

552 **5.2.1 Nitrogen**

553 Nitrate (NO_3^-) leaching is a major reason for loss of N from soils and causes groundwater pollution (Cheng et al.
554 2018). Surface properties of biochar facilitate the adsorption of ions in the soil solution. Electrostatic and capillary
555 forces on the surface of biochar reduce nutrient leaching from soils. For instance, the application of Brazilian
556 pepperwood biochar reduced NO_3^- leaching by 34% through adsorption (Yao et al. 2012). Soil amended with
557 biochar can adsorb NO_3^- through its anion exchange sites, thereby reducing N losses and increasing NO_3^-
558 retention. Moreover, woody biochar application can decrease nutrient leaching through increasing water retention,
559 as reported by Lehmann et al. (2003). Biochar has the capacity to retain inorganic N ions and, therefore, it reduces
560 N leaching and runoff in soils (Steiner et al. 2008). Fig. 7 shows that the application of biochar reduced NO_3^-
561 leaching by 26%. Cao et al. (2019) showed that biochar derived from apple branches reduced leaching of NO_3^- -
562 N by 9.9–68.7% and nitrogen-oxide flux by 6.3–19.2%. Application of mixed hardwood biochar decreased N
563 leaching by 11% in Midwestern agricultural soils (Laird et al. 2010), 72% in sub-alkaline soils of an apple orchard

564 (Ventura et al. 2013), and 46% in a tropical Arenosol (Beusch et al. 2019). Cheng et al. (2018) conducted an
565 incubation study and found that NO_3^- -N leaching was decreased, but NH_4 -N leaching was increased, in biochar-
566 amended soil due to reducing the CEC in biochar with increasing temperature.

567

568 **5.2.2 Phosphorus**

569 Excessive application of P fertilisers has resulted in the leaching of P from agricultural fields to aquatic systems
570 (Karunanithi et al. 2015; Loganathan et al. 2014). Biochar has proven to alter P availability in soils by reducing P
571 leaching through sorption/adsorption. In a column study, biochar produced from Brazilian pepperwood at 600 °C
572 reduced the total amount of phosphate by about 20.6% in biochar-amended soil (Yao et al. 2012). Doydora et al.
573 (2011) found that the application of peanut hull biochar increased the amount of phosphate in the soil solution by
574 39%. The possible mechanisms suggested for the influence of biochar on P availability are change in soil pH and
575 subsequent influence on the interaction of P with other cations and enhanced retention through anion exchange
576 and P precipitation (Atkinson et al. 2010). In natural environments, P is strongly adsorbed onto the surface of
577 Fe(III)-(hydr)oxides in soils (Jaisi et al. 2010). Cui et al. (2011) showed that addition of biochars reduced the
578 amount (30-40%) of P sorbed onto ferrihydrite (the most effective Fe-oxide for P adsorption), which likely
579 improved in P availability in soil. The biochars magnetized with $\text{Fe}^{3+}/\text{Fe}^{2+}$ enhanced phosphate sorption, compared
580 to non-magnetic char (Chen et al. 2011). Leaching of P is reduced by absorbing it on the surface of biochar
581 (Biederman and Harpole 2013). Biochar with a large surface area has high adsorption capacity for the ionic forms
582 of P. So, biochar can reduce ortho-P leaching from nutrient-rich soil and influences P availability (Gul and Whalen
583 2016; Hussain et al. 2017).

584

585 **5.2.3 Other nutrients**

586 Leaching of nutrients depends on soil type, physico-chemical properties of the biochar, and the pyrolytic
587 temperature (Cheng et al. 2018; Yuan et al. 2016). For example, sewage sludge biochar produced at 500 and 700
588 °C reduced the leaching loss of K in a Typic Plinthudult soil more than that of biochar produced at 300 °C (Yuan
589 et al. 2016). Biochar can increase leaching of K in crop fields for the short term (Angst et al. 2014; Guo et al.
590 2013), which results in ground water pollution. For example, application of wood biochar in an acidic and low
591 fertile soil resulted in leaching of K, Ca, and Mg to the 60 cm depth, but concentrations gradually decreased to
592 the 120 cm depth (Major et al. 2012). This might be related to variation in nutrient uptake by plants at different
593 depths. Addition of biochar resulted in increased K leaching by 65% below the A1 horizon (Hardie et al. 2015),

594 which was attributed to a high amount of soluble K in the biochar. Biochar-induced leaching loss of Ca decreased
595 with increasing temperature of biochar production (Cheng et al. 2018). Thus, leaching of nutrients in biochar
596 amended soil depends of several factors, including biochar type and rate of application, soil type, and depth of
597 soil. Long-term field studies are needed to investigate the effect of biochar on nutrient leaching.

598

599 **5.3 Gaseous emission**

600 Nitrogen in soil is lost through leaching and gaseous emission of ammonia (NH_3) and nitrous oxide (N_2O).
601 Inorganic N is reduced in soil mainly through NH_3 volatilization (Liu et al. 2017b). More than 85% NH_4^+ -N is
602 lost from soil due to gaseous emission (Esfandbod et al. 2017). It is necessary to reduce the loss of N from soil
603 for plant growth and development. The physical and chemical characteristics of biochar influence their
604 effectiveness in controlling NH_3 volatilization. Biochar addition to a highly alkaline soil decreased soil pH thereby
605 reducing NH_3 volatilization (Mandal et al. 2016). The NH_3 adsorbed by biochar can, subsequently, become
606 available for plants (Taghizadeh-Toosi et al. 2012). Biochar addition has often been shown to decrease total N_2O
607 emission from soils treated with N sources such as manure, urea, and compost (Bruun et al. 2011; Singh et al.
608 2010; Spokas et al. 2009). Denitrification is the biological process leading to increased N_2O emission from soil.
609 A decrease in denitrification is likely to occur due to adsorption of inorganic N (NH_4^+ , NO_3^-) to biochar surfaces,
610 thus reducing the substrate for denitrification (Taghizadeh-Toosi et al. 2012). Complete denitrification leading to
611 N_2 emission due to biochar addition was explained by enhanced anaerobic conditions (Taghizadeh-Toosi et al.
612 2012), presence of labile C in biochar, elevated soil pH, and enhanced microbial activity (Anderson et al. 2011).
613 Lehmann et al. (2006) hypothesized that biochar could reduce N_2O emissions by inducing microbial
614 immobilization of mineral N in the soil. According to Lu et al. (2018) and Nguyen et al. (2016) biochar inhibited
615 denitrification and thus decreased NO and N_2O emission by 32%. However, biochar could temporarily increase
616 volatilization of N by 19% as NH_3 , which will be ultimately deposited into the soil (Fig. 7). However, Cayuela et
617 al. (2014) carried out a meta-analysis and showed about a 54% reduction in N_2O emissions with biochar
618 application. Biochar reduced the cumulative N_2O emissions, the N_2O -N emission factor, and the yield-scaled N_2O
619 emissions by 5–39, 16–67, and 14–53%, respectively (Li et al. 2017a). The addition of biochar reduced N_2O
620 emissions by 15% from acidic soil in a vegetable field (Wang et al. 2015). In a study by Fungo et al. (2019),
621 addition of biochar reduced cumulative emissions of NH_3 and N_2O by 47% and 22%, respectively, over three
622 years, which indicated that biochar has a residual effect on gaseous emissions of N.

623

624 5.4 Uptake and assimilation of nutrients

625 5.5 Nitrogen

626 The impact of biochar on nutrient concentration, uptake, and crop growth and development are presented in Table
627 6. Biochar application to soil influences N uptake in plants. For example, Amin and Eissa (2017) studied the
628 impact of biochar on N and P use efficiency of zucchini plants (*Cucurbita pepo*) grown in a calcareous soil. They
629 found that the fruit N content increased by 39.23% over the control with the lowest (6.3 g/pot) biochar rate,
630 whereas, with increasing the rate of biochar addition by 12.6 and 25.5 g/pot, the N content decreased by 7.45%
631 and 13.73%, respectively, which was attributed to ‘dilution’ effect caused by increased yield. However, Werner
632 et al. (2018) showed that sole biochar and biochar with NPK fertilizer decreased N concentration in plants by 20
633 and 15%, respectively, which they attributed to immobilization of N in soil. In the USA, Sistani et al. (2019)
634 investigated the effect of hardwood biochar on corn yield and greenhouse gas emission under field conditions in
635 silt loam soil. They found higher N concentration in biomass in the first year of the study, which was a dry period,
636 whereas in the second and third years, which had favourable moisture conditions, N concentration was lower than
637 in the control treatment. Application of biochar has been shown to increase N uptake by 11% (Fig. 7). However,
638 a few studies (Akoto-Danso et al. 2018; Kang et al. 2018) stated the negative impacts of biochar on N
639 concentration and uptake by plants. Results are variable. Mandal et al. (2016) reported that biochar increased N
640 uptake by 76.11% over the control soil, while Nguyen et al. (2016) found no impact on N uptake with the addition
641 of rice husk biochar up to 30 t ha⁻¹.

642

643 5.6 Phosphorus

644 Plants take up P as monovalent or divalent anions (H_2PO_4^- or HPO_4^{2-}), but the availability of these ions may be
645 below the required level for plant growth if they are physically and chemically bonded in soils (Noyce et al. 2017).
646 Addition of biochar increased the P concentration of lettuce leaves (Biederman and Harpole 2013; Gunes et al.
647 2014). Other studies support this observation (Arif et al. 2017; Shepherd et al. 2017; Werner et al. 2018). Residual
648 biochar plus microbial inoculation with and without P-fertilizer increased by 20–52% the P content of maize
649 (Rafique et al. 2020). The impact of biochar on P uptake is mostly positive and few studies show a negative impact
650 (Table 6). For instance, incorporation of various types of biochars (empty fruit bunch, sewage sludge, and chicken
651 litter) at different levels (5–40 t ha⁻¹) increased P uptake by 23–2096% (Table 6). Biochar plus chemical fertilizer
652 increased P and K uptake more than biochar alone (Sistani et al. 2019). However, biochar has been shown to
653 reduce P uptake by plants (Kang et al. 2018; Liu et al. 2017a) and thus decrease crop yield, which might be due

654 to the phytotoxic effects of wood biochar (Liu et al. 2017a). Table 5 gives information on P uptake with different
655 biochars.

656

657 **5.7 Potassium**

658 Biochar addition plus N-fertilizer was positively correlated with K content in sunflower plants, and the treatments
659 improved plant growth and development (Pfister and Saha 2017). Fazal and Bano (2016) did an experiment under
660 axenic conditions in a growth chamber to evaluate the role of biochar, *Pseudomonas* sp., and chemical fertilizer
661 on uptake of K by maize. They observed that K content was increased in maize by 46, 47, and 3% with addition
662 of only biochar, biochar + *Pseudomonas* sp., and biochar + chemical fertilisers, respectively. Biochar can be used
663 as an effective K-fertilizer in terms of its economic, environmental, and slow-release properties (Oh et al. 2014).
664 The concentration of K in plants grown in soil with biochar application has increased up to 112.27% (Table 6).
665 Addition of biochar at 10% increased K in stems, leaves, nut shells, and roots (Prapagdee and Tawinteung 2017).
666 Mycorrhizal inoculation in biochar amended soil increased K content by 11–20% and K uptake by 69% (Rafique
667 et al. 2020). Most studies report that the uptake of K is stimulated due to the addition of biochar (Table 6).
668 However, a few negative impacts of K uptake are presented in the Table 6.

669

670 **5.7.1 Other nutrients**

671 Addition of poultry manure biochar decreased Ca and Mg concentrations in lettuce (Gunes et al. 2014). But,
672 biochar (1%) increased Ca and Mg concentration in chicory (*Cichorium intybus*). Concentration of Ca, Mg, and
673 S increased after 50 t ha⁻¹ biochar addition (Noyce et al. 2017). Application of woody biochar increased the uptake
674 of micronutrients (iron, copper, zinc and manganese) in soil (Gao et al. 2016). Table 6 shows concentrations of
675 Ca, Mg, and micronutrients after biochar addition.

676

677 **5.8 Nutrient use efficiency**

678 The nutrient use efficiency can be defined as yield or biomass per unit input (fertilizer, nutrient content) (Reich et
679 al. 2014; Sarkar and Baishya 2017). It depends upon the soil, plant, and environment (Reich et al. 2014). Biochar
680 can contribute to nutrient use efficiency in plants, both directly through increased nutrient uptake and indirectly
681 by decreasing the loss of nutrients through leaching and gaseous emissions. Several studies (Cao et al. 2019;
682 Coelho et al. 2018; Li et al. 2017a; Nguyen et al. 2017a; Yu et al. 2017; Yu et al. 2018) report that application of
683 biochar increases N uptake, thereby increasing N use efficiency (NUE) in crops. Addition of wood biochar (10 t

684 ha⁻¹) in an alkaline soil improved P use efficiency (PUE) of both wheat and maize (Arif et al. 2017). Zhang et al.
685 (2020) reported that biochar increased NUE (20–53%) and PUE (38–230%), compared to N fertilization, in a rice-
686 wheat rotation during a 6-year field experiment. Application of woody biochar (20%) increased NUE of green
687 bean crops (Prapagdee and Tawinteung 2017). Indirectly, biochar increased NUE by reducing leaching of
688 nutrients (Cheng et al. 2018), decreasing gas emissions (Li et al. 2017a), and increasing soil organic carbon (Arif
689 et al. 2017). Addition of biochar (up to 20 t ha⁻¹) increased NUE and PUE by 90 and 191%, respectively (Table
690 6). Application of several types of biochars (coffee waste, *Dalbergia sissoo*, acacia prunings, maize stalk, chicken
691 litter, mixed wood, and cuttings of acacia) at different levels (2–30 t ha⁻¹) increased the NUE (65–90%) and PUE
692 (44–150%) (Table 6). Nonetheless, application of mixed (70% Norway spruce + 30% European beech) biochar
693 in field crops reduced NUE by 6.09-8.01%, (Table 6) which was due to the presence of polyaromatic hydrocarbons
694 (PAHs) in biochar that reduced the N availability for plants (Haider et al. 2017). Usually, biochar improves NUE
695 in plants (Li et al. 2017a).

696

697 **6. Conclusion and Future Research Recommendations**

698 Biochar can be an important source of plant nutrients and can supply macro-nutrients, secondary nutrients, and
699 micronutrients to plants. Biochar has unique physical and chemical properties that influence nutrient interactions
700 in soil by altering soil properties including pH and CEC. The availability of nutrients in soil with biochar mainly
701 depends on the feedstock type of the biochar, pyrolytic conditions, rate of biochar addition to soil, and the type of
702 soil. Animal manures and waste-derived biochars have higher N, P, and K contents than crop residues and woody
703 biochars. Moreover, manure and waste (municipal and industrial) derived biochars contain more micronutrients
704 than crop residues and woody biochars. Availability of most nutrients are positively correlated with the pyrolytic
705 temperature, except N and S, and that is because of volatilization loss. The effect of biochar on Ca, Mg, and
706 micronutrient (Zn, Cu, Fe, Mn) uptake show inconsistent results. Biochar can retain P, K, and other nutrients in
707 soil by decreasing their leaching loss. Biochar usually improves nutrient use efficiency in plants.

708

709 The following are recommendations for future research:

- 710 ✓ Long-term field studies are needed rather than pot or column studies to understand the impact of biochar
711 in soil.
- 712 ✓ The feedstock selection and application rate should be studied in relation to availability of nutrients.

- 713 ✓ Methods to increase the N content of biochar should be considered, for example by adjusting the pyrolytic
714 conditions, because N is reduced by increasing the pyrolysis temperature.
- 715 ✓ The availability of P as a result of different pyrolytic temperatures needs to be studied.
- 716 ✓ Studies are needed to understand the interaction of biochar and microbes and how they affect nutrient
717 transformation.

718

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722

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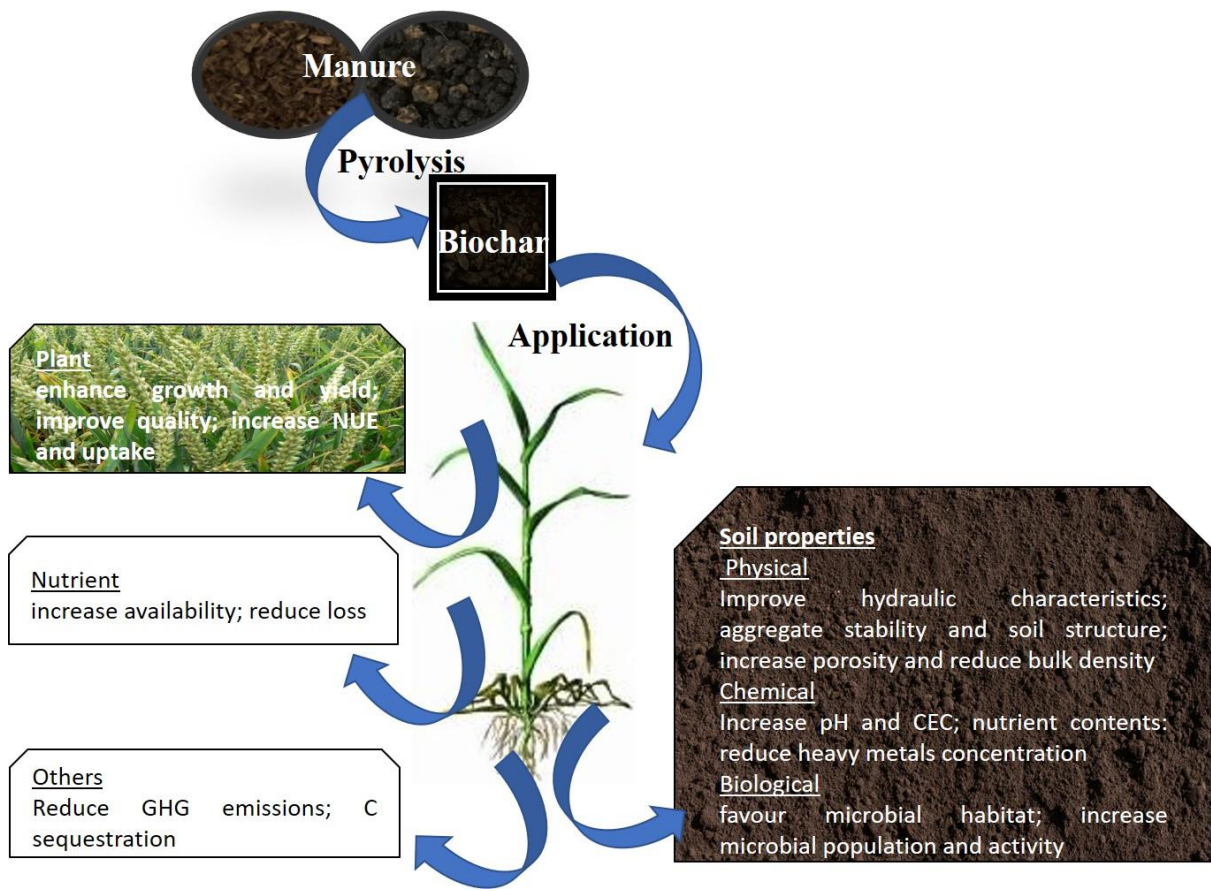
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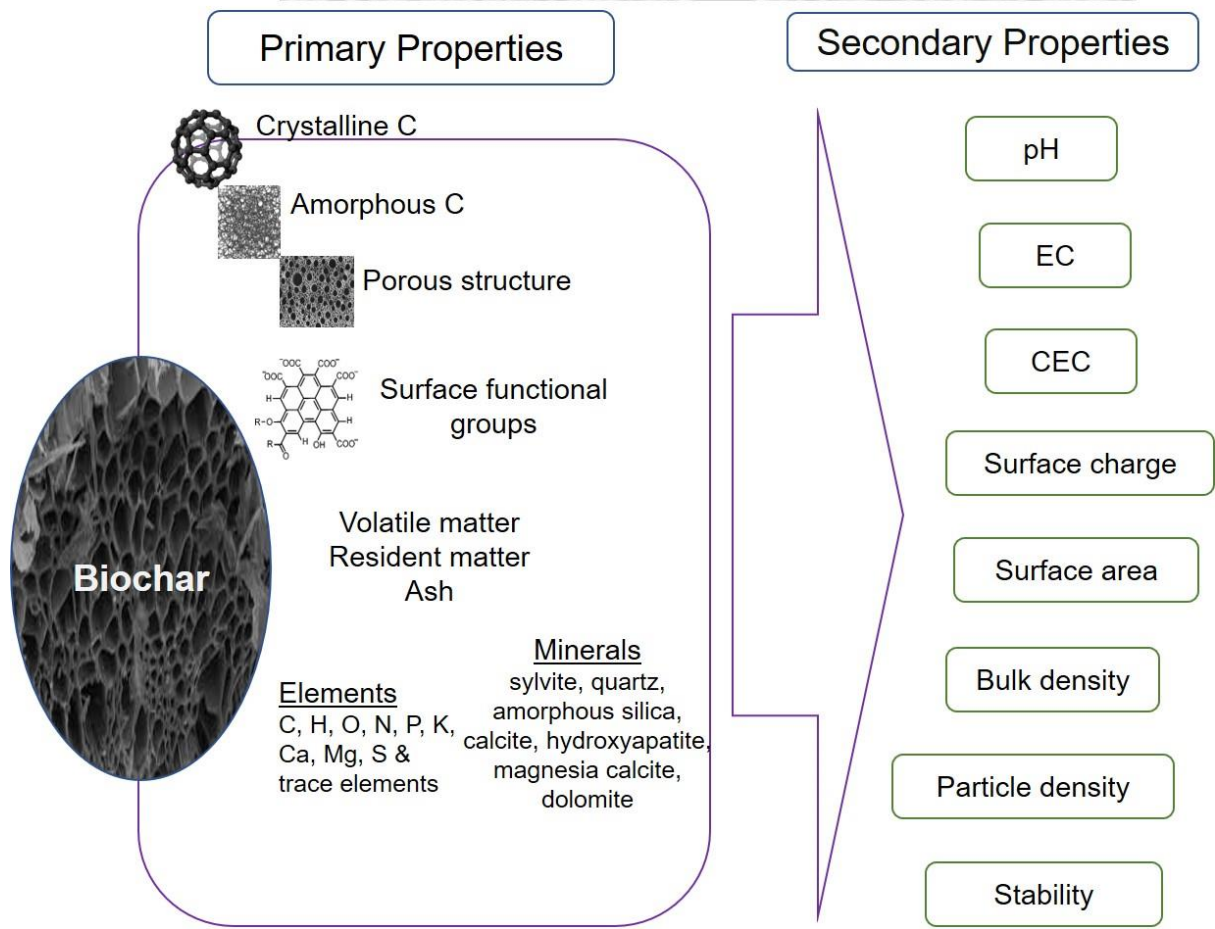


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1488 Figure 1: Conceptual framework for impact of biochar on soils and plants

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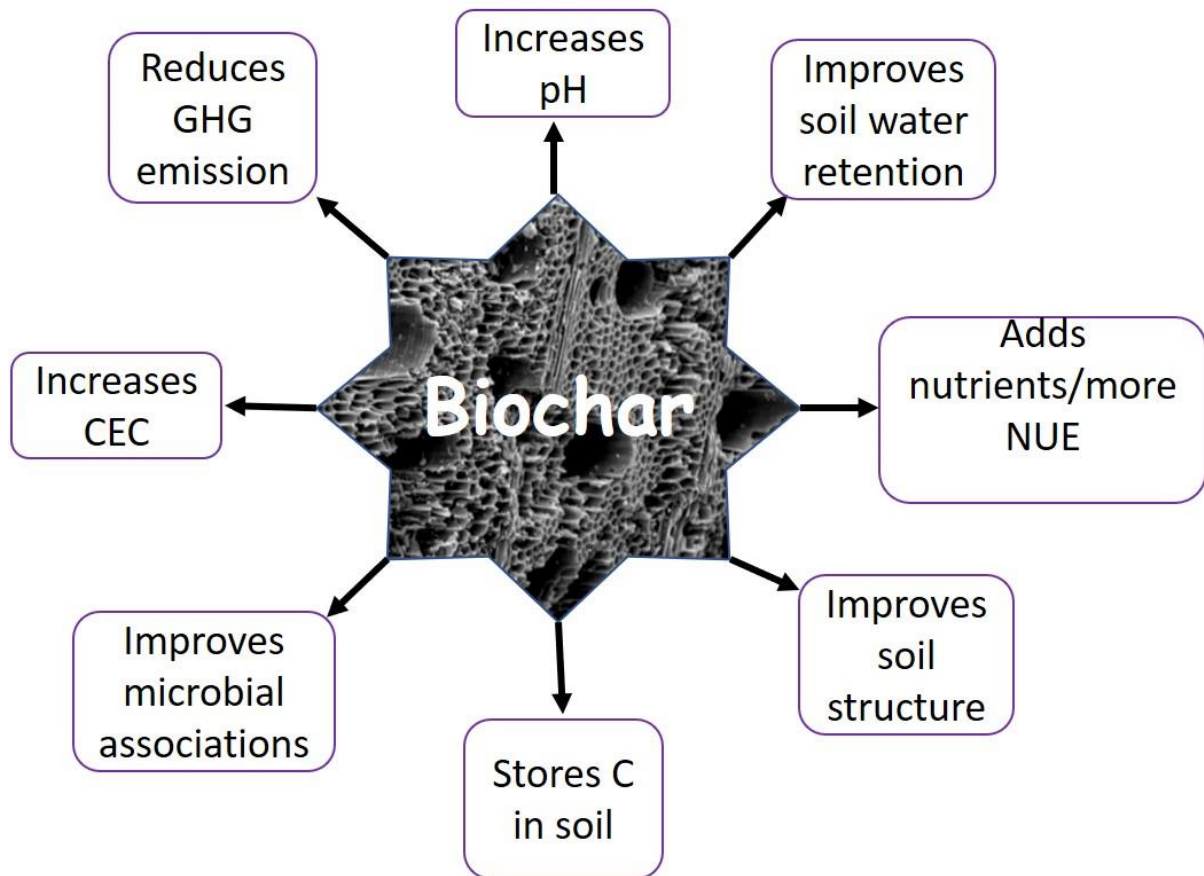
Characteristics of Biochar



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Figure 2: Properties of biochar [modified from (Igalavithana et al. 2018; Xu et al. 2017)]

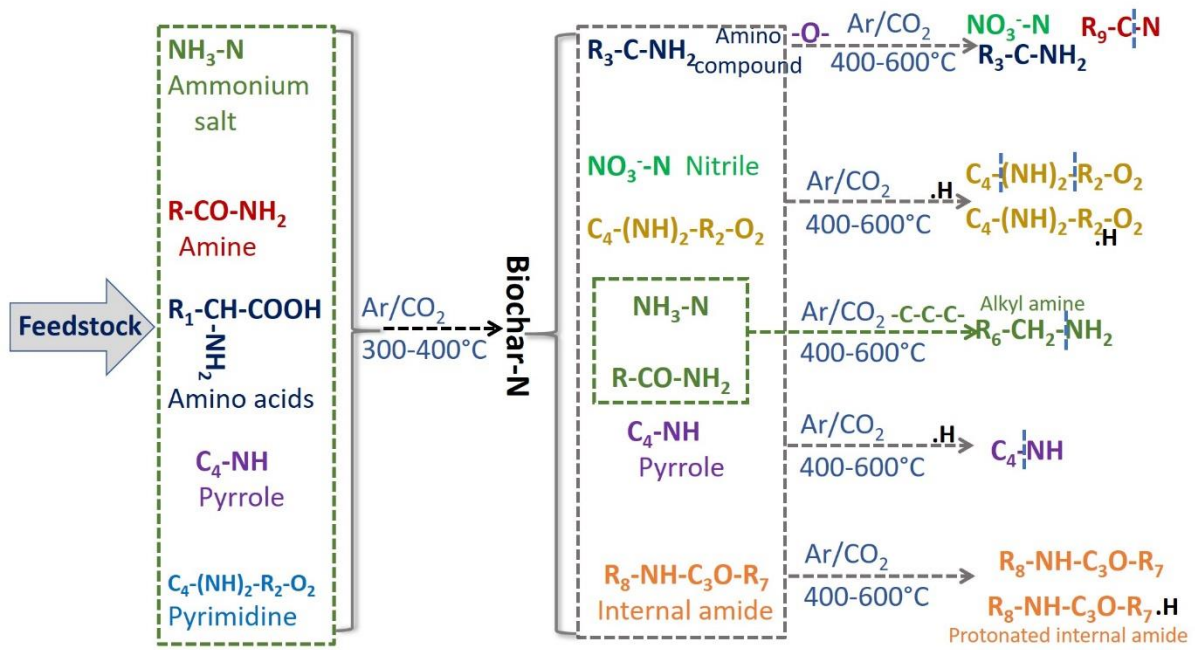
Influence of Biochar on Soil



1493

1494 Figure 3: Influence of biochar on soil properties [adapted from Lopez-Capel et al. (2016)]

1495

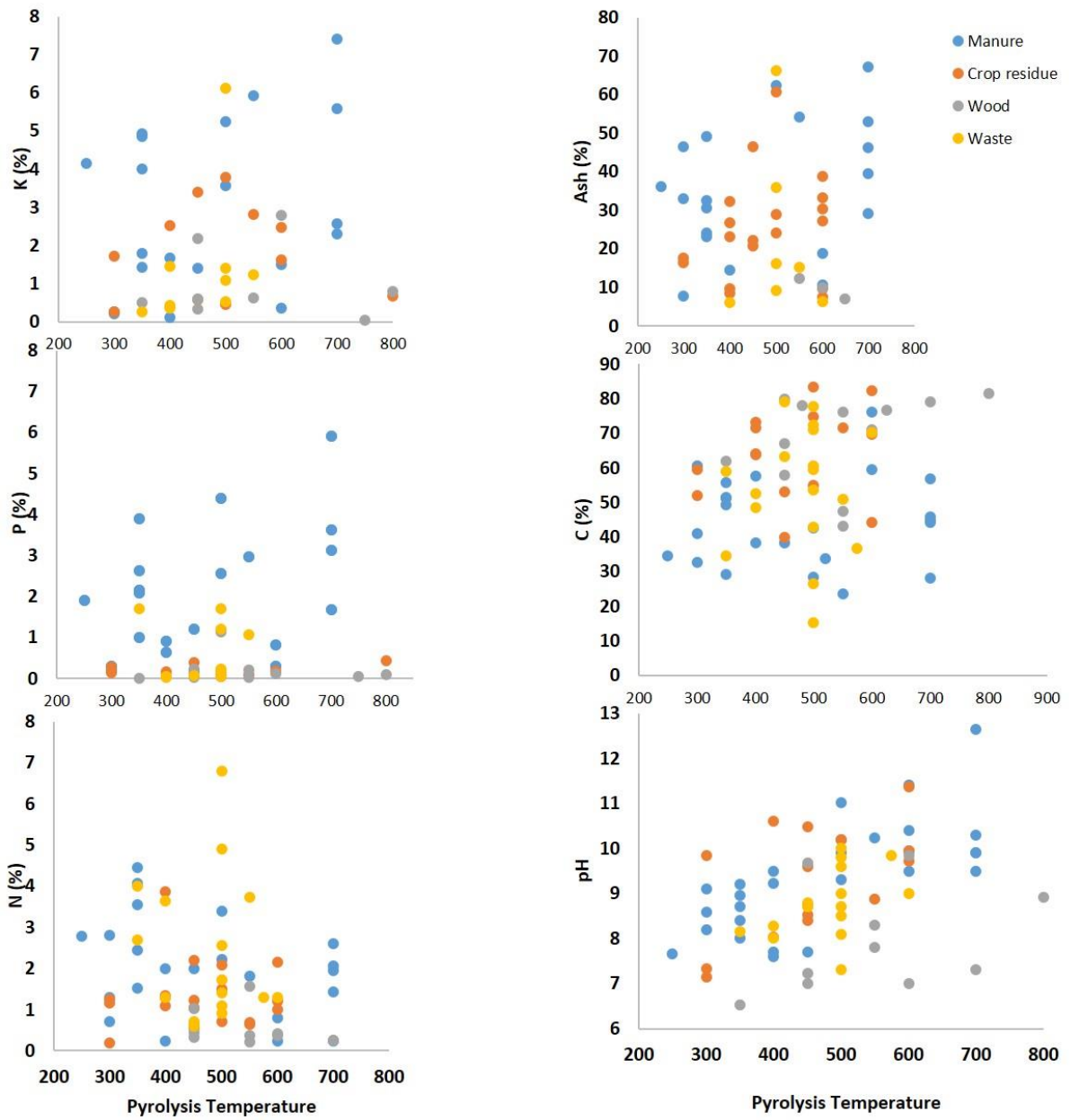


1496

1497 Figure 4: Nitrogen conversion pathways from feedstock-N to biochar-N through pyrolysis process (Leng et al.

1498 2020)

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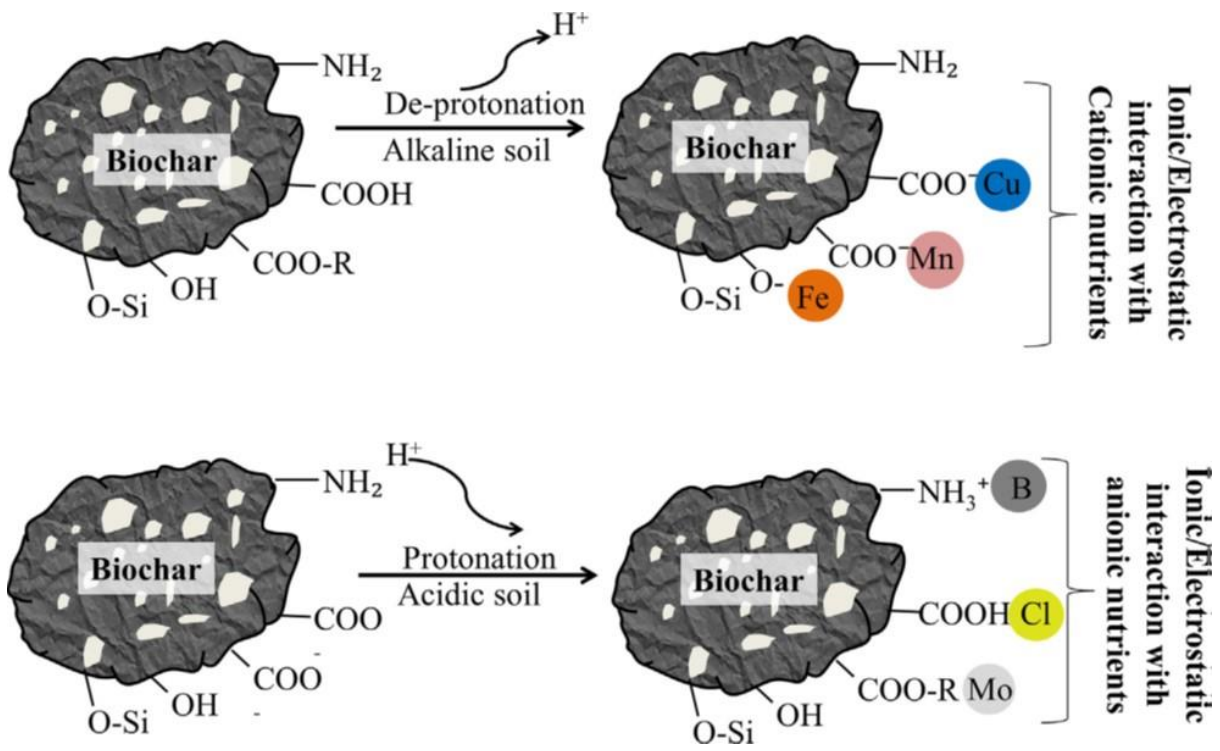
1500

1501 Figure 5: Impact of feedstock and pyrolysis temperature on biochar chemical properties (data obtained from
 1502 Table 1)

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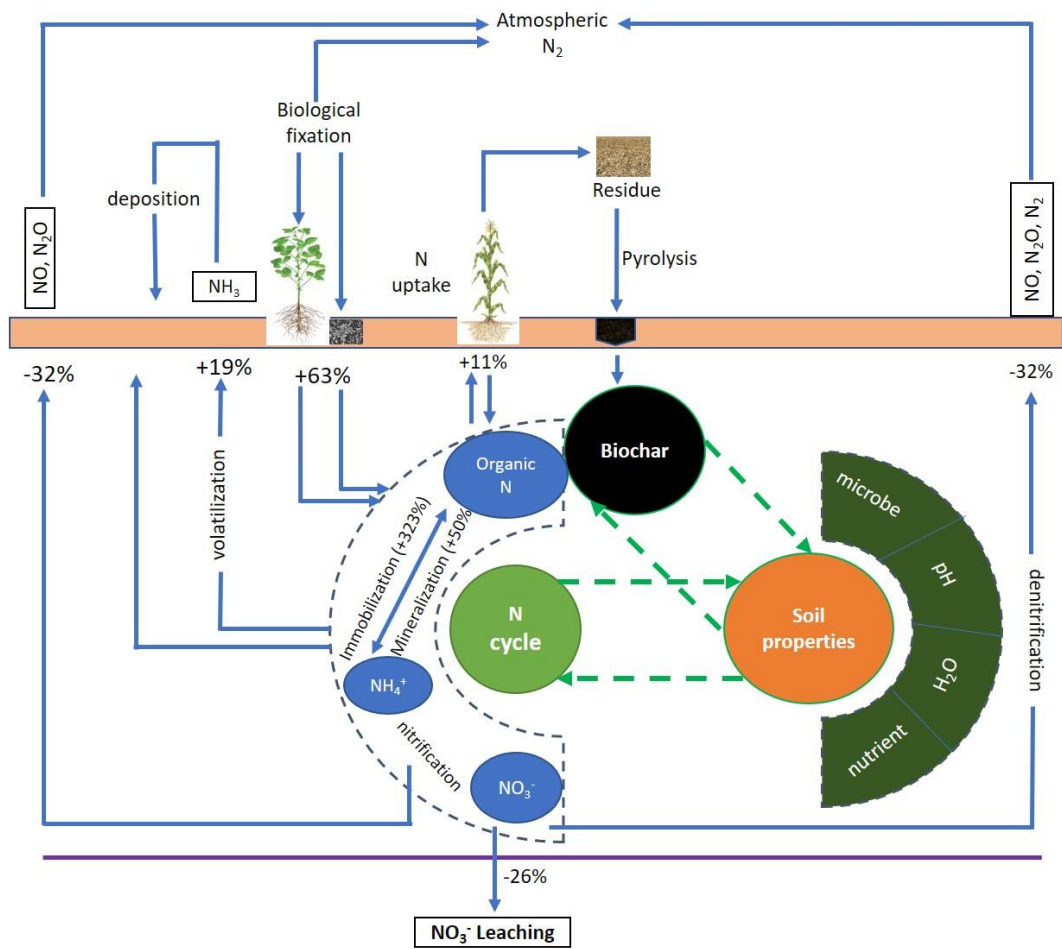


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Figure 6: pH-dependent association and dissociation of nutrients from biochar (Sashidhar et al. 2020)



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1510 Figure 7: Conceptual framework of biochar mediated N cycle [modified from Liu et al. (2018)]

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1512 **Tables**1513 **Table 1: Effect of biochar on soil physical properties**

Biochar	PT(°C)	Application rate (t/ha)	Soil type	Aggregate stability (%)	Temperature (°C)		Porosity (%)		Water content (%)		Bulk density (g cm ⁻³)		Reference
					Control	Amended	Control	Amended	Control	Amended	Control	Amended	
Wheat straw	400	20 40	Irragic Anthrosols	43-48							1.21	1.15 1.14	Zhang et al. (2020)
Maize straw	550	20 40 60	Silt loam		8.5	8.8 8.9 9.0			21.5	23.3 23.4 23.1	1.34	1.29 1.26 1.22	Yan et al. (2019)
Rice husk	350-400	3 6 12	Alfisol	10 18 23							1.60	1.55 1.51 1.44	Oladele (2019)
Paper fiber sludge + grain husks	550	10 20	Haplic Luvisol		17.2	17.5 17.3			15	15.5 17.2			Horák et al. (2019)
Green cuttings	650	3 40	Sandy Cambisol								1.30	1.30 1.27	Greenberg et al. (2019)
Corn straw	500	3 6 9 12	-				49	50 52 54 58					Fu et al. (2019)
Date palm residue	300 400 500 600	8	Loamy sand						25	50 42.5 35 32.5			Alotaibi and Schoenau (2019)
Macadamia nutshell		3	Sand								1.68	1.61	Lim and Spokas (2018)
Pine chip	-	3	Sand								1.68	1.58	Lim and Spokas (2018)
Maize straw	400-500	10 20 40 60	Sandy loam				42.5	48 50 55 56			1.53	1.40 1.32 1.20 1.18	Li et al. (2018)
Barley straw	400	10	Loam				51	55			1.4	1.3	Kang et al. (2018)
Poultry manure	450	5	Alfisol	18							1.60	1.44	Are et al. (2018)

1514 Table 2: Effect of biochar on selected soil chemical properties

Biochar	PT(°C)	Application rate (t/ha)	Soil type	pH		CEC (cmol/kg)		OM (%)		Reference
				Control	Treatment	Control	Treatment	Control	Treatment	
Wheat straw	500	20 40	Irragric Anthrosols	7.00	7.10 7.40			2.57	3.28 3.97	Wu et al. (2019)
Bamboo	450	11.25 45 180	-	4.67	4.80 4.95 5.30			0.7	1.25 1.90 3.55	Tarin et al. (2019)
Hardwood	420	11.25 45 180	-	4.67	4.70 4.90 5.15			0.7	1.13 2.25 4.50	Tarin et al. (2019)
Rice straw	500	11.25 45 180	-	4.67	4.90 4.95 5.45			0.7	1.00 1.90 2.55	Tarin et al. (2019)
Rice straw	400	72	Ultisol	5.00	4.80					Shi et al. (2019)
Peanut straw	400	72	Ultisol	5.80	5.30					Shi et al. (2019)
Rice husk	500	22.5 67.5	Typic Hapludalfs	6.71	6.84 7.20	12.17	13.28 14.44	1.90	2.33 3.22	Ghorbani et al. (2019)
Rice husk	500	22.5 67.5	Typic Hapludepts	4.36	4.76 5.06	5.71	6.87 7.40	0.91	2.03 2.45	Ghorbani et al. (2019)
Chicken manure	535	6.43	Aquic Hapludults	6.69	6.81	6.28	7.01			Clark et al. (2019)
Chicken manure	535	4.23	Typic Hapludalfs	5.10	5.61	11.3	12.1			Clark et al. (2019)
Winter grass	450	45 90 135 180	Entisol	7.70	7.80 7.80 7.90 7.90	14.3	18.2 23.9 27.4 29.6	0.86	1.21 3.45 3.97 6.55	Yadav et al. (2018)
Winter grass	850	45 90 135 180	Entisol	7.70	7.90 8.00 8.10 8.30	14.3	17.2 20.2 24.3 27.1	0.86	0.86 2.07 3.97 6.03	Yadav et al. (2018)

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1517 Table 3: Effect of biochar on soil biological properties

Biochar (rate)	Temp. (°C)	Soil type	Study	Biological properties or microbial response	References
Wheat straw (1%)	400	Fimi-Orthic Anthrosol Ferralic Cambisol	Incubation	<ul style="list-style-type: none"> fresh biochar reduced ammonia-oxidizing archaea (AOA) but increased ammonia-oxidizing bacteria (AOB) gene populations in acidic soil aged biochar increased AOA- and AOB- in both soils 	Zhang et al. (2019c)
Peanut shell (2%)	400	Yellow-brown Fluvo-aquic Luo Black	Incubation	<ul style="list-style-type: none"> increased bacterial diversity but decreased fungal diversity <i>Fusarium</i> population reduced by biochar plus chemical fertilizers 	Zhang et al. (2019b)
Rice straw	500	Sandy loam	Field	<ul style="list-style-type: none"> no effect on AOA but AOB abundance and diversity increased 	Zhang et al. (2019a)
Rice straw	350 480	Clinosol	Field	<ul style="list-style-type: none"> Lactobacillales and Bacteroidales population increased 	Yan et al. (2019)
Corn straw (1.33%)	500	Sandy loam	Pot	<ul style="list-style-type: none"> improved antagonistic percentage and antagonistic ability of <i>Bacillus</i> spp. And <i>Pseudomonas</i> spp. 	Wang et al. (2019)
Straw of reed, smooth grass and rice	450	Clay	Pot	<ul style="list-style-type: none"> increased microbial biomass decreased microbial activity and soil respiration 	Tian et al. (2019)
Moso bamboo (20 and 40 t/ha)	600	Ferrisol	Field	<ul style="list-style-type: none"> reduced urease and acid phosphatase activities 	Peng et al. (2019)
Chicken manure, oat hull, pine bark (3%)	300 500 600	Alfisol		<ul style="list-style-type: none"> increased basal respiration and dehydrogenase (DHA) activity and modified microbial communities. 	Meier et al. (2019)
Wheat straw (40 t/ha)	350- 550	Anthrosol	Incubation	<ul style="list-style-type: none"> fresh biochar increased microbial biomass C (MBC) aged biochar decreased Gram-positive/Gram-negative ratio 	Liu et al. (2019b)
Rice straw (4 and 20 t/ha)	550- 650	Vertisol	Field	<ul style="list-style-type: none"> increased the nifH (nitrogenase iron protein) gene abundance and altered the community structure of soil diazotrophs. 	Liu et al. (2019a)
Corn straw (2.4, 6 and 12 t/ha)	400	Inceptisol	Field	<ul style="list-style-type: none"> improved growth of Gram-positive bacteria and fungi increased MBC and influenced the soil microbial community structure 	Li et al. (2019)
Wheat stalk (1 and 5%)	650	Ge-Eutric Gleysols		<ul style="list-style-type: none"> strengthened network connectivity among rhizosphere bacteria improved linkage between rhizosphere bacteria and soil C 	Huang et al. (2019)

Bamboo biomass (5, 10 20 t/ha)	350-400		Field	<ul style="list-style-type: none"> reduced the Proteobacterial community in soils 	Herrmann et al. (2019)
Sewage sludge (15 t/ha)	300-500	Red-Yellow Latosol	Field	<ul style="list-style-type: none"> increased mycorrhizal colonization in corn plant 	de Figueiredo et al. (2019)
Conifer wood chips (5 and 10%)	280	Cambisol	Incubation	<ul style="list-style-type: none"> decreased DHA, β-glucosidase and phosphatase activities 	Cordovil et al. (2019)

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1520 Table 4: pH and nutrient contents of biochar produced at different pyrolysis temperature

Feedstock	PT ¹ (°C)	pH	C	N			C/ N	P			K	Ca	Mg	S	Zn	Cu	Fe	Mn	Mo	B	Reference
				TN	Available NH ₄ -N (g kg ⁻¹)			T P	Available P (g kg ⁻¹)												
					H ₂ O extract	KCl extract			H ₂ O extract	Olsen-P											
Manure																					
Chicken manure	250	7.66	34.55	2.79	0.07	0.16	12	1.91	5.08	6.76	4.16	1.98	2.14	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure	350	8.95	29.21	2.45	0.07	-	12	2.15	4.57	8.42	4.93	2.17	2.84	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure	550	10.24	23.65	1.81	-	-	13	2.96	2.93	8.74	5.93	3.03	3.78	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Ca*	250	7.84	30.00	2.85	0.27	0.48	11	1.83	2.49	3.17	4.14	4.05	1.67	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Ca*	350	9.32	26.68	2.44	0.01	0.03	11	2.21	1.23	8.68	4.87	4.91	2.18	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Ca*	550	10.61	24.73	1.96	-	-	13	3.06	-	1.22	6.03	5.91	2.67	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Mg [#]	250	7.35	26.40	2.43	0.40	0.30	11	2.05	5.65	6.98	3.92	2.24	4.17	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Mg [#]	350	9.17	26.22	2.42	-	-	11	2.67	3.33	8.36	5.03	2.81	4.73	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Mg [#]	550	10.32	27.04	2.06	-	-	13	3.03	0.05	1.27	5.88	3.09	5.22	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Fe [@]	250	5.75	28.26	2.91	0.44	0.17	10	2.01	1.27	1.23	3.92	2.03	2.03	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Fe [@]	350	5.72	26.44	2.45	0.02	-	11	2.44	1.24	1.23	5.06	2.53	2.88	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure-Fe [@]	550	6.68	27.13	2.17	-	-	13	3.10	0.09	0.51	5.95	3.18	3.87	-	-	-	-	-	-	-	Xiao et al. (2018)
Chicken manure	450	7.7	38.3	2.0			19	1.2			1.4	-	-	-	-	-	-	-	-	-	Madiba et al. (2016)
Poultry litter	500-520	9.30	33.72	3.39			10	2.57			5.24	4.54	1.26	1.36	829.50	583	-	715			Brantley et al. (2016)
Poultry Litter	400	9.5	52.1	5.85			9	1.22			3.88	2.83	1.73	0.08	-	-	-	-	-	-	Subedi et al. (2016)
Poultry Litter	600	10.4	52.8	4.0			13	1.54			5.88	3.59	2.4	0.08	-	-	-	-	-	-	Subedi et al. (2016)
Poultry litter	350	8.70	51.1	4.45			11	2.08			4.85	2.66	0.94	0.61	712	213	13200	640	11	-	Cantrell et al. (2012)
Poultry litter	400	7.70	38.3	2.0			19	0.90			1.0	2.5	0.30	-	238	57	2695	265	5	-	Macdonald et al. (2014)
Poultry litter	700	10.3	45.9	2.07			22	3.12			7.4	0.40	1.45	0.63	1010	310	18900	948	13	-	Cantrell et al. (2012)
Turkey litter	350	8.00	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)

Turkey litter	700	9.90	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)
Cow manure	300	8.59	41.02	0.71			58	0.19			0.26	-	-	-	-	-	-	-	-	-	Beheshti et al. (2017)
Bull manure	300	8.20	60.6	1.3			47	0.30			0.20	0.94	0.40	0.11	162	-	376	137	-	-	Enders et al. (2012)
Bull manure	600	9.50	76.0	0.8			95	0.30			0.36	0.94	0.51	0.10	193	-	311	165	-	-	Enders et al. (2012)
Digested dairy manure	400	9.22	57.7	0.24			240	0.65			1.66	2.26	0.97	0.27	131	-	1656	145	-	-	Enders et al. (2012)
Digested dairy manure	600	9.94	59.4	0.23			258	0.83			1.49	2.65	0.85	0.29	200	-	2356	191	-	-	Enders et al. (2012)
Dairy manure	350	9.2	55.8	1.51			37	1.0			1.43	2.67	1.22	0.11	361	99	26700	525	7.8	-	Cantrell et al. (2012)
Dairy manure	700	9.9	56.7	0.24			236	1.69			2.31	4.48	2.06	0.15	423	163	44800	867	10	-	Cantrell et al. (2012)
Swine manure	300	9.11	32.58	2.80			12	-			-	-	-	-	-	-	-	-	-	-	Xu et al. (2019)
Swine manure	500	11.02	28.43	2.21			13	-			-	-	-	-	-	-	-	-	-	-	Xu et al. (2019)
Swine manure	700	12.64	28.23	1.42			20	-			-	-	-	-	-	-	-	-	-	-	Xu et al. (2019)
Swine manure	400	7.6	54.9	2.23			246	0.98			1.62	2.03	1.57	0.02	-	-	-	-	-	-	Subedi et al. (2016)
Swine manure	600	11.4	57.9	1.79			324	1.55			3.53	2.89	2.13	0.04	-	-	-	-	-	-	Subedi et al. (2016)
Pig manure	500	9.90	42.7	-				4.39			3.56	3.47	2.80	-	1010	780	6960	1230	-	-	Zhao et al. (2018)
Swine solids	350	8.40	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)
Swine solids	700	9.50	44.1	2.61			17	5.9			2.57	6.15	3.69	0.85	4981	2446	74800	2240	27.4		Cantrell et al. (2012)
Crop residue																					
Rice husk	450	8.53	39.90	0.54			74	0.16			0.58	-	-	-	-	-	-	-	-	-	Bu et al. (2017)
Rice husk	-	9.50	-	0.1			-	0.15			0.20	-	-	-	-	-	-	-	-	-	Jatav et al. (2018)
Barley straw	400	8.02	71.50	1.3			55	-			-	0.20	-	-	-	-	-	-	-	-	Kang et al. (2018)
Rice straw	550-650	9.71	44.27	0.64			69	0.09			2.82	-	-	0.24	-	-	-	-	-	-	Si et al. (2018)
Wheat straw	300	7.15	52.12	0.2			261	0.27			0.25	-	-	-	-	-	-	-	-	-	Beheshti et al. (2017)
Wheat straw	350-550	9.60	-	1.05			-	-			-	-	-	-	-	-	-	-	-	-	Zheng et al. (2017)
Wheat chaff	450	8.40	53.1	2.2			24	0.40			3.40	-	-	-	-	-	-	-	-	-	Madiba et al. (2016)
Maize straw	300	9.84	-	1.25			-	-			-	-	-	-	-	-	-	-	-	-	Song et al. (2018)
Maize straw	450	10.47	-	1.22			-	-			-	-	-	-	-	-	-	-	-	-	Song et al. (2018)
Maize straw	600	11.37	-	1.21			-	-			-	-	-	-	-	-	-	-	-	-	Song et al. (2018)
Corn stalks	500-600	8.87	71.50	0.69			104	-			1.61	-	-	-	-	-	-	-	-	-	Yao et al. (2017)

Wheat straw and peanut shell	500	10.20	83.40	1.5			56	-						0.30	-	-	-	-	-	-	El-Naggar et al. (2018)
Elephant grass	400	-	63.86	3.87			17	-						-	-	-	-	-	-	-	Ferreira et al. (2018)
Elephant grass	500	-	74.85	2.08			36	-						-	-	-	-	-	-	-	Ferreira et al. (2018)
Elephant grass	600	-	82.23	2.15			38	-						-	-	-	-	-	-	-	Ferreira et al. (2018)
Kunai grass	500	10.20	55.00	0.7			79	0.10			0.46			-	-	-	-	-	-	-	Baiga and Rao (2017)
Switch grass	400	-	73.10	1.35			54	-						0.32	-	-	-	-	-	-	Purakayastha et al. (2016)
Corn stover	300	7.33	59.5	1.16			51	0.14			1.71	0.65	0.59	0.07	132	-	963	142	-	-	Enders et al. (2012)
Corn stover	600	9.95	69.80	1.01			69	0.18			2.46	0.94	0.86	0.08	70	-	1362	226	-	-	Enders et al. (2012)
Soybean	500	-	-	-			-	0.06			3.78	1.57	1.17	0.11	28	-	699	58	-	-	Enders et al. (2012)
Pearl millet	400	10.60	64	1.1			58	0.16			2.52	1.47	1.06	0.22	-	-	-	-	-	-	Purakayastha et al. (2015)
Wood																					
Sugar maple sawdust	450	7.22	80.00	0.32			250	0.02			0.32	0.50	0.06	-	23.90	5.01	49.70	368	-	-	Noyce et al. (2017)
<i>Eucalyptus camaldulensis</i> Traditional kiln	350	6.52	61.86	-			-	0.05			0.51	0.54	0.04				500				Butnan et al. (2015); Butnan et al. (2018)
<i>Eucalyptus camaldulensis</i> Flash carbinization	800	8.92	81.50	-			-	0.09			0.78	1.04	0.06	-	-	-	229	-	-	-	Butnan et al. (2015)
Apple branch	450	9.67	67.01	0.57			118	0.18			0.60	2.42	0.32	-	37.30	9.90	5745.80	91.50	-	-	Li and Shangguan (2018)
Castor stalk	550	-	43.18	1.57			27	0.22			0.62	0.90	-	-	-	-	-	-	-	-	Hilioti et al. (2017)
Bamboo	600	9.84	70.90	0.41			173	0.11			2.78	-	-	0.46	-	-	-	-	-	-	Lu et al. (2018)
Hardwood	550	7.80	76.00	0.22			345	0.02			-	-	-	0.08	-	-	-	-	-	-	Nguyen et al. (2018)
Cashew wood residue	-	-	-	0.94			-	0.01			0.13	-	-	-	18.45	10.21	185.04	32.27	-	-	Miranda et al. (2017)
Hardwood	600-650	7.00	76.60	0.38			201	-			-	-	-	-	-	-	-	-	-	-	Aller et al. (2017)
Eucalypt green waste	650-750	7.30	79.00	0.26			303	0.04			0.03	0.05	0.02	0.08	200	12	7000	180	-	6.10	Abujabhah et al. (2016)
Willow wood waste	550	8.30	47.50	0.38			125	-			-	-	-	0.19	83.50	2.55	0.05	110	<0.30	9.25	Agegnehu et al. (2016)
Acacia	400-500	7.01	57.80	1.02			57	1.14			-	0.27	0.001	-	-	-	-	-	-	-	Arif et al. (2016)

Macadamia shell	450-480	8.76	78.03	0.43			181	0.24			2.19	0.37	0.17	-	-	-	1211	-	-	-	Wrobel-Tobiszewska et al. (2015)
Industrial and Municipal Waste																					
Sugarcane bagasse	450-500	8.79	63.27	0.67			94	0.07			-	-	-	-	-	-	-	-	-	-	Gerdelidani and Hosseini (2018)
Sugarcane bagasse	350	-	59	4			15	-			-	-	-	-	-	-	-	-	-	-	Batista et al. (2018)
Castor cake	550	-	50.81	3.73			14	1.07			1.23	0.37	-	-	-	-	-	-	-	-	Hilioti et al. (2017)
Sewage sludge	350	8.15	34.56	2.7			13	1.70			0.26	-	-	-	-	-	-	-	-	-	Khanmohammadi et al. (2017)
Sewage sludge	500	7.30	43.0	6.8			6	0.11			-	-	-	-	-	-	-	-	-	-	Gonzaga et al. (2019)
Sewage sludge	500	8.10	26.6	-			-	1.70			0.52	6.57	0.64	-	1520	380	22100	450	-	-	Zhao et al. (2018)
Sewage sludge	500	8.70	15.26	1.73			-	-			-	-	-	-	-	-	-	-	-	-	Yue et al. (2017)
Orchard pruning biomass	500	9.80	77.8	0.91			63.5	0.23			1.39	2.5	2.87	0.005	0.01	0.009	0.033	0.008	-	-	Baronti et al. (2014)
Leave waste	500	9.00	60.7	1.1			55	0.21			1.08	5.46	0.36	0.10	70	-	1504	555	-	-	Enders et al. (2012)
Grass waste	500	9.60	53.5	4.9			11	1.20			6.13	2.06	0.63	0.63	150	-	1557	360	-	-	Enders et al. (2012)
Food waste	400	8.27	52.4	3.65			14	0.05			1.46	5.17	0.53	0.08	39	-	4431	179	-	-	Enders et al. (2012)
Orange bagasse	500	10.00	72.3	2.55			28	0.05			-	-	-	-	-	-	-	-	-	-	Gonzaga et al. (2019)
Coffee waste	400-500	8.7	79	0.7			113	0.03			0.35	0.40	0.08	0.03	45	15	150	40	-	-	Prakongkep et al. (2015)
Bagasse	400-500	8.7	71	0.6			118	0.08			0.43	1.20	0.21	0.03	400	15	4800	300	-	-	Prakongkep et al. (2015)
Sugarcane filtercake	575	9.85	36.7	1.3			28	-			-	-	-	-	-	-	-	-	-	-	Eykelbosh et al. (2014)
Municipal solid waste	400	8.00	48.6	1.3			37	-			-	-	-	0.1	149	63	-	-	-	-	Jin et al. (2014)
Municipal solid waste	500	8.50	59.5	1.4			43	-			-	-	-	-	213	101	-	-	-	-	Jin et al. (2014)
Municipal solid waste	600	9.00	70.1	1.3			54	-			-	-	-	0.1	356	157	-	-	-	-	Jin et al. (2014)

1521 l= Pyrolysis temperature *- CaCl₂ # = MgCl₂.6H₂O, @ = FeCl₃.6H₂O

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1526 Table 5: Biochar and nutrient availability changes in different soils

Expt. condition	Soil type/test crop	BC source	PT (°C)	BC rate	Nutrient availability changes over control (%)								References		
					C	NO ₃ -N	NH ₄ -N	Tot. N	Avail. P	Tot. P	K	Secondary		Minor	
		Woody													
Incubation	Silty clay loam	Yellow pine	550	10 Mg/ha		2.04 (-)								(Baechle et al., 2018)	
Pot	Khorat and Wahiawa/maize	upper branches of eucalyptus trees	350 and 800	1, 2, 3, 4%	708.54 (+) 271.90 (+)						145.24(+) 13(+)	Ca(268) (133.53) (+) Mg(106.14)(+) Mg(89.49)(-)	Mn(311.61) (+)	Butnan et al. (2018)	
Field	Silt-clay/wheat	Apple branch	450	0, 1, 2, 4, 6%		48.66– 256.49(+) 72.52– 85.53(-)	46.42(+) 18.38(-)			32.34– 51.41(+) 13.70– 35.13(0-)				Li and Shangquan (2018)	
Pot	Yellow loamy/rice	Bamboo	600	0.16 kg/pot	228.41 (+)	22.61(+)	41(+)	9.51(+)	3.54(-)		191.13(+)			Lu et al. (2018)	
Field	Ferralsol/Forage peanut	Hardwood	550	10 t/ha	21.60(+)	42.75(+)	24.06(-)	2.63(+)						Nguyen et al. (2018)	
Field	Silty loam/maize-mustard	<i>Eupatorium adenophorum</i>	450-500	5, 10, 15, 20, 40 t/ha	175.69 (+)			11(+)	422.4(+)		80.95(+)	Ca(78.26)(+) Mg(60.66)(+)		Pandit et al. (2018)	
Pot	<i>Brassica juncea</i>	Oak wood	400	5%							61535.07 (+)	Mg(1158.92)(+)	Mn(2702)(+) Cu, Fe(-)	Rodriguez-Vila et al. (2017)	
Pot	Sand, sandy loam and silty sand/sugar maple and red pine	Sugar maple sawdust	450	5, 20, 50 t/ha	64.5(+)					0.97(-)		92.5(+)	Ca(3)(-) Mg(4.05)(-)	Mn(17.1)(+)	Noyce et al. (2017)
Greenhouse	Yellow Latosol/rice and cowpea	Cashew wood residue		3.5, 7, 10 t/ha	19.4(-)						28.97(+)	46.12(+)	Ca and Mg(3.39)(-)	Miranda et al. (2017)	
Field	Clay and loamy sand/chickpea	<i>Acacia nilotica</i> <i>Eucalyptus obliqua</i>	450-550	0, 5, 10, 20 t/ha	57.52(+)			33.33(+)			42.17(-)	5.13(+)	Ca(3.38)(-) Mg(3.57)(+)	Lusiba et al. (2017)	
Greenhouse	Courval sandy loam	Softwood chips	500	20 Mg/ha			15.16(+)							Backer et al. (2017)	
Field	Fine-loamy, mixed, superactive/corn, soybean and switchgrass	Hardwood	600-650	22.4 t/ha	37(+)			26(+)				11 (+)		Aller et al. (2017)	

Pot	Loam; sandy loam; clay loam	Eucalypt green waste	650-750	2.5, 5, 10%		103(+) 110(+) 207(+)	53 (-) 32 (-) 61 (-)				8(+) 16(+)	Ca(19)(+) Mg(+)	Na(28) (+) Al(68)(-) Fe(13)(-) Cu(16) (-) B(40)(-)	Abujabba et al. (2016)
Field	Dark reddish brown Ferrasol; Red Ferrosol/Maize	Willow wood waste	550	10 t/ha	43-73(+)	10(+)	36(+)		59-117(+)			Ca (31-54)(+)	Al (37.5)(-)	Agegnehu et al. (2016a)
Field	Acidic Eutric Nitisol/Barley	Stem, bark and branches of Acacia wood	Earth klin	2, 10 t/ha	30 (+)			15(+)		29(+)	17(+)	Ca (23)(+) Mg (16) (+)		Agegnehu et al. (2016b)
Field	Silty clay loam/maize	Acacia	400-500	25, 50 t/ha	483.33 (+)			66.67(+)		200 (+)				Arif et al. (2016)
Crop residue														
Field	Loam/Chinese cabbage	Barley straw	400	10 t/ha				20.86(+)	9.76(+)		24(+)	Ca(9.81)(+) Mg(32.26)(+)		Kang et al. (2018)
Field	Silt loam/rice	Rice straw	550-650		0.40(+)			1.90(+)	32(+)		22.79(+)	Ca(2.47) (+) Mg(4.80)(-)		Si et al. (2018)
Pot	Calcareous	Maize straw	300 450 600	1%	247.41 (+)			42.37(+)	105.32(+)		469.73(+)			Song et al. (2018)
Field	Sandy loam/wheat-maize	Wheat straw	350 550	40, 50, 100%	7.66(+)			16.46(+)	119.10(+)					Zheng et al. (2017)
Field	Clay loam/soybean-maize	Corn stalks	500-600	0, 2, 4, 8%	349.26 (+)	119.35(+)	2.22(-)	120.39(+)	15.78(+)	17.86(+)	9.11(+)			Yao et al. (2017)
Greenhouse	Alluvial soil/rice	Rice husk		2.5, 5, 7.5, 10, 15, 20 t/ha	70(+)								Fe(54.63)(+) Cu(192.99) (+) Zn(162.64) (+) Mn(87.37)(+)	Jatav et al. (2018)
Soil column	Riparian	Rice husk	450	1, 2, 3, 10%		88.11(+)	53.35(-)	58.64(+)	85.05(+)					Bu et al. (2017)
Pot	Calcareous sandy/wheat	Corn cobs		20, 40, 60 Mg/ha	166.67 (+)				25.51(+)		75.78(+)			Amin (2016)
Incubation		Elephant grass	400 500 600	5, 15 g/L	2.11(+)					16619.75(+)	3122.03(+)	Ca(45.6)(+) Mg(460)(+) S(1579.71)(+)	Zn(17.72)(-) Cu(20.25)(-) B(114.28)(-)	Ferreira et al. (2018)

													Mn(60.98)(+)	
Microcosm	Silty clay loam	Rice straw, rice hull, and Maize stover	500	1.5, 3%	16.86(+)		161.90(+)			140 (+)	122.61(+)			Bashir et al. (2018)
Field	Fluvisol/wheat-maize	Rice husks (70%) and cotton seed hulls (30%)	400	30, 60, 90 t/ha	29-41.5(-)									Dong et al. (2018)
Field	Farmland	Wheat straw and peanut shell	500	8 t/ha							10.53(-)	Ca(1.80)(-) Mg(3.37) (+)		El-Naggar et al. (2018)
Incubation	Clay loam, loam and sandy loam	Sugar cane bagasse	450-500						23.72-63.67(+)					Gerdelidani and Hosseini (2018)
Greenhouse	Loamy, kaolinitic, thermic Grossarenic Kandiodult/maize	Coconut husks, orange bagasse and pine woodchips	500	5, 10, 20, 60 t/ha				30.39(+)	21.88(-) 13.28(+)	18.51(+)				Gonzaga et al. (2018)
Pot	Loamy/turf grass	Sewage sludge	500	0, 1, 5, 10, 20, 50%	4443.65(+)			6209.09(+)	3819.88(+)		740.77(+)			Yue et al. (2017)
Greenhouse	Calcareous	Sewage sludge	350	7.3, 14.5, 29 Mg/ha		16.11(+)		1.18(+)	32.79(+)		2.79(+)			Khanmohammedi et al. (2017)
Incubation	Silt loam	<i>Miscanthus</i> straws, coffee husks and woody material	600	1, 3%					75(+)					Houben et al. (2017)
Growth chamber	Commercial/tomato and castor bean	Castor cake and castor stalks	550	1, 5%				59.30(-) 9.05(+)		81.20(+)			Zn(32.74)(+) Mn(25.19)(-) Cu(25.52)(-) Fe(6.50)(-) Fe(17.51)(+)	Hilioti et al. (2017)
Incubation and greenhouse	Sandy clay loam/Chinese cabbage	Kunai grass	500		1900(-)	75(+)								Baiga and Rao (2017)
Others														
Incubation	Calcareous	Wheat straw and cow manure	300 and 500	5, 10 t/ha						290.91(+)				Beheshti et al. (2017)
Greenhouse	Loam/maize	Poultry litter	500-520	5, 10 Mg/ha				55.77(+)		27.27(+)		Ca(4.35)(-) S(75)(+)	Mn (52.67)(-)	Brantley et al. (2016)
Pot	Sandy/wheat	Wood and peanut shell –	450	1, 2 %					208(+)					Madiba et al. (2016)

		Chicken manure – wheat chaff												
Screen house	Organic/Rice	unknown		0, 2 t/ha		1.72(+)		4.45(-)						Dewi et al. (2018)

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1530 Table 6: Impact of biochar on different crops

Expt./crop	Source of biochar and application rate	PT (°C)	Changes over control (%)				Crop growth (%)	References		
			Nutrient concentration	Nutrient uptake	NUE	Crop yield				
						grain			biomass	
Field/various	Rice husk (20 t/ha)	500	N(5.20)(-), (2.11)(+), P(11)(+)				9-15 (+)	Akoto-Danso et al. (2018)		
Incubation and germination/rice and tomato	Rice husk (0.5, 1, 5, 10, 25, 50%)	480						Seedling emergence(17-20)(-)	Anyanwu et al. (2018)	
Germination/ <i>Quercus serrata</i> and <i>Prunus sargentii</i>	Oak tree and bamboo()	700-800 1200						Seedling quality index(8.3-19.9)(+)	Aung et al. (2018)	
Roof and ground/Ryegrass, <i>Sedum lineare</i> and cucumber	Sewage sludge(5, 10, 15, 20%,)						54-54.2(+)	Promoted plant growth	Chen et al. (2018)	
Screenhouse/Rice	Unknown(2 t/ha)						6.3-13.3(+)		Dewi et al. (2018)	
Pot/Chinese melon	Pinewood(5%)							Plant height, No. of leaves and stem dia (43, 192. 60, 66.5)(+), respectively	Elbasher et al. (2018)	
Greenhouse/Okra	Wheat straw(5, 10%)	350-550						Plant growth increased; salinity threshold level(81.2)(+)	Elshaikh et al. (2018)	
Pot/Bean	Maple residue(5, 10%)	560	K(28.57), Ca(6.20), Mg(10)(+)				20.22(+)	Plant growth increased	Farhangi-Abriz and Torabian (2018)	
Spinach	Cattle manure(1.25, 2.5, 5%)	600					51(+)	Stomatal conductance(11-63)(+)	Gavili et al. (2018)	
Greenhouse/Maize	Coconut husks, orange bagasse and pine wood chip(5, 10, 20 and 60 t/ha)	500	N(0.88), P(0.15)(+)				90(+)		Gonzaga et al. (2018)	
Greenhouse/Rice	Rice husk((2.5, 5.0, 7.5 10, 15, 20 t/ha))			Fe(480), Cu(570), Zn(336), Mn(322)(+)			8.5(+)	7.5(+)	Panicle length, grain/panicle, test weight, (78.37), (85.33), (34.55)(+), respectively	Jatav et al. (2018)
Field/Chinese cabbage	Barley straw(10 t/ha)	400	N(0.43), P(0.08), K(0.28)(+)	N, P, K (-)			64.9(+)		Kang et al. (2018)	
Mesocosm/ Broadleaf cattail	Alder(95%), birch, oak, linden and willow(10%)						170(+)		Kasak et al. (2018)	

Field/Spring barley	paper fiber sludge and grain husks (10, 20 t/ha)	550				77.78(+)	44(+)	Plant height(23.79)(+)	Kondrlova et al. (2018)
Field/Corn, cotton, peanut,	Re oak(22.4, 44.8 t/ha)	450-600				33(+)			Lamb et al. (2018)
Pot/Wheat	Apple branch(1,2,4,6%)	450				7.4-12(+) 6.25- 21.83(-)			Li and Shangguan (2018)
Greenhouse/Maize	Coffee ground and coffee husk(4, 8, 12 and 16 t/ha)	530			N(71), P(44)(+)			Improve plant growth	Lima et al. (2018)
Pot/Rice	Bamboo(0.16kg/pot)	600				81.82(+)	58.82(+)		Lu et al. (2018)
Pot/Wheat-maize	Rice residue(10, 20, 40 t/ha)						40(+)		Mavi et al. (2018)
Pot/Bean	Biosolid(4, 8, 16, 32 t/ha)	190		P, Ca, Zn (+)			96-112(+)		Melo et al. (2018)
Growth chamber/Crabgrass	Mixture of softwoods and loblolly pine + switchgrass (2%)	450					72.72(+)		Mitchell et al. (2018)
Field/Maize-Mustard	<i>Eupatoriumadenophorum</i> (5,10,15,25,40 t/ha)	400-500				50- 134(+)			Pandit et al. (2018)
Greenhouse/Rice	Rice straw and sugarcane bagasse(0.3, 0.9%)	350				260- 321(+)			Sadegh-Zadeh et al. (2018)
Pot/Sunflower, Maize	Miscanthus (25, 50, 75%)	350				33-50(+)	42-70(+)	Physiology, biochemistry and antioxidant defense(+)	Shahbaz et al. (2018)
Field/Rice	Rice straw(2.25 t/ha)	550-650				33(+)	20-29.4(+)	Grains/panicle (72.7)(+)	Si et al. (2018)
Greenhouse/Maize	Cotton husks, eucalyptus residue, sugarcane filtercake, swine manure (1, 2, 3, 4%)						20(+)		Speratti et al. (2018)
Field/Wheat	Wood of <i>Dalbergia sissoo</i> (1, 2, 3, 4, 5, 6, 7, 8, 9 and 10%)	500-700	N (25-48)(+)	N(50)(+)	N(65)(+)	38(+)	19(+)		Abbas et al. (2017)
Pot/Zucchini	Maize stalk(6.3, 12.6, 25.5 g/pot)	400			N(90.03)(+)	26.7- 195(+)			Amin and Eissa (2017)
Field/Maize-wheat	Acacia prunings(10 t/ha)	1000			P(69.23- 150)(+)	18-24(+)		Plant height, grains/panicle, 1000-grain weight and harvest index (+)	Arif et al. (2017)
Hydroponics/leafy vegetables	Rice husk(1:1 ratio)	500	Ca, Mg, Mn, Zn(120-350)(+)	N(12)(+)			100-140(+) 55.8-87.1(-)	Shoot length (49)(-) Shoot and leaves number(200)(+)	Awad et al. (2017)
Greenhouse/Corn	Softwood chips(20 t/ha)	500	N(15.5)(+)				17(+)	Total root length (18)(+) Specific root length(5)(+)	Backer et al. (2017)

								Tissue density(7)(-)	
Pot/Chinese cabbage	Kunai grass(10 t/ha)	500		N(14.89)(+)		48.92(+)	35.67(+)		Baiga and Rao (2017)
Field/Maize	Chicken litter(10, 20 t/ha)	550	N(31.90), P(256.25), K(112.27), Ca(20.82), Mg(11.76)(+), Fe(72.5)(-)	N(706.62), P(2096.34), K(1189.68), Ca(674.15), Mg(550.63), Fe(212.93)(+)	P(190.96)(+)	339.23(+)	512.70(+)		Ch'ng et al. (2017)
Field/Rice	Rice straw(2, 40 t/ha)	400-500				10(+)		Grains/panicle (5.20)(+) Seed setting rate (3.05)(+) 1000-grain weight (1.05)(+) No. of effective tillers/hill(1.95)(+)	Cui et al. (2017)
Field/Corn	Sewage sludge(15 t/ha)	300 and 500		N(49.27), P(98.73), K(31.83), Ca(58.92), Mg(96.90), S(53.93), Cu(85.71), Zn(127.27), Fe(14.89), Mn(50)(+)		33.33-46.67(+)			Faria et al. (2017)
Field/major crops & cover crops	Norway spruce (70%) +European Beech (30%) (15, 30 t/ha)	550-600	K(16)(+), Mn(25-42)(-)		N(6.09-8.01)(-)	9.18-11.00(-)	11.68-25.68(-)	Plant height (7-14)(-)	Haider et al. (2017)
Greenhouse/Maize	Sewage sludge(7.3, 14.5, 29 t/ha)	350	N(6.14), P(15.39)(-), K(1.46)(+), Fe(10.07), Zn(17.52), Cu(12.22), Mn(1.54)(-)	N(9.66), P(23.26), K(2.84)(-)			11.67(-)		Khanmohammadi et al. (2017)
Pot/ Sugar maple and Red pine	Maple sawdust and wood ash(5, 20, 50 t/ha)	450	N(1.5), P(28.03), K(46.96), Ca(1.83), Mg(7.22), S(28.57)(+)				20(+)		Noyce et al. (2017)
Glasshouse/Corn	Empty fruit bunch (0, 5, 10, 15 and 20 t/ha)	350-450	N(148), P(236), K(185), Ca(181), Mg(154)(+)	N(564), P(666), K(678), Ca(600), Mg(500)			67-150(+)		Abdulrahman et al. (2016)
Field/Maize	Maize cobs (4 t/ha)	350				154-425(+)	152-246(+)		Abiven et al. (2015)
Field/Maize	Willow wood waste (2.5, 10 t/ha)	550	N(5-14), P(11-41)(+), $\delta^{15}\text{N}$ (1.3-2.2 times)	$\delta^{13}\text{C}$ (10.9-11 times)		10-29(+)	12-18(+)		Agegnehu ,Bass , et al. (2016)
Field/Barley	Stem, bark and branches of Acacia wood (2, 10 t/ha)	350-450	N(6.5-11)(+), $\delta^{15}\text{N}$ (1.2 times)	N(37-64)(+)	N(45)(+)	30-79(+)	56-176(+)		Agegnehu ,Nelson , et al. (2016b)

Field/Barley	Stem, bark and branches of Acacia wood (2, 10 t/ha)		N(39), P(11), K(11)(+)			48(+)	52(+)		Agegnehu ,Nelson , et al. (2016a)
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