# Biochar production and applications in agro and forestry systems: A review

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## HIGHLIGHTS

- Biochar production technologies were compared and linked to biochar properties.
- Biochar effects on soil properties, nutrition and fertility were summarized.
- Biochar benefits to plant growth, C sequestration and GHG emissions were analyzed.
- Limitations and knowledge gaps of current research on biochar were discussed.
- Research needs enabling biochar use in agro and forestry systems were identified.

## GRAPHICAL ABSTRACT
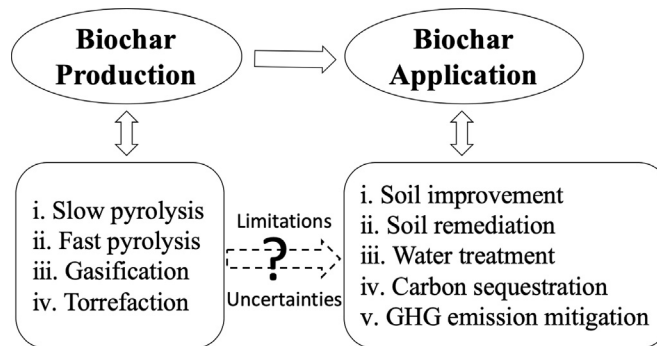
## ABSTRACT

Biochar is a product of biomass thermochemical conversion. Its yield and quality vary significantly with the production technology and process parameters, which also affect its performance in agro and forestry systems. In this review, biochar production technologies including slow pyrolysis, fast pyrolysis, gasification, and torrefaction were compared. The yield of biochar was found to decrease with faster heating rate or more oxygen available. The benefits of biochar application to agro and forestry systems were discussed. Improvements in soil health, plant growth, carbon sequestration, and greenhouse gas mitigation are apparent in many cases, but opposite results do exist, indicating that the beneficial aspect of biochar are limited to particular conditions such as the type of biochar used, the rate of application, soil type, climate, and crop species. Limitations of current studies and future research needed on biochar are also discussed. Specifically, the relationships among biochar production technologies, biochar properties, and biochar performance in agro and forestry systems must be better understood.

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## 1. Introduction

Biochar is mainly produced through thermochemical conversion processes such as slow pyrolysis, fast pyrolysis, torrefaction, and gasification, under various process parameters (Leng et al., 2019). These

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processes irreversibly change the physical state and chemical composition of biomass into biochar in the absence or limitation of oxygen supply under specific temperatures and pressures. The chemical components of biomass undergo severe cross-linking, decomposition and depolymerization, converting the renewable biomass into a carbon-rich solid residue called biochar, along with a condensable organic liquid known as bio-oil or tar, and a non-condensable combustible gas consisting of hydrogen, carbon oxides, light hydrocarbons and some other compounds depending on reaction conditions (Giudicianni et al., 2013).

Biochar has been identified as a promising strategy to sequester carbon (C), produce energy, increase soil productivity, and improve soil and environmental quality (Clough and Condron, 2010; Qian et al., 2015; Hua et al., 2009). The numerous benefits of biochar illustrate its potential to contribute to the economic sustainability of emerging cellulosic bioenergy production systems (Lehmann, 2007; Laird et al., 2009; Sohi et al., 2010). On the other hand, land application of biochar can permanently sequester C in the soil and reduce net emissions of greenhouse gases (Lehmann et al., 2006; Laird, 2008), increase crop production through improved nutrient availability and soil physical, chemical, and biological properties (Yamato et al., 2006; Asai et al., 2009), and reduce loss of nutrients, sediment, and pollutants (Major et al., 2009; Cao and Ma, 2009; Wang et al., 2010). Biochar application can be a means of not only sequestering carbon in the soil but also returning essential organic matters lost with biomass removal from agro and/or forestry systems for energy production. Thus, biochar can potentially provide two simultaneous economic benefits. One, it may improve the agronomic and environmental sustainability of biomass production systems. Two, it may improve the economic sustainability of bioenergy enterprises by offsetting feedstock purchases with revenue from biochar sales.

However, biochar impacts on soil, environmental, and agronomic characteristics have not been systematically studied. While biochar has the potential to generate revenue and enhance the sustainability of agriculture and environment, the agricultural and bioenergy industries will be reluctant to pay for biochar until its precise effects on soil properties and crop production are shown. Complete development of biochar as a commercial product must establish concrete benefits of the product to soil properties and crop production and link these benefits to biochar properties and its appropriate use and economic value. One of the most important factors to make this a reality is the understanding of how this product is made and how the production process affects its performance. Its benefits on crop production, environment, and soil will be a moot point if it is not reproducible and consistent.

Thus, the objectives of this review were to compare biochar production technologies, and link the processes to biochar yield and properties, and associate biochar properties to its benefits to agro and forestry systems. Technologies including slow pyrolysis, fast pyrolysis, gasification and torrefaction were compared in this review. Biochar applications in agro and forestry systems and their effects on soil health, plant growth, carbon sequestration, and greenhouse gas mitigation were summarized. Limitations of current studies on biochar were also discussed.

## 2. Biochar production technologies

Depending on the thermochemical operating parameters and the intrinsic nature of biomass, biochar has different physical and chemical properties. Several units and reactors have been developed for the production of biomass in order to achieve higher yield and quality of target product. These reactors are similar in terms of principle, but differ in the use of oxygen, heating rate, and final temperature, which may change the quality and distributions of final products. Fig. 1 shows various types of thermochemical processes for biochar production including slow pyrolysis, fast pyrolysis, gasification and torrefaction. Based on different reaction conditions, especially the amount of oxygen available, the yield and quality of biochar produced in these processes are vastly different. For instance, high yield and quality biochar can be obtained through prolonging the residence time of biochar to many hours even several days at around 400 °C pyrolysis temperature, which typically belongs to biomass slow pyrolysis.

### 2.1. Slow pyrolysis

Biochar prepared from various organic and non-organic materials, such as agricultural residue, forest residue, algal biomass, scrap tire, heavy crude oil, have been utilized extensively as the precursor of
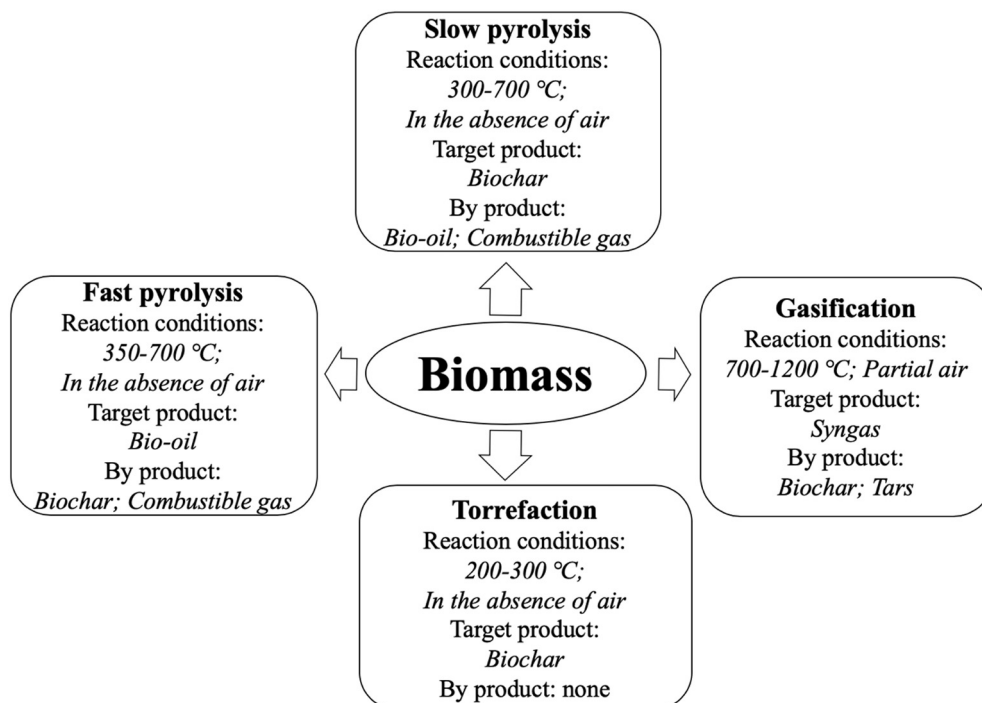


**Fig. 1.** Biomass thermo-chemical conversion technologies for biochar production.

biochar through slow pyrolysis (Liao et al., 2018). Slow pyrolysis is a process in which biomass undergoes decomposition at a relatively moderate temperature (350–500 °C), which provides the sufficient residence time for biomass pyrolysis vapor and increases its secondary cracking level as much as possible. "Slow" in the slow pyrolysis process indicates low heating rate; meanwhile, the "optimum char formation temperature region" (Weinstetn and Broido, 1970) is also a crucial factor influencing the quality and yield of biochar. Generally, the quality of biochar is related to its carbon content, pH value, specific surface area, porosity, and nutrients. Among these, the quality of biochar is more closely related to its carbon content (Shackley et al., 2014; Yao et al., 2018). As shown in Table 1, higher quality biochar (high carbon content) can be obtained based on these pyrolysis parameters including relatively high pyrolysis temperature, longer residence time and lower heating rate. For instance, biochar obtained from the pyrolysis of wood at a high temperature (750–900 °C) and long residence time (> 30 min) is claimed to be much better char material to substitute for coal and coke in steelmaking (Mousa et al., 2016; Jahanshahi et al., 2015). The carbon content of biochar obtained from slow pyrolysis of red cedar wood reached up to 88.88% at 500 °C pyrolysis temperature and 6 °C/min heating rate; meanwhile, higher heating value of biochar achieved 32.95 MJ/kg, suggesting high quality of biochar (Yang et al., 2016). Higher pyrolysis temperature is essential for improving the quality of biochar in slow pyrolysis processes since more volatiles are removed from biochar, increasing its carbon content. In addition, reducing the heating rate favors more sufficient heat conduction, which is conductive to the carbon deposition reaction and thus to the increase in biochar production (Veses et al., 2015).

In addition to these three parameters, other operating parameters of biomass slow pyrolysis, including particle size, presence of a catalyst, pyrolysis atmosphere, also have a direct impact on the quality and yield of biochar. The reactions leading to the formation of additional biochar could be favored by increasing the ratio of catalyst to biomass, particle size, feedstock residence time, and increasing the residence time of pyrolysis vapor contacting with some partially converted biomass (Garcia-Perez et al., 2007; Veses et al., 2015). In addition, biomass feedstock is the crucial factor affecting the yield and quality of biochar. The yield of biochar using forestry plants as the precursor is about 30% at 500 °C pyrolysis temperature, 60 min residence time and 10 °C/min heating rate (Solar et al., 2016). Compared to this, biochar yield from the pyrolysis of lignin reached up to 45.69% (Farrokh et al., 2018), suggesting that lignin content is an important parameter for biochar yield. Lee et al. (2013) also reported that biochar yield is highly dependent on the ash and lignin contents of biomass.

Besides biochar, bio-oil could be a product or byproduct of slow pyrolysis. In a slow pyrolysis process, the pyrolysis vapors released from

biomass contain the condensable and non-condensable components in a relatively high pyrolysis temperature. The condensable components can be collected as bio-oil, which is also called as "wood vinegar" due to that it contains a certain amount of acetic acid. Bio-oil is mainly consisted of oxygenated organic compounds, such as acids, esters, ketones and phenols (Setter et al., 2020). These numerous chemicals in bio-oil can be extracted and used as value-added bioproducts (Wang et al., 2014a, 2014b; Shen et al., 2011).

Earth kiln or metal kiln are usually used as the fixed bed pyrolysis reactors for biochar production, in which biomass is piled and heated in the airtight kiln for many hours or even several days (Garcia-Perez et al., 2010). A kiln is made from clay or metal, a type of oven, that produces sufficient heat to complete slow pyrolysis processes of biomass. In these fixed bed pyrolysis reactors, the solid reactants may not be heated uniformly, and the gas-solid contact is poor in a fixed bed reactor. Auger pyrolysis reactor is extensively used in industry because of its simplicity of construction and operation (Brassard et al., 2017; Veses et al., 2015). In addition, through adjusting the rotating speed of the screw, the residence time of biomass in the auger pyrolysis reactor can be easily controlled, and the continuous biochar production can also be realized simultaneously (Brassard et al., 2017). Garcia-Perez et al. (2007) compared a batch with a continuous auger reactors for the slow pyrolysis of pine. The char yield (30 and 31 wt%) are basically the same for both reactors, suggesting that the reactions leading to char formation are very similar for both pyrolysis reactors. Except for the auger pyrolysis reactor, another continuous pyrolysis reactor (bubbling fluidized bed) has also been studied for biomass slow pyrolysis. Patel et al. (2019) developed the slow pyrolysis of biosolid with 60 min solid residence time in a bubbling fluidized bed reactor. No matter which reactor is used in the slow pyrolysis process, it should be noted that the pyrolysis vapor is usually not condensed, but burned directly to provide heat for the operation process due to that pyrolysis is an endothermic process.

### 2.2. Fast pyrolysis

Slow pyrolysis occurs under slow process conditions (lower heating rates and relatively long residence time), which is known as carbonization. Fast pyrolysis, in contrast, involves very high heating rates, about 1000 °C/min, to the pyrolysis temperature around 500 °C, and the residence time of vapor is normally <2 s (Choi et al., 2017). In a fast pyrolysis process, the biomass particles experience rapid decomposition to generate pyrolysis vapors and biochar (10–15 wt%). The condensable composition in the pyrolysis vapors is quenched and collected in the downstream facilities, which is a dark-brown liquid called bio-oil, and biochar is the byproduct of this process. It is understandable that higher pyrolysis temperature reduces the yield of biochar owing to facilitating

**Table 1**
The yield and physicochemical properties of biochar from slow pyrolysis.

| Biomass feedstock | Slow pyrolysis parameters | | | Yield(%) | Biochar composition | | | | Ref. |
|---|---|---|---|---|---|---|---|---|---|
| | T (°C) | RT (min) | HR (°C/min) | | C | H | N | S | |
| Cow manure | 300 | 120 | 10 | 58.0 | 51.30 | 4.52 | 1.70 | – | Yue et al., 2017 |
| Pine wood | 300 | 60 | 17 | 43.7 | 71.3 | 4.7 | – | – | Ronsse et al., 2013 |
| Coffee husk | 350 | 30 | 0.5 | 39.82 | 69.96 | 3.63 | 3.58 | 0.24 | Setter et al., 2020 |
| Neem press seed cake | 450 | 60 | 20 | 38.3 | 52.39 | 2.57 | 2.23 | 0.12 | Dhanavath et al., 2019 |
| Wheat straw | 475 | 180 | 8 | – | 69.9 | 2.5 | – | – | Heikkinen et al., 2019 |
| Palm shell | 500 | 60 | 10 | 35.5 | 60.12 | 9.21 | 0.42 | 0.92 | Qureshi et al., 2019 |
| Hinoki cypress | 500 | 60 | 10–15 | 23.3 | 85.79 | 3.89 | 0.23 | – | Yu et al., 2019b |
| Lignin | 500 | 480 | 5 | 45.69 | 85.9 | 3.56 | 1.23 | 0.121 | Farrokh et al., 2018 |
| Algae | 500 | 60 | 10 | ~32 | 45.26 | 1.24 | 2.57 | – | Chaiwong et al., 2013 |
| Walnut shell | 500 | 60 | 15 | ~30 | 77.97 | 3.22 | 1.13 | – | Gupta et al., 2019 |
| Rubber wood | 500 | 20 | 10 | 24.25 | 87.17 | 1.23 | 0.40 | – | Halim and Swithenbank, 2016 |
| Redcedar sapwood | 500 | 30 | 6 | 30.9 | 85.8 | 2.4 | 0.35 | 0.35 | Yang et al., 2016 |
| Redcedar heartwood | 500 | 30 | 6 | 21.0 | 88.88 | 2.6 | 0.35 | 0.4 | Yang et al., 2016 |
| Corn straw | 550 | several | 30 | ~24 | 92.83 | 1.49 | 0.84 | 0.06 | Delgado et al., 2013 |

T: temperature; RT: residence time; HR: heating rate.

the release of gaseous volatile matters, while high heating rate also has the similar effect. Under a high heating rate, biomass feedstock is rapidly heated and the pyrolysis vapors released are rapidly transported from the pyrolysis reactor. These pyrolysis vapors have less residence time in the high temperature zone, thus reducing the amount of carbon deposition. For instance, the yield of safflower seed biochar decreased about 3–8% with increasing the heating rate from 10 to 50 °C/min (Angın, 2013). The yield of poplar wood biochar decreased from 34.83 to 31.95 wt% at 400 °C final pyrolysis temperature by increasing the heating rate from 10 to 50 °C/min (Chen et al., 2016). Aguado et al. (2000) observed that increasing heating rate from 5 to 40 °C/min resulted in the decrease in char yield from 38.8% to 26.4%. Furthermore, an increase in pressure can improve biochar yield due to that vapor residence time is prolonged within the biomass particles which promotes the char forming reactions (Mohan et al., 2014). Antal et al. (1996) reported that biochar yield reached up to 41–62% in a high-pressure pyrolysis reactor. Wang et al. (2013) reported that the char yield slightly increased from 24.9 wt% to 27.5 wt% when the pyrolysis process of pine sawdust was carried out in a closure fixed bed reactor. In addition, different fast pyrolysis parameters and reactor designs on the yield and quality of biochar are summarized in Table 2, which vary very widely also depending on the biomass used.

Higher pyrolysis temperature is beneficial for increasing the carbon content of biochar and its specific surface area due to the release of volatiles from the biomass particle. For instance, the specific surface area of rapeseed stem biochar increased from 1 to 45 m$^2$/g with increasing pyrolysis temperature from 200 to 700 °C (Zhao et al., 2018). The carbon content of biochar derived from the pyrolysis of pine sawdust increased from 70.68% to 78.75% with increasing the pyrolysis temperature from 550 to 750 °C (Peng et al., 2012). The heating rate has more complicated effects on the quality of biochar in fast pyrolysis processes. Onay (2007) explained that the biochar produced at higher heating rate presents a higher carbon content and the specific surface area compared to low heating rate biochar because varying heating rate resulted in differences in the devolatilization rate and thus modifying the structure of biochar. Chen et al. (2016) also found that increasing heating rate enhanced the carbon content of biochar; meanwhile, the BET surface area of biochar exhibited a first increasing and then decreasing trend. However, Mohan et al. (2014) reported that high heating rates reduced the specific surface area and pore volume of biochar owing to the rapid depolymerization at the biochar surface. These studies indicate that high heating rate seems to improve the carbon content of biochar, but have no direct effect on the BET specific surface area of biochar.

In a fast pyrolysis process, several pyrolysis reactors, including bubbling fluidized bed, circulating fluidized bed, ablative reactor, rotary cone, auger or screw reactors have been extensively developed for obtaining higher bio-oil yield (Qureshi et al., 2018). The description of these fast pyrolysis reactors can be found in lots of literatures (Brown, 2011; Bridgwater, 2012). Generally, biochar needs to be separated from the pyrolysis vapors as quickly as possible to minimize the pyrolysis vapor cracking reactions. There is about 15 wt% byproduct char produced during pyrolysis by fluidized bed reactors, rotary cone or ablative reactors (Bridgwater, 2012), while biochar yield can reach up to about 25 wt% by an auger/screw reactor (Raclavska et al., 2015). It should be noted that in an industrial process, the biochar and/or pyrolysis gas are usually used as a fuel for providing the process heat.

### 2.3. Gasification

Gasification usually takes place at 700–1000 °C, in which biomass undergoes an incomplete combustion with various gasifying agents such as air, pure oxygen, or steam and oxygen to produce a gas product. Generally speaking, in a biomass gasification process, researchers firstly focus on how to improve the quality and yield of syngas, reducing some contaminants like fly ash, nitrogen oxides, sulfur dioxide and tar (Han and Kim, 2008). As an undesirable byproduct of this process, the evaluation of char under different gasification conditions maybe more concerned by researchers. The quality of biochar produced from biomass gasification is closely related to its carbon content (Shackley et al., 2014). It is mainly affected by gasified parameters including equivalence ratio (ER), feedstock properties, gasifying agent and pressure. Among these parameters, ER value is regarded as the most important affecting the gasification process, and the optimum value is around 0.25–0.28 according to the physical-chemical properties of biomass (Benedetti et al., 2018). Generally, increasing ER leads to the increase in gasification temperature, which affects the quality of biochar produced as shown in Table 3.

The yield and quality of char as a function of ER have been explored extensively in recent years. Yao et al. (2018) reported that char yield decreased from 0.22 to 0.14 kg/kg biomass with increasing ER from 0.1 to 0.6; meanwhile, carbon content of the produced biochar slightly decreased from 88.17% to 71.16%. Muvhiiwa et al. (2019) reported that carbon content of biochar decreased from 89% to 80% at 700 °C and from 93% to 86% at 900 °C when oxygen flow rate was increased from 0.15 to 0.6 kg/h. These studies showed that the increase in ER in gasification processes reduces the biochar yield and carbon content of biochar. Higher ER value indicates that more oxygen is fed into the gasifier, which results in both positive and negative impacts for the quality of biochar. On one hand, it strengthens the heterogeneous reactions to convert more carbon from the solid phase into gaseous species, facilitating the formation of micropores and further increasing the specific surface area of biochar (Kumar et al., 2017). On the other hand, more oxygen molecules in the gasification process may cause the strong ablation of biochar, reducing its mechanical strength and yield, as well as increasing its ash content.

Currently, various types of biomass gasifiers, the fixed bed (e.g., the updraft gasifier and the downdraft gasifier or their combinations and variations), the fluidized bed (e.g., the bubbling fluidized bed gasifier

**Table 2**
The yield and physicochemical properties of biochar from fast pyrolysis.

| Biomass | Reactor | Pyrolysis temperature (°C) | Yield (%) | Biochar composition | | | | | Ref |
|---|---|---|---|---|---|---|---|---|---|
| | | | | C | H | N | S | O | |
| Wheat straw | Airtight twin-screw reactor | 500 | 26 | 56 | 2.3 | 1.0 | – | – | Funke et al., 2018 |
| Sweet sorghum | Fluidized bed reactor | 500 | 23.8 | 69.03 | 2.78 | 0.59 | – | 276 | Yin et al., 2013 |
| Corn stalks | Fluidized bed reactor | 550 | – | 72.28 | 3.14 | 1.09 | 0.9 | 22.47 | Wang et al., 2014b |
| Yellow poplar | Fluidized bed-type pyrolyzer | 500 | 5.1 | 76.3 | 2.3 | 0.7 | – | 20.7 | Hwang et al., 2015 |
| Corn cobs | Bubbling fluidized bed | 500 | 18.9 | 77.6 | 3.05 | 0.85 | 0.02 | 5.11 | Mullen et al., 2010 |
| Pine sawdust | Fixed-bed reactor | 550 | – | 70.68 | 3.6 | 2.4 | 0.21 | 23.11 | Peng et al., 2012 |
| Rice husk | Conical spouted bed | 500 | 26 | 45.2 | 1.5 | 0.4 | – | 1.7 | Alvarez et al., 2015 |
| Pine sawdust | Fixed-bed reactor | 500 | – | 70.68 | 3.6 | 2.4 | 0.21 | 23.11 | Yan et al., 2010 |
| Douglas fir | Bubbling fluidized bed | 480 | 11.2 | 75.8 | 1.56 | 0.33 | 0.13 | 19.57 | Wu et al., 2016 |
| Lvory nut | lab-scale pyrolyzer | 500 | 15.82 | 69.59 | 2.93 | – | – | 18.31 | Ghysels et al., 2019 |
| Bamboo | Horizontal screw conveyor | 500 | 24.4 | 81.7 | 3.7 | – | – | – | Kajita et al., 2010 |
| Rice husk | Fixed bed reactor | 550 | 38.86 | 44.73 | 1.80 | 0.73 | – | 7.69 | Zhang and Xiong, 2016 |
| Brown macroalga | Bubbling fluidized bed | 375 | 56.08 | 30.67 | 2.72 | 2.09 | – | 64.53 | Choi et al., 2017 |

**Table 3**
The yield and physicochemical properties of biochar from gasification.

| Biomass | Reactor | Gasification temperature (°C) | Biochar composition | | | | | Ref. |
|---------|---------|------------------------------|------|------|------|------|------|------|
| | | | C | H | N | S | O | |
| Raw straw | dual-fixed bed reactor | 800 | 63.81 | 0.95 | 1.69 | 0.13 | 5.24 | Xu et al., 2019 |
| Dealcoholized marc of grape | lab-scale drop-tube | 1200 | 52.97 | 3.92 | 1.65 | 0.47 | 40.97 | Hernández et al., 2020 |
| Wood chips | Dual stage gasifier | 900 | 78.97 | 0.68 | 0.20 | – | – | Benedetti et al., 2018 |
| Pellet | Rising co-current | 700 | 83.39 | 0.98 | 0.23 | – | 1.86 | Patuzzi et al., 2016 |
| Coconut shells | fluidized bed gasifier. | 750 | 87.7 | 1.3 | 0.3 | – | 6.8 | Millán et al., 2019 |
| Japanese cedar | horizontal quartz tube | 900 | 94.6 | 0.6 | 0.3 | – | – | Bai et al., 2014 |
| Wood pellets | nitrogen plasma torch reactor | 700 | 83.48 | 1.89 | 0.41 | – | 14.22 | Muvhiiwa et al., 2019 |
| Pine | fixed-bed reactor | 800 | 86.31 | 2.27 | 0.14 | 0.01 | 6.23 | Huang et al., 2013 |
| Beech bark | batch dense fluidized bed | 850 | 75.49 | 0.56 | – | – | 6.06 | Morin et al., 2016 |

and the circulating fluidized bed gasifier), have been developed. Sansaniwal et al. (2017) reviewed the development of these biomass gasifiers in recent years. It is worth to note that small scale gasifiers are typically autothermal, atmospheric and use air as the gasifying agent. Compared with ER, different gasifier designs have slight effects on the yield and properties of biochar. Many researches showed that the carbon content of char mainly depended on the ER instead of the types of gasifiers (Benedetti et al., 2018; Morin et al., 2016; Hernández et al., 2020). Even so, in a top-lit updraft gasifier developed by James et al. (2016, 2018), biochar yield reached up to 39.3% for the gasification of rice hulls. Adeniyi et al. (2019) also developed a top-lit fixed-bed updraft gasifier. By using this gasifier, biochar yield was 14.29 wt% for elephant grass, and the specific surface area of biochar reached up to 475 m²/g.

### 2.4. Torrefaction

Another developing thermal-chemical process called biomass torrefaction is mainly used for producing a "charred" product that can be used as a fuel and/or soil amendment (Barskov et al., 2019). In a typical torrefaction process, biomass feedstock is heated directly and/or indirectly to temperatures between 200 and 300 °C in an inert atmosphere at a low heating rate (i.e., lower than 50 °C/min) and a relatively long residence time (20–120 min) (Wang et al., 2017). During this process, about 30% of the mass belonging to some highly reactive volatile compounds are transformed into torrefied vapor (Ma et al., 2019). The production of the dark brown solid fuel containing 90% of the initial energy content is the target product of this process, torrefied

biochar, and an energy densification of about 1.3 can be achieved (van der Stelt et al., 2011). The energy density of torrefied biochar can be increased to close to that of coal (22–23 MJ/kg) used for heating and power generation (Phanphanich and Mani, 2011; Zwart et al., 2006). The torrefied volatiles produced is usually burned directly in a gas combustor for providing energy for the torrefaction process. In order to obtain high energy density of torrefied biochar, high torrefaction temperature and long residence time are essential in the torrefaction process, which result in the reduction of the quality and energy yield of torrefied biochar. According to Niu et al. (2019), the optimum torrefaction condition of biomass may be to maintain the solid yield in the range of 60–80%, in order to obtain relatively high higher heating value and mass energy density of biochar and energy yield.

Biomass physical-chemical properties, including moisture content, higher heating value, ash content, affect the quality of torrefied biochar (Medic et al., 2012). Among these, the moisture content should be the most crucial one due to that it predominantly determines the energy input of the torrefaction process (van der Stelt et al., 2011). It is well-known that biomass feedstock is composed of cellulose, hemicellulose and lignin. Torrefaction of these three major components has been studied to explore the crucial factor for torrefied biochar yield. The yield of biochar from hemicellulose torrefaction is the lowest among the three major components (Chen et al., 2019]. With the increase in torrefaction temperature and residence time, the content of hemicellulose and cellulose decreased in the torrefied biochar, while the content of lignin increased correspondingly (Wang et al., 2018a). Although the residence time of biomass is an important factor for the quality of torrefied biochar, torrefaction temperature has more significant influence compared

**Table 4**
The yield and physicochemical properties of biochar from torrefaction.

| Biomass | Torrefaction temperature (°C) | Mass yield (%) | Energy yield (%) | Biomass composition | | Biochar composition | | Ref. |
|---------|-------------------------------|----------------|------------------|------|------|------|------|------|
| | | | | C | H | C | H | |
| Pine chips | 225–300 | 89–52 | 94–71 | 47.21 | 6.64 | 49.47–63.67 | 6.07–5.58 | Phanphanich and Mani, 2011 |
| Stem wood | 260–310 | 97.1–45.9 | 98.8–62.8 | 50.3 | 6.2 | 51.4–69.2 | 5.9–5 | Broström et al., 2012 |
| olive pomace pellets | 200–250 | 79.92–53.04 | 94.5–68.4 | 54.93 | 6.33 | 57.31–63.61 | 6.33–4.68 | Brachi et al., 2019 |
| Raw pellets | 200–250 | 79.92–53.04 | 93.65–49.85 | 50.91 | 6.25 | 52.22–66.65 | 6.06–3.34 | Brachi et al., 2019 |
| Sugarcane bagasse | 200–300 | 79–52 | 98–79 | 32.5 | 5.01 | 34.5–50.3 | 4.98–3.4 | Kanwal et al., 2019 |
| Corn stover | 200–300 | 97.1–57.4 | 98.52–84.41 | – | – | 45.8–58.7 | 5.5–4.7 | Medic et al., 2012 |
| Peat | 230–270 | 82–70 | 91–87 | 52.09 | 5.79 | 59–65.3 | 5.49–5.26 | Krysanova et al.,2019 |
| Rice straw | 200–300 | 94.35–70.49 | 98.52–84.41 | 42.57 | 5.84 | 45.06–50.94 | 5.46–4.9 | Kai et al., 2019 |
| Bamboo | 210–300 | 95.34–59.98 | 97.36–75.11 | 46.12 | 6.11 | 48.54–61.23 | 6.08–4.8 | Ma et al., 2019 |
| Empty fruit bunches | 200–300 | 87.5–67.4 | 90.3–70.7 | 43 | 6 | 46.2–59 | 5.5–5.1 | Lam et al., 2019 |
| Parts of the plant | 250–300 | 77–63 | 88–80.5 | 46.5 | 5.1 | 56.4–65.6 | 6.0–5.9 | Cardona et al., 2019 |
| Spent coffee grounds | 200–300 | 97–62.82 | 98.07–78.84 | 52.99 | 7.29 | 53.94–68 | 7.28–6.85 | Zhang et al., 2018 |
| Medicine residue | 200–300 | 92.7–63 | 97.93–79.87 | 52.86 | 7.22 | 54.42–68.22 | 7.09–6.62 | Zhang et al., 2018 |
| Microalga residue | 200–275 | 89.35–62.64 | 91.98–79.45 | 36.49 | 6.12 | 41.27–61.63 | 5.95–5.38 | Zhang et al., 2018 |
| Licorice residue | 210–280 | 92–51 | 99.3–72.9 | 42.5 | 6.41 | 44.5–58 | 6.41–5.74 | Xin et al., 2018 |
| Biomass chips | 230–290 | 86–43.1 | 90.5–60.5 | 43.7 | 6.05 | 45.1–54.1 | 5.8–4.35 | Wilk et al., 2015 |
| Spruce stem | 225–300 | 92.4–68.6 | 93.05–79.88 | 48.78 | 6.27 | 50.06–62.17 | 6.09–5.72 | Wang et al., 2017 |
| Spruce stump | 225–300 | 92.7–55.6 | 94.26–64.76 | 47.38 | 6.49 | 49.21–60.21 | 6.21–5.89 | Wang et al., 2017 |
| Spruce bark | 225–300 | 90.4–63.0 | 96.93–74.8 | 49.09 | 6.06 | 55.4–67.34 | 5.53–3.89 | Wang et al., 2017 |

to duration (Kai et al., 2019). As shown in Table 4, for all kinds of biomass samples, torrefaction resulted in the biochar product having higher carbon content, but lower hydrogen content with increasing torrefaction temperatures. Pala et al. (2014) explained that both dehydration and decarboxylation are the main degradation reactions that contribute to significant mass loss during torrefaction. Furthermore, some researchers studied the torrefaction process of biomass in different agents (air or $N_2$). As expected, the mass and energy yields of the torrefied biochar of oxidative torrefaction is worse than that of the non-oxidative treatment (Brachi et al., 2019).

High quality biochar can be obtained in biomass slow pyrolysis due to that biomass experiences "deep pyrolysis" in a relatively mild temperature for a long time. Almost all the volatiles are completely released from biomass feedstock, which significantly increases the carbon content of solid biochar. Compared with that, the torrefied biochar has a lower moisture and volatile content because the original biomass feedstock only experiences "light pyrolysis" even at 200 °C for 20 min. In such a low torrefaction temperature, the feedstock may be just dried and does not subject to many chemical reactions. Even so, torrefied biochar still attracts extensive attentions due to its advantages. For instance, most of the moisture can be removed from the biomass feedstock, which reduces the transportation cost and increases the storage time of the feedstock The energy density of the torrefied biomass can be increased through decomposing the reactive hemicellulose fraction from the feedstock (van der Stelt et al., 2011). The torrefied biomass can also be easily ground into fine powders for use in pulverized coal-fed power plants compared to raw biomass materials (Barskov et al., 2019).

### 2.5. Biomass effects on biochar

The main components of lignocellulosic biomass feedstock are cellulose, hemicellulose and lignin. The degradation pathways of these three components have been investigated (Stefanidis et al., 2014). The initial pyrolysis temperature of these three components is different, and it is 170–240 °C for hemicellulose, 240–310 °C for cellulose, and lignin is the most stable which decomposes at 300–550 °C (Krzesińska, 2017; Williams and Besler, 1996). Interactions among these three components during pyrolysis have been demonstrated previously (Caballero et al., 1997), which indicates that the biomass pyrolysis process is extremely complex. For instance, the interaction between hemicellulose and lignin is beneficial for producing lignin-derived phenols while it hinders the generation of hydrocarbons (Wang et al., 2011). The interaction between cellulose and hemicellulose has a weak effect on the formation and distribution of biochar (Kan et al., 2016). Lignin also significantly interacts with cellulose during pyrolysis due to that lignin hinders the polymerization of levoglucosan from cellulose thus reducing biochar formation (Hosoya et al., 2007). Thus, it is still unrealistic to predict the pyrolysis characteristics of biomass simply based on the thermal behavior of the three individual components, so as to obtain the characteristics of biochar. In addition, a variety of biomass raw materials, different pyrolysis conditions, and various pyrolysis reactors, also affect the yield and quality of biochar. It implies that the current studies on the biomass pyrolysis mechanism cannot accurately predict biochar properties. The effect of biomass feedstocks on the yield and quality of biochar in a fast pyrolysis or gasification process is relatively unexplored due to the fact that the main product of these two processes is the liquid bio-oil and synthesis gas, respectively.

The differences in chemical compositions of lignocellulosic feedstock depend on the nature, type, origin and environmental conditions of the crop (Xuan et al., 2014). The nature of the lignocellulosic feedstock used affect the chemical composition and the properties of biochar (Yaashikaa et al., 2019). For instance, biochars produced from forestry waste often have higher carbon content than biochar made from agricultural biomass and animal wastes. The nitrogen content of biochar produced by feedstocks with high nitrogen content (such as algae) is

often higher than that produced from forestry biomass. When biochar is used as barbecue char, metallurgical carbon, or the preparation of activated carbon, forestry feedstocks should be chosen preferentially. In contrast, biochar produced from agricultural crop residues are desirable as a soil conditioner or fertilizer. The economic feasibility of biochar production should be emphasized. It is determined by many factors, such as transportation, the cost of biomass feedstock, the value of biochar, and the value of other value-added chemicals, which have been summarized in the literature (Oni et al., 2020; Zhang et al., 2019).

## 3. Biochar applications in agro and forestry systems

### 3.1. Biochar for soil improvement

#### 3.1.1. Soil physicochemical properties

Beneficial effects of biochar application on soil physical properties have been extensively reviewed, for example, the presence of biochar in the soil mixture can increase the net soil surface area, increase soil aeration and improve soil bulk density, porosity and packing (Chan and Xu, 2009; Palansooriya et al., 2019). In addition, biochar application directly changes the relationships of soil-water by increasing soil aggregate stability, soil-preparation workability, water infiltration and water holding capacity (Qambrani et al., 2017; Purakayastha et al., 2019). The decrease in bulk density and increase in soil porosity can contribute to the movement of water, heat, gases in soils and the improvement of soil quality (Lehmann et al., 2003; Lian and Xing, 2017). The changes on the physical nature of soil can be attributed to a large surface area and low bulk density of biochar due to a wide pore size distribution (Downie et al., 2009).

In addition to the improvement on soil structural quality and soil aggregation with biochar application, biochar also influences on soil chemical properties. Application of biochar into soil can alter its pH value. The beneficial effect is pronounced especially for acidic soils due to the alkaline nature of many biochars (Lehmann et al., 2015; Palansooriya et al., 2019). The alleviation of soil acidity has been attributed to the following parameters: 1) the alkaline nature of certain biochars; 2) high pH buffering capacity, because of the increased cation exchange capacities (CECs), the release of cation, such as K, Ca, Mg, and Na from biochars is a major factor for the increase in pH; 3) functional group effects, biochar functional groups like –COO– and —O— also contribute greatly to biochar alkalinity; and 4) mineral element effects such as Ca, K, Mg, Na, and Si in feedstocks form carbonates or oxides during the pyrolysis, which react with $H^+$ and monomeric Al species in acid soils by reducing exchangeable acidity and increasing pH (Yuan et al., 2011; Ahmed et al., 2016; Dai et al., 2017). Biochar may alter soil pH, which in turn can change nutrient solubility, thereby modifying the nutrient availability. The associated increase in soil pH with biochar addition would result in a greater availability of primary and secondary nutrients like K, P, Ca, Mg (Asai et al., 2009; Kookana et al., 2011). The other advantage of increased pH due to biochar addition is the reduction of Al toxicity in acidic soils (Purakayastha et al., 2019).

The CEC of soils is an essential property in relation to the soil fertility. The presence of biochar directly increases soil CEC. The higher CEC of biochar-amended soils may be attributed to the following reasons: 1) oxidation of aromatic carbon and development of carboxyl groups in the biochar; 2) the dominance of negatively charged surface functional groups; 3) increased specific surface area of the products (Glaser et al., 2002; Liang et al., 2006; Suddick and Six, 2013; Palansooriya et al., 2019). The increase in soil CEC benefits the nutrient retention of the soil profile and increases nutrient availability to plants roots (Laird et al., 2010). Additionally, the release of cations, such as K, Ca, Mg, and Na from biochars due to increased CEC is also a major factor for higher soil pH as discussed previously. The increase in soil CEC is positively correlated with its application rate and the ash content of biochar after its application (El-Naggar et al., 2019). Considering all these

effects on soil physicochemical properties, biochar is beneficial for the quality and functionality of agricultural soils, for example, its application can improve the physical properties of clay and sandy soils by facilitating soil water retention and increasing soil aeration; change nutrient solubility, thereby modifying the nutrient availability and decreasing nutrient leaching; also facilitate microbial activity and accelerating chemical reactions in the rhizosphere.

### 3.1.2. Soil nutrition and fertility

Upon application to soils, biochar can directly serve as a source or sink for available nutrients (Akhtar et al., 2014; Chan and Xu, 2009), because biochar itself contains nutrients derived from the feedstock (Palansooriya et al., 2019). Biochar incorporation into soil proves to be an effective method for enhancing nutrient cycling, further mediating biochar-plant root interactions, thus, affecting root growth and overall plant performance (El-Naggar et al., 2019; Purakayastha et al., 2019). Biochar also can indirectly alter the soil nutrient content and availability, when exogenous nutrients are laden on biochar, it can be used as a slow-release fertilizer for supplying nutrients (Zhou et al., 2015). In addition to nutrients derived from the feedstock (N, P, K, Ca, Mg, S, Fe, Mn, Cu, Zn, and Si), both macro-nutrients and micro-nutrients (e.g., $Cu^{2+}$, $Fe^{2/3+}$, $Mn^{2+}$, $Zn^{2+}$) can be absorbed. Due to the large surface area and porous microstructure of biochar, biochar-bound nutrients release in a slow fashion (Yao et al., 2011; Clough et al., 2013). In other words, the porous networks within the biochar create some structural obstacles, physical wrapping or chemical sorption that allow nutrients with slow desorption for plant uptake (Xiao et al., 2018; Yu et al., 2019a, 2019b). Collectively, the characteristics imply that a biochar-based slow-release fertilizer could reduce leaching and runoff, increase nutrient bioavailability and consequently enhance nutrient use efficiency and crop yield (Gwenzi et al., 2015, 2017).

Biochar addition to soils can directly interfere with and participate in the key nutrient cycling processes by physico-chemical interactions and microbial activities (Agegnehu et al., 2017; Bornø et al., 2018; Xu et al., 2018). The unique porous characteristics of biochar along with its heterogeneous surface functional groups can take part in diffusion-controlled adsorption of elements, surface complexation and ligand exchange reactions, which ultimately control the plant-available nutrient dynamics in soils (Liu et al., 2013; Nielsen et al., 2018). For example, biochar can have an indirect influence on soil N cycling, resulting in a decrease in N leaching and an increase in the recovery of N fertilizer. Because the adsorption of some inorganic forms of N onto biochar decreases ammonia and nitrate losses from soil and can potentially allow the retention of nutrients and further slow release (Haider et al., 2017). Since biochar is a C-rich substrate with a high C/N ratio, biochar application into soil can trigger microorganisms to decompose the native soil organic matter. Nitrogen (N) is required during this process due to the priming effect (Blagodatskaya and Kuzyakov, 2008). The addition of biochar into soil not only increases the total and available N in the soil, but also increases N utilization efficiency and decreases N accumulation efficiency by adjusting organic N mineralization, ammonia volatilization and nitrification/denitrification in agricultural soils (Zheng et al., 2013; Gul and Whalen, 2016). The changed cation and anion exchange capacities of soils after biochar application also further influences N retention (Clough et al., 2013; Slavich et al., 2013; Mandal et al., 2018). Biochar acting as C source also influences soil phosphorus (P) transformation. For example, the reduced $NaHCO_3$-extractable P content due to P immobilization with the high C:P ratios of biochar was reported to correlate with increased soil microbial activity and reduced soil acidity or increased CEC (Xu et al., 2018). In addition, biochar with high ion exchange capacity might alter P availability by enhancing the anion exchange capacity or by influencing the activity of cations that interact with P (Liang et al., 2006). Moreover, the application of some biochars could increase soil pH and alter the concentrations of various elements (e.g. $Al^{3+}$, $Fe^{3+}$, $Fe^{2+}$, $Ca^{2+}$, $Mg^{2+}$), which are responsible for making complex with P and changing its availability.

Biochar itself is a huge source of K, and it can directly take part in the retention of K in the soil due to its high CEC (Purakayastha et al., 2019). Indirectly, Biochar application also promotes soil nutrient retention based on its general properties, such as pH, CEC, porosity, and specific surface area (Chan et al., 2007; Singh et al., 2010). Therefore, the application of biochar has many additional benefits for plant nutrient cycling, such as increasing retention and use efficiency, reducing leaching, thereby improving soil fertility (Laird et al., 2010; Randolph et al., 2017).

### 3.1.3. Plant growth

Biochar affects the physical properties of soil that may subsequently have a direct effect on plant growth. The effectiveness of biochar application on improving crop productivity in fertile or healthy soils is commonly much lower than in nutrient-poor and degraded soils (Laghari et al., 2016; Hussain et al., 2017). Amendment of biochar to the nutrient deficient soils resulting in improved plant growth could be attributed to the following factors: 1) nutrients provided by biochar; 2) enhanced fertilizer use efficiency (Yu et al., 2019a, 2019b); 3) increased CEC, soil pH, moisture retention and nutrient retention and bioavailability; 4) decreased soil tensile strength and improved soil structure (Hass et al., 2012; Gwenzi et al., 2015, 2017); and 5) induced favorable rhizosphere environment for earthworm population and microbiota (Qambrani et al., 2017; Yuan et al., 2019). Generally, a key obstacle for plants growing especially in poor soils is root establishment and growth. The improved soil properties ultimately influence the root area and encourage great root development; the expanding volume of plant roots in soil is beneficial for the capture of more nutrients and improved plant growth (Uzoma et al., 2011).

Plant stress is one of the major problems encountered in agricultural environments. Biochar has been reported to display great potential to mitigate plant stresses for both biotic and abiotic types of stresses (Kavitha et al., 2018). For example, amending soils with biochar addition improved the antioxidant response of quinoa in addressing the complex conditions of drought and salt accumulation by increasing plant-promoting hormones (Thomas et al., 2013; Ramzani et al., 2017). Biochar application to saline and sodic soils displays the beneficial influence on alleviating the negative effects of salts, because the more surface charges on biochar can substitute for Na by K, Ca, and Mg, thus resulting in reduced levels of exchangeable sodium percentage (Lashari et al., 2015; Luo et al., 2017). In addition to the biotic stresses, biochar application can trigger microbial activities to mitigate plant pathogenicity that threatens plant health; the release of microbial inhibitors like volatile organic compounds can deter soil pathogens thereby, enhancing plant growth (Zhu et al., 2017).

### 3.2. Biochar for soil remediation and water treatment

In addition to soil fertility improvement, biochar can be used as a remediation agent to alleviate soil pollution. Biochar in soil displays various interactions with inorganic and organic pollutants, these interactions affecting the mobility and bioavailability of the pollutants could be beneficial for remediating contaminated soils (Younis et al., 2016).

Unlike organic contaminants, heavy metals cannot be degraded by microorganisms, and soils affected by heavy metals can cause a major environmental and health concern via direct exposure and the food chain (Yuan et al., 2019). Numerous studies have shown that the capability of biochar to mitigate pollution attributes not only to the surface sorption, but also to various functional groups and inorganic ions present in the biochar that may make a great contribution to stabilize metals in soils (Uchimiya et al., 2011a, 2011b; Xu and Fang, 2015; Wang et al., 2018b). Generally, biochar impacts both metal mobility and bioavailability in soils by the following mechanisms as shown in Fig. 2: 1) Electrostatic attraction: the negative charges on the surface of biochar particles can facilitate the electrostatic attraction of positively charged metals, an increase in pH with alkaline biochar also can intensify the
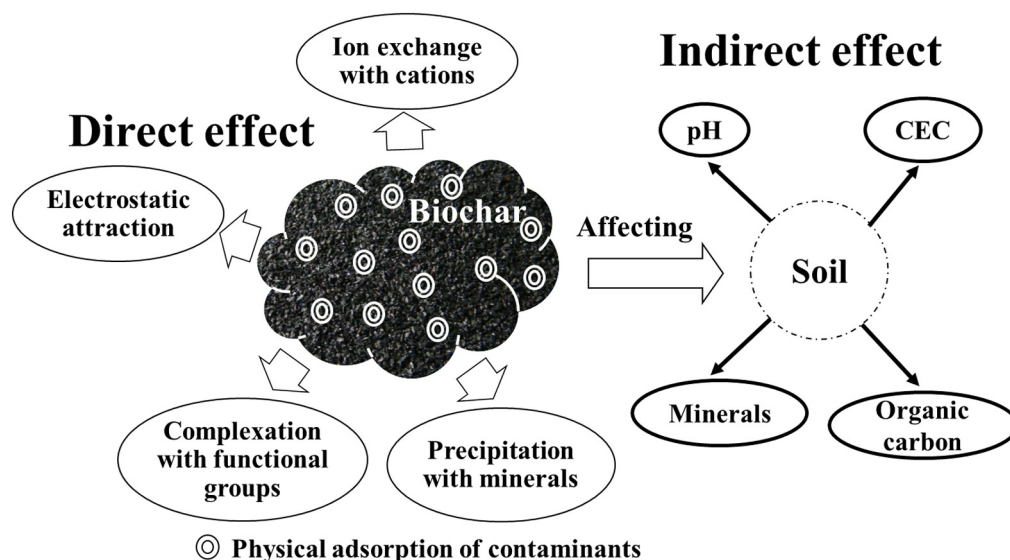
**Fig. 2.** The mechanisms of biochar influencing the availability of soil metals.

negatively charged surface (Ahmad et al., 2016; Kavitha et al., 2018;He et al., 2019); 2) Ion exchange: biochar generally exhibits significant CECs and can release cations, moreover, adsorbed $Ca^{2+}$, $Mg^{2+}$, $K^+$, or $Na^+$ on biochar can be exchanged for metal ions present in the soil (Lu et al., 2012;); 3) Complexation: the surface functional groups (e.g., –OH, –COOH, –C=O-, and C=N) on biochar surface promotes insoluble and stable complex formation (Ahmad et al., 2014; Tan et al., 2017); 4) Precipitation: the mineral elements contained in biochar may precipitate with metals, forming insoluble precipitates. In addition, some biochars are alkaline, the application of biochar could then cause liming effects in soils and thus induce heavy metal precipitation (Ahmad et al., 2014; Yu et al., 2019a, 2019b). Several indirect actions may also be responsible for the beneficial effect of heavy metal immobilization by biochar (Fig. 2), such as modification of soil pH, CECs, changes in the redox state of heavy metals, and increases in soil mineral contents and soil organic carbon content (Rizwan et al., 2016; Palansooriya et al., 2019).

It is worth noting that multiple mechanisms can be involved in the adsorption process for one metal, while in a multi-contaminant systems, metals can compete with other metals for the same sites and functional groups to produce reciprocal inhibition (Chen et al., 2011; Wang et al., 2018b). In addition, the mechanisms of biochar on stabilizing heavy metals vary with the metal type. For example, the adsorption of Pb and Cd may be affected by the pore structure and predominantly governed by ion exchange, while Cu removal may be related to surface functional groups, which could promote complex formation and enhance the ability to bind the metals (Xu and Fang, 2015).

Biochar amendment can result in evident adsorption on other inorganic pollutants, such as $F^-$, $ClO_4^-$, Cr, As and Hg. For example, the aromatic and hydrophobic surfaces of biochars dominate the adsorption of $F^-$, $ClO_4^-$ etc. (Yu et al., 2019a, 2019b). The formation of $(-COO)_2Hg(II)$ and $(-O)_2Hg(II)$ between Hg(II) and oxygen functional groups play a dominant role in Hg(II) removal (Wang et al., 2018b). In addition, biochar can change the valence of those oxy-anion species like As(III) vs. As(V), Cr(III) vs. Cr(VI), because biochar with a large surface area and more porous regions displays both positively and negatively charged surface properties, meanwhile, biochar addition can promote the occurrence of soil oxidation-reduction reactions by mediating microbial activities (Wang et al., 2018b; Yuan et al., 2019).

Unlike inorganic contaminants, biochar used for remediation of organic contaminants in soils is not widely reported, although biochar contains a fraction of colloidal and dissolved C, which can be used for absorbing organic compounds like PAHs (Qian et al., 2016). In addition,

biochar can adsorb and promote the degradation and redox reactions of organic compounds because of its graphitic and (semi-) quinone structures, which can accept/donate electrons and also produce free radicals (Yu et al., 2019a, 2019b). However, the effectiveness of biochar to immobilize or degrade organic contaminants in agricultural or forestry soils is restricted by the type of source material and pyrolysis temperatures (Yavari et al., 2016). For example, only highly surfaceous, carbonaceous biochar would be useful for stabilizing soils contaminated with compounds such as sulfamethazine (Teixidó et al., 2013).

Because of the specific features of biochar including large specific surface area, porous structure, enriched surface functional groups and mineral components, biochar has been made as a promising adsorbent to remove contaminants from aqueous solutions (Abdolali et al., 2014; Rangabhashiyam and Balasubramanian, 2019). Biochar adsorbents have already displayed a great capacity to remove various heavy metals and toxic organic contaminants (e.g. dyes, pesticides, herbicides, antibiotics) from water treatment systems. Both Langmuir and Freundlich isotherm models have the perfect fit of the adsorption data when used to describe how these contaminants interact with biochar, and the pseudo-second-order kinetic model properly describes the experimental data (Kostas et al., 2015; Inyang et al., 2016). The possible adsorption mechanisms usually involve integrative effects of several kinds of interactions including electrostatic attraction, ion-exchange, physical adsorption, surface complexation and/or precipitation as mentioned above (Gwenzi et al., 2017; Qambrani et al., 2017).

### 3.3. Biochar for carbon sequestration

Carbon sequestration is a procedure that carbon is captured, and soil organic carbon content is increased, leading to an increase in soil carbon sink and a change in land management (Powlson et al., 2011). Biochar has been widely accepted as a promising C sequestration tool for enhancing soil carbon sink, because biochar possesses high levels of resistance to soil chemical and biological degradation, as biochar production through the thermochemical conversion of biomass increases the recalcitrance and stability of the carbon (Herath et al., 2015). Additionally, the enhanced chemical stability of biochar is attributed to its condensed aromatic content (Awad et al., 2013; Purakayastha et al., 2015). It has been estimated that the mean residence time of biochar labile fraction (pool size = 97%) is 556 days (Wang et al., 2016). Approximately 63% carbon is stabilized on a dry weight basis of biochar (Graber and Hadas, 2009; Gwenzi et al., 2017). Therefore, biochar application to soil potentially sequesters soil carbon for hundreds or thousands of

years, which can be attributed to the following two reasons: 1) Biochar application into soil may have an inhibitory effect on native soil organic carbon (SOC) mineralization over the long term (Zimmerman et al., 2011; Wang et al., 2016). It has been found that the dissolved organic C (DOC) content in soil is reduced significantly due to the sorption of DOC onto the biochar surface, it is also called sorptive protection measures (Zimmerman et al., 2011; El-Naggar et al., 2019); 2) Biochar addition in soil can increase microbial biomass carbon and reduce the metabolic quotient due to its influence on C and N availability, resulting in more incorporation of biomass carbon rather than carbon mineralization (Whitman et al., 2014; Zheng et al., 2016).

The application of biochar as an amendment to especially low fertility soil has been considered as a particularly effective way to maintain soil SOC (Laird, 2008; Sohi et al., 2010). Maintaining or increasing soil SOC has positive impacts on the quality and functionality of agricultural soils: increase in aggregate stability, retention of contaminants, preservation of water infiltration, and decrease in water run-off as well as erosion (Powlson et al., 2012). These effects indirectly contribute to climate change mitigation by decreasing the quantity of fertilizers required for crop production (Khan et al., 2007). Overall, biochar transforms labile carbon from the active carbon pool to the passive pool; its application could contribute to carbon sequestration and displays great benefit to soil management practices (Gwenzi et al., 2017).

### 3.4. Biochar for the mitigation of greenhouse gas emissions

The agricultural sector is a primary contributor to atmospheric greenhouse gas (GHGs) emissions (Kavitha et al., 2018). Biochar application in soil has been useful in not only carbon sequestration but decreasing gaseous emissions. It has been reported that more GHG is consumed than emitted for some of the biochar cycles, including biochar derived from crop residues, poultry litters, sewage sludge, cattle manure, and food wastes, indicating when biochar is applied to soil, a net negative GHG emission and a positive impact on climate change can be achieved (Cao and PawlOwski, 2013; Alhashimi and Aktas, 2017).

Biochar positively aids in the reduction of GHGs emissions such as $CH_4$, $N_2O$, $NH_3$ and $CO_2$ in ecologically and economically sustainable systems (Vithanage et al., 2015). As $CO_2$ emission from soil respiration is almost ten times higher than that of fossil fuel burning, it is crucial to reduce $CO_2$ emission from agricultural soil for the mitigation of the climate change (Spokas, 2010). In the carbon cycle, when atmospheric $CO_2$ is fixed by photosynthetic organisms (e.g. plants), it then can be transferred into biomass (>90% carbon) (Yu et al., 2017). If the biomass in soil is mineralized or degraded by microbes, it causes the evolution of $CO_2$ to the atmosphere (Qambrani et al., 2017). In contrast, if the biomass is paralyzed into more stable carbon as biochar, and when the biochar is applied to soil, the stable and recalcitrant of the carbon in biochar causes it to store the captured carbon in the soil for long periods of time (Gwenzi et al., 2017; Yuan et al., 2019). Indirectly, biochar in soil has the ability to improve nutrient use efficiency or water retention, which in turn results in energy savings, reduces irrigation frequency and fertilizer use, furthermore indirectly reduces greenhouse gas emissions (Sohi et al., 2010).

Methane ($CH_4$) is approximately 20 times more powerful than $CO_2$ in absorbing thermal radiation trapped in the earth's troposphere, resulting in the augment of global warming (Watson et al., 2000). The emission of CH can be facilitated with neutral pH and sufficient nutrients under anaerobic conditions through methanogenesis. A possible mechanism that explains the observed reduction in CH emissions after biochar application is the increased soil aeration that can enhance methanotrophic activity with a reduction in methanogenic activity (Woolf et al., 2010; Xiao et al., 2017). Similarly, biochar aids in the biological immobilization of inorganic N that helps to retain N and decrease ammonia volatilization (Lehmann and Rondon, 2006). It has been reported that biochar application to soil significantly reduced denitrification by reducing the $N_2O/(N_2 + N_2O)$ ratio, leading to up to 90% $N_2O$ reduction (Cayuela et al., 2013). The possible mechanisms accounting for the reduction of $N_2O$ emission include at least two aspects: 1) biochar plays a role of "electron shuttle" by transferring electrons to soil denitrifying microorganisms, which promotes the reduction of $N_2O$ to $N_2$; 2) the improved soil physical properties with biochar application stimulates nitrification, and some nitrifier-inhibitory compounds like phenolics existing in biochar can result in reduced $N_2O$ emission as well as the generation of $NO_3^-$-N (Van Zwieten et al., 2010; Awasthi et al., 2017). Additionally, biochar affects soil N flux through (i) direct sorption of $NO_3^-$, $NH_4^+$, organic N species and enzymes on biochar surfaces and within pores, and (ii) biochar-induced organo-mineral associations (Van Zwieten et al., 2010), thereby potentially reducing the inorganic nitrogen pool available for the nitrifiers and decreasing ammonia volatilization from agricultural fields (Tsutomu et al., 2004; Qambrani et al., 2017).

## 4. Limitations or uncertainties

As previously discussed, and summarized in Fig. 3, biochar has some potential benefits in agro and forestry systems. Generally, biochar additions can substantially increase soil fertility, improve soil physical properties, and enhance crop production compared with soils without biochar (Glaser et al., 2001), but discrepancies do exist. Van Zwieten
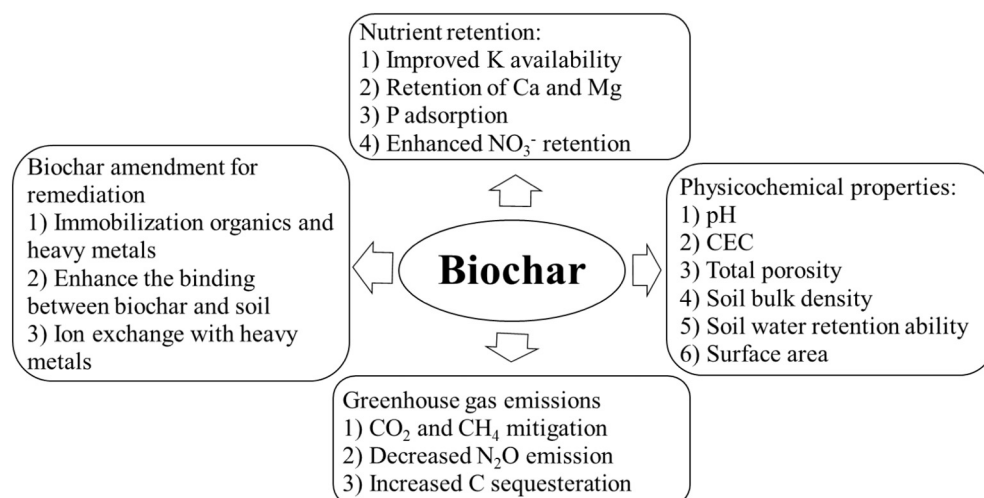
Nutrient retention:
1) Improved K availability
2) Retention of Ca and Mg
3) P adsorption
4) Enhanced $NO_3^-$ retention

Biochar amendment for remediation
1) Immobilization organics and heavy metals
2) Enhance the binding between biochar and soil
3) Ion exchange with heavy metals

**Biochar**

Physicochemical properties:
1) pH
2) CEC
3) Total porosity
4) Soil bulk density
5) Soil water retention ability
6) Surface area

Greenhouse gas emissions
1) $CO_2$ and $CH_4$ mitigation
2) Decreased $N_2O$ emission
3) Increased C sequestration

**Fig. 3.** Benefits of biochar in agro and forestry systems.

et al. (2010) found greater response to biochar in acidic soils than in calcareous soils. Most other studies have focused on biochar application to nutrient poor acid soils and have attributed crop response to increases in N and P availability, fertilizer use efficiency, base cation concentrations, and pH, with corresponding decreases in exchangeable Al (Hossain et al., 2010; Chan et al., 2008; Chan et al., 2007; Lehmann et al., 2003), but impacts on nutrient rich soils are minimal.

Field studies have shown mixed effects of biochar on crop production. Crop yields may (Asai et al., 2009) or may not (Gaskin et al., 2010) increase with the application of biochar, depending on soil type and fertilizer management. Asai et al. (2009) found that biochar applied to low P soils increased rice yield, but no increase was found on high P soils. Similarly, Yamato et al. (2006) found that biochar increased crop yield when applied to low P soils. Biochar also increased soil pH, base saturation, and CEC and decreased exchangeable Al, all of which could also contribute to yield increases (Yamato et al., 2006). Other studies have also found yield increases with biochar application and attributed improved crop yields to increased nutrient availability, but the mechanisms for the yield increases were not explained (Sohi et al., 2010; Kimetu et al., 2008; Steiner et al., 2007). Gaskin et al. (2010) reported that biochar application both increased and decreased yield depending on rate, soil, biochar source, and year, and thus clear trends linking biochar to crop response were absent. The primary trend observed by Gaskin et al. (2010) was an increase in base cation concentrations in biochar amended soils, which was accompanied by temporary increases in pH.

Studies have also shown mixed effects of biochar applications on soil physical and biological quality. In a lab experiment, Busscher et al. (2010) found that addition of pecan shell biochar to loamy sand at rates of 0, 11, 22, and 44 Mg ha$^{-1}$ reduced soil penetration resistance but had no effects on soil aggregate stability and water infiltration. In a greenhouse experiment, Chan et al. (2008) reported that tensile strength of soil cores decreased, suggesting that biochar application can decrease risks of soil compaction. Biochar addition may also affect earthworm population and related biological activities (Chan et al., 2008), which influence soil macroporosity and water movement through the soil. Increased soil porosity and aggregate stability with biochar can increase rain or irrigation water infiltration and soil water retention while reducing runoff and soil erosion (Piccolo et al., 1997).

The effect of biochar addition on GHGs emissions including $CO_2$, $CH_4$ and $N_2O$ has also been broadly reported with some varied results. The application scopes ranged from soybeans, grass ecosystems (Rondon et al., 2005), common beans (Rondon et al., 2007), rice production (Zhang et al., 2012) or wheat plots (Castaldi et al., 2011) to different agricultural soils (Cayuela et al., 2013). Rondon et al. (2005) found that $N_2O$ emissions were decreased by up to 50% for soybeans and by up to 80% for grasses growing in a low-fertility oxisol from the Colombian savanna. Castaldi et al. (2011) cultivated wheat with biochar addition and found that in char treated plots, soil $N_2O$ fluxes were from 26% to 79% lower than $N_2O$ fluxes in the control plots. Similar results were obtained by Zhang et al. (2012), who investigated biochar effects on $N_2O$ emission in rice paddy during a 2-year consecutive field experiment, and observed a consistent reduction in $N_2O$ emission in a single crop cycle after biochar amendment.

In contrast to decreases in $N_2O$ emission in most cases, wide variations in the rates on $CO_2$ emissions from soils treated with biochar have been reported in the literature. For example, Spokas et al. (2009) observed a rate of >20% ($w/w$) in reduced emission of $CO_2$ from a silt loam soil amended with wood chip biochar compared to un-amended control. Liu et al. (2011) reported that $CO_2$ emission was reduced from the waterlogged paddy soil amended with bamboo (*Bambuseae spp.*) and rice straw biochar pyrolyzed at 600 °C. In contrast, Bell and Worrall (2011) observed a significant increase in soil respiration from unplanted plots but not from vegetated plots under lump-wood biochar amendment at the rate of 62.5 t ha$^{-1}$ (approximately 50 t C ha$^{-1}$ input) to an arable soil from Northeast England. Similarly, A 100-day incubation study conducted by Spokas et al. (2009) demonstrated that when three different soil types were amended with 16 types of biochars, three kinds of effects including repression, no change, and stimulation of $CO_2$ respiration due to biochar addition were observed.

The emissions of $CH_4$ in soils are considered to be repressed due to biochar amendment in most cases. Liu et al. (2011) observed that $CH_4$ emission from the paddy soil amended with biochar was reduced by 91.2%, compared with those without biochar. Karhu et al. (2011) found that there was a decrease in $CH_4$ emission in an agricultural soil from Southern Finland under birch biochar amendment at 9 t ha$^{-1}$. In contrast to these findings showing methane emission reduction, Castaldi et al. (2011) investigated the impact of biochar application to a Mediterranean wheat crop on greenhouse gas fluxes, and concluded no significant differences of $CH_4$ fluxes among different biochar treatments and the control.

## 5. Future studies needed

Evidently, the relationships between biochar production and key biochar properties are missing in the literature. Because there are so many different variables in biochar production, biochars from different processes or producers are vastly different, which makes it difficult to compare one biochar to another. On the other hand, most research has focused mainly on the carbon content of biochar as its quality standard, but other properties such as pH, surface area, porosity, water holding capacity, cation/anion exchange capacity, surface functional groups, and nutritional value are also very important to its applications in soils. For these reasons, it is almost impossible to predict or standardize the properties of biochar from different laboratories or producers. The "optimum" properties of a biochar would also be dependent on the end uses. For instance, a biochar for energy use would be different from a biochar for wastewater treatment. The former requires high heating value, while the latter needs high adsorption capability of the biochar. Thus, future research on elucidating the effect of the production processes on biochar properties would be critical.

Similarly, the relationships between biochar properties and its performance in agro and forestry systems are not widely available in the literature. Mixed effects of biochar on plant growth and greenhouse gas emissions have been reported, due to differences in biochar properties, their application rate and means of application to the soil, soil type, plant species, and even climate conditions. Apparently, the mechanisms of how biochar interacts with soils and plants are critical but largely unknown at least in a systematic way. Considering the vast variations in biochar properties, it is thus very difficult, if not impossible, to predict biochar performance in a specific system. More efforts would be needed to link biochar properties to soil and crop responses in both climate-controlled environment and in the field.

## 6. Conclusions

The yield and quality of biochar from the thermochemical conversion processes of biomass are vastly different due to differences in the amount of oxygen available, heating rate, and reaction temperature. Generally, the yield of biochar decreases with faster heating rate or more oxygen available. Beneficial impacts of biochar amendments in agro and forestry systems, such as improved soil health, better plant growth, carbon sequestration and reduced greenhouse gas emissions have been widely reported, but mixed or opposite results do exist, thus the benefits of biochar application are often limited to particular conditions such as the types of biochar, rates of application, soil type and conditions, and crop species. Systematic investigations are needed to elucidate the relationships among biochar production technologies, biochar properties, and biochar performance in agro and forestry systems.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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