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Review

Biochar-plant interaction and detoxification strategies under abiotic stresses for achieving agricultural resilience: A critical review

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ABSTRACT

The unpredictable climatic perturbations, the expanding industrial and mining sectors, excessive agrochemicals, greater reliance on wastewater usage in cultivation, and landfill leachates, are collectively causing land degradation and affecting cultivation, thereby reducing food production globally. Biochar can generally mitigate the unfavourable effects brought about by climatic perturbations (drought, waterlogging) and degraded soils to sustain crop production. It can also reduce the bioavailability and phytotoxicity of pollutants in contaminated soils via the immobilization of inorganic and/or organic contaminants, commonly through surface complexation, electrostatic attraction, ion exchange, adsorption, and co-precipitation. When biochar is applied to soil, it typically neutralizes soil acidity, enhances cation exchange capacity, water holding capacity, soil aeration, and microbial activity. Thus, biochar has been was widely used as an amendment to ameliorate crop abiotic/biotic stress. This review discusses the effects of biochar addition under certain unfavourable conditions (salinity, drought, flooding and heavy metal stress) to improve plant resilience undergoing these perturbations. Biochar applied with other stimulants like compost, humic acid, phytohormones, microbes and nanoparticles could be synergistic in some situation to enhance plant resilience and survivorship in especially saline, waterlogged and arid conditions. Overall, biochar can provide an effective and low-cost solution, especially in nutrient-poor and highly degraded soils to sustain plant cultivation.

1. Introduction

Additional food crops and lands are needed to alleviate hunger brought on by population growth, estimated to reach 9.6 billion by 2050 (Tripathi et al., 2019). However, several environmental challenges such as the industrial revolution, improper use of fertilizers or pesticides, and global climatic warming limit the expansion programs of food crops and endanger the plant yield nowadays. Climate change consequences lead to the release of greenhouse gases, changes in the seawater level, soil degradation and drought, waterlogging effects, and increased frequency of extreme weather events (Hasnain et al., 2022a). The impact of these unpredictable weather extreme spells on food crops may even vary if one or a combination of these factors are active on-site. Extreme weather conditions such as high-temperature fluctuation and prolonged drought have co-occurred and caused adverse effects on water balance, mineral nutrition, and photosynthesis (Duarte et al., 2015). In turn, this

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enhances energy-consuming defence mechanisms, reduced membrane integrity, and adversely affects plant yield or elevates mortality (Becker et al., 2017). For instance, a four-degree increase in temperature can impose a 15–35% crop yield reduction in Africa and Asia, while estimates for the Middle East ranged from 25% to 35% (Munir et al., 2022a). Furthermore, hyperosmotic salinity is becoming another limiting factor for plant growth via its marked influence on leaf water relations, ion toxicity and imbalance can alter crucial biochemical processes (Hussain et al., 2015).

Elevated levels of salinity affect 7% of the total world's land areas, in which the related adverse environmental impacts lead to an economic loss of USD 27.2 billion per annum (Yang and Sun, 2020a). Moreover, salinity stress is estimated to affect more than 30% of the global cultivable lands by 2050 (Hasnain et al., 2022b; Wani et al., 2020), and changes in seawater levels may increase this portion even more. Another complex stress that compromises crop production and food security is induced by flooding. Countries representing more than 70% of the global population (e.g., China, India, the United States and Indonesia) might face increases in flood risk by changes in seawater levels and seasonal and extreme weather events (Hasnain et al., 2021; Sri Shalini et al., 2020). Flooding induced-stress restraints crop production due to waterlogging, variable salinity, rhizosphere oxygen depletion leading to anaerobic conditions in the root area, and, consequently, several major physiological effects such as reducing foliar chlorophyll, photosynthesis, and finally to leaf senescence and growth reduction (Jakhar et al., 2022). In addition, heavy metal and metalloid pollution from natural sources such as volcanism, mining, related human activities and the industrial activities would create more challenges to plant growth (Khilji et al., 2022; Yazd et al., 2020). Soil heavy metals and metalloids, absorbed and accumulated in plant tissues can disturb cellular ionic homeostasis, alter activities of cytoplasmic enzymes, and damage cell structures due to oxidative stress (Munir et al., 2022b; Yadav, 2010), leading ultimately to impairments at the photochemical level (Santos et al., 2014). Fluctuations in temperature occur naturally during plant growth and reproduction. However, extreme variations levels during hot summers, even in extreme weather events, lead to alterations in the optimal physiological plants' reactions for proper growth, thus impairing plant development and fruit set (Duarte et al., 2015). New and emerging environment-friendly methods are required to improve plant performance in nutrient-poor, polluted, degraded, dry or saline lands; to improve plant productivity under unfavourable conditions. In recent years, the amendment of biochar was proven holistically as a practical, effective and sustainable option for the mitigation of greenhouse gas (GHG) emissions, pollution control and the optimization of soil properties for cultivation across various soil types (Zhang et al., 2019a). Biochar exhibits a great potential to tackle water contaminants due to the wide availability of feedstock, low cost and favourable physical/chemical surface characteristics. However, there are also potential negative aspects of biochar applications, including inorganic and/or organic contaminants originating from the source feedstock to produce biochar and certain negative alteration of soil properties for specific types of soil (Lehmann and Joseph, 2009). The current scientific evidence indicates that we need to customize specific biochar type (with plausible functional groups and symbiotic microbes) to match certain soil types, and fulfilling societal expectations like developing safe circularly-derived nutrients while minimizing GHG gas emissions to reduce our environmental footprint during food production.

For instance, the sportive properties of biochar appeared to be responsible generally when biochar acts to mitigate the impacts of stress, either by reducing the exposure of plants to stress agents or by strengthening the resilience to stress factors in plants (Abideen et al., 2022). For heavy metals, metalloids and organic pollutants, the direct reductions in exposure due to sorption into plant tissues are presumed to be of primary importance (Buss et al., 2011; Yu et al., 2006). The physical characteristics of biochar can also substantially increase the water-holding capacity of soils and therefore improve the water status of plants, particularly during drought periods (Karhu et al., 2011).

This review aimed to provide insight into both the positive and negative impacts of biochar on soil health under various and usually challenging conditions. The strategic incorporation of biochar in sub-optimal soils and substrates to restore cultivation in saline zones and to aid planting regime using brackish water for irrigation, is of great importance for meeting global food production. The toxicity of sodium and chloride and their interactive effects on the soil cation exchange capacity, soil nutrient retention, soil enzyme activities and diversity of microbial communities under such conditions are limiting factors for brackish and saline cultivation (Novak et al., 2012). Plants under brackish to saline conditions store different metabolites that help to maintain physiologically the osmotic potential under these circumstances. The biochar amendments under brackish to saline conditions increase tissue nitrogenous compounds such as proline and glycine betaine which are essential metabolites for physiological homeostasis to support growth under harsh conditions (Kammann et al., 2011). There is a positive correlation found in the literature that nitrogen metabolism and photosynthesis enhance plant survivorship after biochar amendments while growing under saline conditions; the precise mechanism(s) for plants to grow under saline conditions is still unclear. It is plausible that the biochar amendments could play a vital role in the antioxidant mechanism system by storing secondary metabolites and strengthening the efficacy of photosystem II during high salt imposition (El-Naggar et al., 2021; Chen et al., 2020; Yao et al., 2020). The present review addresses the following question: 1) The potential of biochar to mitigate the plant stress conditions such as soil improvement, plant-soil interaction and building resilience in plants. 2) The potential of biochar to trigger the plant stress resilience mechanism growing under sub-optimum conditions and 3) identifying knowledge gaps in biochar characteristics and especially the relationship between biochar (type, interactions) and plant stress resilience.

2. Biochar background

Biochar is an accelerated imitation of the active component of a distinctive dark-coloured soil called "*terra preta*" (Xiang et al., 2020). The latter was the product of ancient Amazon Indians' methods to change infertile, sandy soils into prosperous and sustainable fields (Maroušek et al., 2019). Biochar is a heterogeneous substance rich in aromatic carbon and minerals and is mainly used as a versatile and sustainable soil amendment. Biochar is a solid product obtained via pyrolysis of biomass such as wood, crops, sludge and manure under limited O_2 conditions at elevated temperatures (~300–700 °C) in an inert atmosphere (Yeboah et al., 2020). Biomass types, production methods, pyrolysis temperature, heating rate, and residence time play a significant role in determining the properties of biochar (Yang et al., 2019; El-Naggar et al., 2021). Biochar can be produced using either a small traditional unit or a large unit. On a small scale, about 50–1000 kg/hour of biomass is used as input, while in a large unit, up to 8000 kg/hour of biomass can be operated (Heidari et al., 2019). It is cost-effective to produce high-performance biochar on a large scale, even in underdeveloped countries, using simple and low-cost methods (da Silva Veiga et al., 2020).

2.1. Biochar composition, surface chemistry and soil biochar alterations

Biochar structure comprises of carbon, nitrogen and hydrogen, and containing inorganic elements such as sodium, potassium, calcium, magnesium, iron, manganese and silicon that provide unique chemical properties for biochar (Xu and Chen, 2013; He et al., 2020). The addition of biochar to soil typically causes an increase in soil pH and nutrient acquisition and therefore plays a role in improving plant nutrition and stress tolerance (Leng et al., 2020d; Akhil et al., 2021). Aliphatic, aromatic, hydroxyl, carboxyl, carbonyl, amide, and acyl groups are common surface functional groups of biochar (Liu et al., 2019a). They provide important sites for the adsorption, and catalytic degradation of pollutants by associating/dissociating hydrogen bonds with protons. They also influence the degree of sorption, pH buffering, surface charge (usually negative) and hydrophilicity or hydrophobicity alterations (El-Naggar et al., 2019a). Free radicles play an essential role in the surface chemistry of biochar and their excessive occurrence can negatively affect seed germination and plant growth (Tang et al., 2020). The biochar surface area changes with its porosity, < 0.9 nm Nanopores, < 2 nm Micro pores and > 50 nm Macro pores. These last facilitate microbe presence by promoting habitat niche and playing a vital role in soil aeration and hydrology while smaller pores are involved in molecule adsorption (Trompowsky et al., 2005).

Changes in the biochar matrix greatly influence the biochar-soil interactions, which are dependent on their physicochemical properties, soil type, and their prevailing environmental conditions (post-application whilst in the soil). The functional groups at the surface of biochar can be exposed to oxidation and carboxylation of carbon, altering cation exchange sites on biochar surfaces. Besides, biochar stability is directly related to the feedstock type and production conditions while inversely associated with the presence of saprophytic organisms like fungi (Leng et al., 2019b). However, when compared to other organic soil amendments, the high stability of biochar is useful as an additive with slow-nutrient release properties to improve degraded soil conditions and this feature is important for maintaining plant productivity under stress conditions (Lehmann and Joseph, 2015). The significant factors for biochar stability include the degree of aromatic condensation, resulting from biochar production temperature (Leng et al., 2019c).

2.2. *Impact of production conditions and feedstock types on biochar properties*

Combustion is the oldest method of plant biomass oxidation in which material is burned with little or no oxygen (pyrolysis or "charring") at 800–1000 °C. Pyrolysis is an efficient thermochemical technology for transforming biomass into biochar, bio-oil and syngas. The latter is essentially the conversion of biomass into various fractions by gasification under a controlled amount of oxygen and with the release of gases (carbon monoxide, hydrogen and methane) (Mallick, 2019). Pyrolysis is considered the most cost-effective and feasible at a plant moisture content of around 50%. Pyrolysis temperature, processing time, and pressure affect the physical and chemical properties of biochar, such as yield, ash, specific surface area, pore structure, type and number of functional groups, and cation exchange capacity (Leng and Huang, 2018a). As the temperature increases, biochar yield and acidic functional groups decrease, while the pH, ash content and carbon stability increase. At 500–900 °C for 2 h as residence time, the specific surface area and pore area of resultant product tend to increase. However, when this period prolongs beyond 2 h, the specific surface area and pore area could decrease rapidly due to the potential collapse of its porous structure (Oh and Seo, 2019). Pyrolysis at low to moderate temperatures converts cellulose, hemicellulose and lignin into aliphatic carbon, while high-temperature pyrolysis converts these compounds into aromatic carbon. Volatile matter, hydrogen and oxygen contents of the biochar decline within the range of 400–700 °C. With increasing pyrolysis temperature, aliphatic alcohol and acid surface functional groups are likely to be converted into neutral or basic fused aromatic groups (Mukherjee et al., 2011). Therefore, the pyrolysis temperature dramatically affects the chemical and surface properties of biochar.

It is noteworthy that higher pyrolysis pressures increase the number of re-condensation reactions, leading to increased water content in bio-oils while reducing the energy content and quality (Carrier et al., 2012). Furthermore, the porosity of biochar is improved under vacuum treatment. The carbonization process produces biochar from lignocellulose biomass at 250–350 °C for 10–60 min (Antal et al., 2003). Carbonization is the conversion of organic matter like plants and dead animal remains into carbon through destructive distillation. Carbon-free emission is a major issue in the carbon industry, as well as the energy during biochar production (Chen et al., 2020). Enthalpy is the energy required to produce biochar and syngas from biomass which mainly depends on the types of feedstock and operating conditions (Polin et al., 2019). Biochar properties are greatly influenced by the feedstock types, moisture and ion content (Blanco-Canqui, 2017). The biochar yield decreases as the temperature increases. Carbon content and surface area increase with higher temperature settings (Kemmou et al., 2018). The composition of cellulose and lignin varies in the feedstock and greatly affects the biochar yield and properties (Panwar et al., 2019). Plant biomass having high lignin produces macro-porous structured biochar, while biomass having high cellulose content produces micro-porous structured biochar (Ansari and Gaikar, 2019). Moisture content affects the biochar reaction. It was shown that the ash content of raw feedstock correlates positively with the biochar yield percentage and negatively with the fixed carbon percentage of biochar (Pandey et al., 2020). The pyrolysis of animal manures produced biochar with high ash content, which is positively related to the nutrient and chemical composition of the organic materials (Cantrell et al., 2012). In biochar derived from manures, the various N and S functional groups are more abundant than in lignocellulosic biochar (Koutcheiko et al., 2007).

3. Potential of biochar to ameliorate stresses in crops

It is anticipated that the application of biochar (alone or in combination with other substrates) to degraded soils can be useful in strengthening crop resilience to cope with abiotic and biotic stresses (Fig. 1) (Farooq and Pisante, 2019). When applied strategically, biochar brings agricultural benefits by improving soil structure, enhancing soil fertility and its ability to handle soils with heavy metals, metalloids and other pollutants (Mansoor et al., 2021). Many studies have reported the role of biochar in sustaining plant growth and enhancing resilience to stress when biochar was added during abiotic/biotic stress conditions (Danish et al., 2020; Yao et al., 2020; Mansoor et al., 2020). However, the effects of adding biochar on improving stress resilience in plants depends upon the properties and application rates of biochar as well as the type of soil and the specific site prevailing environmental conditions.

3.1. *Effects of biochar on plant resilience to various stress type*

3.1.1. *Drought*

Drought is common environmental stress, which diminishes plant biomass, foliar chlorophyll, nutrient diffusion, and mass flow of water-soluble nutrients (Zhu, 2002; Abideen et al., 2021). Therefore, plants evolved many morphological, physiological and biochemical adaptations to cope with drought conditions through various strategies (avoidance, tolerance and escape) (Kooyers, 2015; Ali et al., 2017). The impacts of biochar on the soil water holding capacity (WHC), total pore space, and water retention are key factors in improving soil water retention and availability under drought (Ali et al., 2017). Biochar application generally sustained the growth of many species undergoing drought testing; increased plant height and leaf area of rice (Agegnehu et al., 2016); okra (Jabborova et al., 2021); maize (Olmo et al., 2014; Situmeang et al., 2015; Sattar et al., 2020) and reed (Ullah et al., 2021). Abideen et al. (2020a) reported an improved one-fold *Phragmites karka* biomass, (1.5%) root-to-shoot ratio with the application of 0.75% peanut husk biochar produced at 750 ^{0}C. Plant cells can adjust osmotically by accumulating organic solutes that control water influx, reduce efflux, turgor maintenance and inhibit harmful effects of reactive oxidative species and damage to biomembrane and photosystem II efficiency (Neelma et al., 2022). The reduced burden on the plant water balance upon biochar-amended soils leads to a lower burden on photosynthesis and, consequently, higher growth rates were observed (Ahmed et al., 2016). The higher activity of photosynthesis was reflected by higher water use efficiency, stomatal conductances and photosynthetic rates (Haider et al., 2015; Batool et al., 2015). The addition of peanut husk

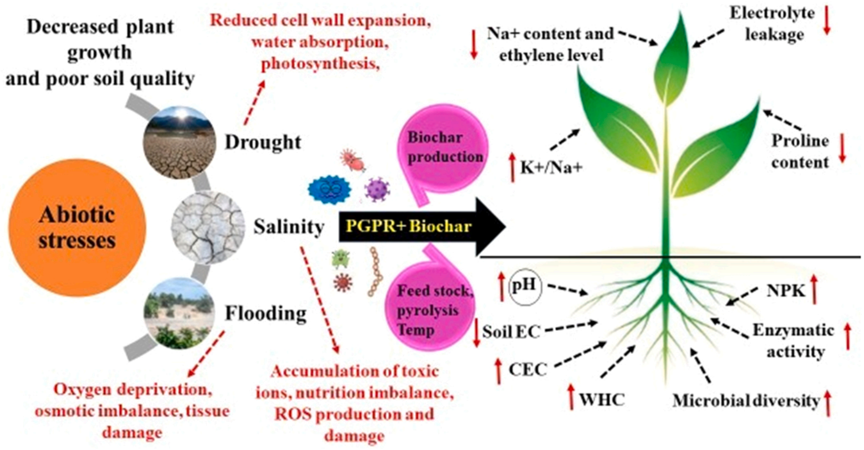

Fig. 1. Effects of plant growth promoting bacteria (PGPB) and biochar on plant resilience to drought, salinity and flooding stress.

biochar at 0.75% (produced at 750 ^{0}C) to the soil under drought conditions, increased the chlorophyll content and net photosynthesis rate of *P. karka* by 14%, respectively (Abideen et al., 2020b). Rizwan et al. (2018) also showed enhanced foliar chlorophyll *a* and *b* by 78% and 96% respectively, after the addition of wheat biochar (biochar was prepared from wheat straw as a feedstock at 450 °C) during cultivation of *Oryza sativa* under drought conditions. Drought stress increases reactive oxygen species, leading to oxidative stress that affects cellular functions by damaging nucleic acids and oxidizing proteins. Plants have enzymatic antioxidant systems to protect them from the various destructive oxidative reactions. Farhangi-Abriz and Torabian (2017) reduced the enzyme activities by applying 20% maple biochar in *Phaseolus vulgaris*, under reduced water conditions. Lyu et al. (2016) reported a decrease in superoxide dismutase activity and peroxidase by biochar in *Pyrus ussuriensis*. Adding wheat biochar at 5% reduced the malondialdehyde concentration by 31%, electrolyte leakage by 34%, and hydrogen peroxide by 40% of *Oryza sativa* (Rizwan et al., 2018). In summary, the negative effects of drought on plant growth can be ameliorated by adding biochar; reducing the reactive oxygen species that are curtailing plant growth. The higher availability of water due to biochar amendments is the other key benefit that can sustain gas exchange and antioxidant defence during drought. The strategic usage of biochar during drought to sustain plant functionality and ultimately crop productivity is of great importance in arid areas.

3.1.2. Salinity

Chemical properties of biochar, like the type and number of functional groups, ash composition, ion species and cation exchange capacity are of special importance in saline soils, besides the WHC, specific surface area, pore structure and total pore space (Kanwal et al., 2018). However, even without focusing on these properties, it was shown that biochar amendment (produced from raw peanut shells at 550 ^{0}C) to non-saline (Xu et al., 2015) and saline soils have a positive impact on plant biomass and pod yield increased to 2- and 3-folds respectively

Table 1
Effects of different biochar feedstock and pyrolysis temperature on plant growth and various physiological parameters under saline soil conditions.

Species	Soil type	Feedstock	Pyrolysis ∘C	Application	Effects	References
Solanum tuberosum	Sandy loam	Hard wood 80% and soft wood 20%	500	0% and 5%	Improved growth, tuber yield, decreased Na^{+}/K^{+} in xylem sap	Akhtar et al. (2015)
Zea mays	Sandy loam	Hard wood 80%, soft wood 20%	500	0% and 5%	Higher leaf area, root growth, nutrient flux	Rafiq et al. (2016)
Triticum aestivum	Sandy loam	Hard wood 80% and soft wood 20%	500	0% and 5%	Higher growth, stomatal density, grain yield, nitrogen and phosphorus uptake	Bhattacharjya et al. (2016)
Solanum lycopersicum	Sandy soil	*Conocarpus* wood	400	0%, 4% and 8%	Improved plant growth and total yield	Castañeda et al. (2020)
Lactuca sativa	Alkaline soil	Coniferous wood pellets	550	0, 1.37%	Enhanced plant biomass, soil nitrogen, phosphorus, carbon and microbial communities	Trupiano et al. (2017)
Triticum aestivum	Alkaline soil	1:3 wheat straw and poultry manure composted for 6 weeks	50–550	0, 0.15 tons/ha	Improved grain yield, decreased soil Na^{+}	Qayyum et al. (2017)
Zea mays	Reclaim tidal land, silt loam	Rice hull	550	1%, 2% and 5%	Improved biomass, low Na^{+} and antioxidant enzymes	Phuong et al. (2020)
Zea mays	Aqui-entisol	1:3 wheat straw and poultry manure, composted 6 weeks	50–550	0, 0.15 tons/ha	Enhanced height, root length, leaf area, grain yield, photosynthesis	Manolikaki and Diamadopoulos (2019)
Alpinia zerumbet	Sandy loam soil	Chopped wheat straw	450	0% and 5%	Increased photosynthetic chlorophyll, carboxylation efficiency and decreased oxidative stress	Zulfiqar et al. (2021)
Triticum aestivum	Sandy loam soil	Dried leaves and sawdust	350	1% and 2%	Improved germination and growth, root and shoot length, leaf water potential, osmotic potential increased, SOD activity proline	Kanwal et al., 2018
Eucalyptus camaldulensis	Sandy loam	Farmyard manure	450°C	6%	Higher chlorophyll contents, photosynthetic rate and stomatal conductance	Yousaf et al. (2021)
Ocimum basilicum	Loam soil	Banana leaves and false stems	300	0, 1% and 2%	Reduced NH_3 volatilization increased, growth, photosynthesis and absorption of nutrients. of basil plants	Ding et al. (2020)

(Table 1). In saline soils, the cation exchange capacity might reduce the impact of ion toxicity and nutrient imbalance (Tan et al., 2020). It was shown, that biochar can reduce the combined effects of ion toxicity, ion imbalance and water availability on plant development. In a potato trial, adding 5% biochar (derived from used hardwood) increased shoot biomass, root length and tuber yield undergoing salt stress (Akhtar et al., 2015). Increased maize biomass was observed in plants cultivated in reclaimed tidal land soils containing soluble salts upon rice hull biochar application (Mavi et al., 2020). *Fagus grandifolia* sawdust biochar when applied at the rate of 50 t ha^{-1} led to an improvement (50%) in *Abutilon theophrasti* and *Prunella vulgaris* growth under saline conditions (Thomas et al., 2013). Lashari et al. (2013) reported a 60% increase in wheat grain yield when using biochar amendment (12 t ha^{-1}) in saline soil. With an addition of 12 t ha^{-1} of wheat straw-derived biochar, Lashari et al. (2015) showed that key growth parameters in maize have improved (height from 23% to 39%, density from 76% to 81%, root length from 47% to 53%, leaf area index from 65% to 110%); and this was accompanied by grain yield improvement from 140% to 195% under saline conditions. Halophytes can accumulate organic metabolites such as glycine betaine, pinitol, β-alanine betaine, choline-*O*-sulphate, and pinitol proline and soluble carbohydrate to maintain the osmotic balance of tissues at the cost of energy. Farhangi- The accumulation of osmotic substances in leaves and roots of *Phaseolus vulgaris* was reduced upon amendment with 20% maple biochar to invest energy in biomass production (Abriz and Torabian, 2017).

Salinity causes oxidative stress in plants by producing reactive oxygen species. Biochar alleviates these effects by regulating the biosynthesis of ant oxidative enzymes (Abbas et al., 2018). In maize, poultry 12 t ha^{-1} of wheat straw biochar and poultry manure compost mixture decreased the malondialdehyde contents by 20% (Lashari et al., 2015). Biochar produced from maple residues (*Acer pseudoplatanus* L.) reduced oxidative stress by promoting ascorbate peroxidase antioxidant enzyme activities by 55% in bean seedlings under salt stress (Farhangi-Abriz and Torabian, 2017). In saline and sodic field studies, biochar amendments (34–101 t ha^{-1}) enhanced leaf water status, plant height (24%), foliar chlorophyll, K^+ concentration (2–3 folds) and K^+/Na^+ (Ran et al., 2019). Also, lettuce plants' nutrient status was improved under biochar application (produced from pellets of coniferous wood chips) in saline soils. The lettuce plants receiving biochar application showed increased phosphorus and manganese in their tissues (Hammer et al., 2015). For several other species, their nutrient status were also enhanced after adding biochar: phosphorus concentration in maize (Kim et al., 2016); iron, zinc, copper, phosphorus, potassium and manganese concentrations in tomato plants (Usman et al., 2016). Biochar applied at the rate of 5% decreased Na^+ ions or increased K^+ ions in the xylem sap of potato (Akhtar et al., 2014; Lashari et al., 2015). In wheat seedlings, biochar applications in saline soil led to decreased Na^+ and increased K^+ concentrations in the plant tissues (Abbas et al., 2018). Biochar application at the rate of 5% to saline soils improved the stomatal density and stomatal conductance in wheat, tomato, and herbaceous plants (Ali et al., 2017). The positive impact of biochar on the photosynthesis of salt-treated plants was reflected in the reduction of oxidative stress. It was shown that 2% biochar (produced from mulberry, *Morus alba* L., wood residues) amendment to saline soils led to a reduction of electrolyte leakage, malondialdehyde content, antioxidants and anti-oxidative enzymes in *Satureja hortensis* and *Vigna unguiculata* (Mehdizadeh et al., 2019; Osman et al., 2019). T. Gao et al. (2020); Y. Gao et al. (2020) observed improvement in plant water use efficiency by more than 19% and leaf water use efficiency by more than 20% with biochar application. These studies showed that biochar could improve plant physiology (enhancing antioxidant enzymes, mineral uptake and decreasing sodium uptake) and growth, as well as the adjacent soil properties.

3.1.3. *Flooding and waterlogging*

Among abiotic stresses, flooding affects the plants' performance and survivorship (Tian et al., 2020). Soil microbes consume all available oxygen, producing different toxic compounds during flooding and leading to anoxic soil conditions, ceasing root growth and accelerating root death (Kaur et al., 2020). Flooding causes epinasty, chlorosis, leaf abscission and premature fruit drop, reduces root permeability, inhibits photosynthesis due to stomatal closer and leads to phytohormonal imbalances (Grichko and Glick, 2001). In flooded rice paddy soils, wheat straw biochar improved plant yield by up to 14% (Zhang et al., 2010). Soil amendments with hardwood biochar comprised of oak (Quercus spp.), hickory (Carya spp.) and yellow poplar (*Liriodendron tulipifera*), have the potential to remediate sandy soil remaining after flood events and improve crop yields by increasing WHC and soil nutrient content (Basiri Jahromi et al., 2020). Biochar produced from mixed hardwood with or without bark amended, improved the quality attributes of a poor soil, such as the soil water, nutrient concentration (C, N, P, K, EC), cation exchange capacity and surface area in a temporarily flooded sandy soil trial. The effect of biochar can be effective alongside nitrogen and phosphorus fertilizers for improving plant acquisition of K^+ and phosphorus that significantly enhanced rice biomass and filled grains in cold and waterlogged paddy fields (Liu et al., 2016; Si et al., 2018). In another study, Dong et al. (2015) conducted a two-year field study to determine the effects of bamboo biochar and rice straw on rice in paddy soil with or without urea. Rice yield was improved under wheat straw biochar amendments due to higher ammonia content, soil moisture, total carbon and pH of rhizosphere soil with or without urea (Cui et al., 2017). Application of 3–9 tons/ha increased wheat biomass, grains yield, and straw yield by improving nitrogen, phosphorus, potassium, calcium, soil organic carbon content and magnesium uptake in wheat crops under paddy soil (Cui et al., 2017; Zhao et al., 2014). The wheat straw biochar addition increased the accumulation of Mn, Mo, Na and Zn in both rice straw and grain and decreased the leaching of nutrients, organic carbon and nitrogen at rice harvest and increased the leaching of Ca, Na and Mg. The biochar increased the pH, TOC and nitrogen and significantly changed the phospholipid-derived fatty acids (PLFA) concentration indicating different microbial community patterns in soils with rice compared to their controls. Thus, the results indicated that wheat straw biochar increased the productivity of rice (Muhammad et al., 2017). PLFAs are an essential group of structural components for all microbial cellular membranes. PLFA analysis is a technique widely used to estimate the total microbial biomass and to observe broad changes in the community composition of the living microbiota of soil and aqueous environments.

Flooded soils have a significant impact on greenhouse gas (GHG) emissions from soil. It can be expected that mainly reduced species such as CH_4 and much less oxidized greenhouse gases such as N_2O and CO_2 are released into the atmosphere. A major anthropogenic source of CH_4 is flooded rice fields, at least partly due to the anaerobic decomposition of crop residue in oxygen-limited conditions (Shan et al., 2008). The evidence available to date suggests that biochar can reduce CH_4 and also N_2O emissions from field soil. Biochar application decreased CH_4 emissions by reducing methanogenic archaea abundance in flooded paddy soil (Qi et al., 2020). Conversely, Zhang et al. (2010) found that applying wheat straw biochar at 0, 10 or 40 t/ha caused greater CH_4 emissions in the first growing year. Zwieten et al. (2010) and Zhang et al. (2010) applied several contrasting biochar materials to poor soil in a laboratory and field experiment and all biochars significantly reduced N_2O emissions from flooded soil, compared to the un-amended control. Zhang et al. (2010) found in flooded paddy rice in China that a statistically significant 130% increase in N fertilizer use efficiency when 40 t/ha of biochar was applied to the soil, compared to the un-amended control. There are several studies available about the enhanced detoxification of organic and inorganic substances after biochar amendment to flooded soils. Recent studies have highlighted the role of biochar in immobilizing potentially toxic elements (PTEs) in soils (Beesley et al., 2010). Biochar amendment reduces the release of toxic elements such as PTE under dynamic redox conditions in contaminated floodplain soil

(Rinklebe et al., 2016). Rice hull and woody biochar remediate tricyclazole from flooded alluvial paddy soil by increasing sorptive properties from 9.26 to 17.89 (García-Jaramillo et al., 2015). Biochar application is a promising strategy for plant growth and productivity in flooded paddy soil and with varying effects upon GHG emissions.

3.1.4. Soil inorganic contaminants

High concentration of trace metals reduces plant growth, water uptake and photosynthesis (Duruibe et al., 2007). Past literature has confirmed that the addition of biochar was generally effective to reduce the impact of polluted soils by immobilizing specific toxic metals and restoring a balanced mineral nutrition to the plants. The surface chemistry of biochar and metal adsorption efficiency depends upon the type of biomass, hetero-carbons and pyrolysis temperature (Mandal et al., 2018; Saletnik et al., 2019). High ash content and carbonaceous residue of biochar significantly participated in the heavy metal immobilization behaviour of zinc (Chen et al., 2012; Melo et al., 2016). Xu et al. (2013) demonstrated that biochar from dairy manure led to the immobilization of zinc as zinc phosphate and zinc carbonate. Similar results were shown for Zn immobilization by Wagner et al. (2015) in sewage field soils and by Nzediegwu et al. (2019) for Cd and Zn immobilization by plantain peel biochar in tuber flesh of *Solanum tuberosum.* Tables 2 and 3 illustrate the applicability to remediate organic and inorganic contaminants according to the type of biochar with different pyrolytic conditions and mechanisms. It was shown that the immobilization of heavy metal has a direct impact on growth on polluted sites (Penido et al., 2019). Biochar amendment reduced metal bioavailability and uptake and improved plant growth by up to 45% (Mohamed et al., 2017). Five percent amendment of *Gliricidia sepium* biochar led to 40-fold higher tomato biomass and a reduction in bioaccumulation of nickel, chromium and manganese by 93–97% in contaminating serpentine soil (Herath et al., 2015).

Previous studies show that plant growth can be enhanced by biochar amendment on polluted sites and also by the concomitant improvement of plant nutrition (Kavitha et al., 2018). While improving water retention, the biochar carbonaceous residue was able to absorb organic pollutants while the ash improved the soil pH and provided essential nutrients to plants (Qian et al., 2016). Zeeshan et al. (2020) examined the effects of *Acacia arabica* biochar with two different < 3 mm and 6–9 mm particle sizes in tomato under heavy metal stress. The < 3 mm biochar amendment improved plant parameter such as height (32%), fresh weight (50%) dry weight (33%), flowers (57%), fruits yield (69%), total chlorophyll (17%), carotene (15%) and soil parameter such as mineral nitrogen (100%), potassium (29%) and phosphorus content (30%), organic matter (2%), pH (1%) and EC (12%). The supplementation with 6–9 mm biochar was less effective but led still to an increase in plant height by 22%, fresh weight by 17% and dry weight by 24%, flowers by 16% and fruits yield by 48%. This observed effect was attributed to particle size and consequently higher specific surface area, pore structure, total pore space and cation exchange capacity. The amendment of biochar produced from wood chips and wheat straw pellets to metal-polluted soils led to greater growth by increasing the soluble fraction of Na^+, K^+ and Cl^- in water pores reducing Zn availability (Latini et al., 2019).

Several studies showed positive effects of post-treatment of biochar amended to heavy metal polluted soils. The combination of biochar with *Rhizophagus clarus* enhanced maize dry biomass (93%), roots (32–61%) and phosphorus concentration (1%) in cadmium-spiked soil (Rafique et al., 2019). The biochar acidification increased the plant's available nitrogen (14%), phosphorus (76%), potassium (38%), and calcium (38%) concentration under metal stress in maize (Rafique et al., 2019). In addition to the reduction in metal bioavailability and uptake, the improvement of nutrient availability and plant growth, show several

Table 3
Responses of Biochar Application on Organic and Inorganic Containments Remediation.

Containments	Results	Reference
Arsenic, zinc, cadmium	300 folds Cd and 45 folds Zn reduction	Zhang et al. (2020a)
Zinc, lead, cadmium	71% Cd, 87% Zn and 92% Pb reduction	Khan et al. (2020)
Lead, cadmium, nickel, copper	Sorption occurs ranging from 57%– 97%	Zhao et al. (2019a)
Polycyclic aromatic hydrocarbons	Reduction in concentrations up to 40–50%	Rombolà et al. (2019)
Pentachlorophenol	Levels decreased from 4.53 to 0.17 mg/l	He et al. (2019)
Chlorantraniliprole	Reduction in the bioavailability of pesticides	Wang et al. (2020a)
Simazine	97% sorption potential	Ashoori et al. (2019)
Glyphosate	Reduce leaching of the herbicide glyphosate	Jia et al. (2020)
Phosphate	Elimination rates of up to 73%	Huang et al. (2019)

Table 2
Effects of biochar in organic and inorganic contaminant remediation and mechanisms.

Containment (Organic)	Biochar type	Temperature (∘C)	Matrix	Mechanism	Reference
Chlorpyrifos	Woodchips	450–850	Soil	Adsorption	Khorram et al. (2017)
Sulfamethazine	Hardwood	600	Water	Adsorption	Huang et al. (2017)
Atrazine	Dairy manure	200	Water	Sorption	Zhang et al. (2018)
Phenanthrene	Soybean stalk	300–700	Water	Partitioning	Zhang et al. (2019b)
Deisopropylatrazine	Broiler litter	350 – 700	Water	Sorption	Goswami et al. (2019)
Fipronil	Cotton straw	450–850	Water	Adsorption	Ashoori et al. (2019)
Atrazine	Dairy manure	450	Soil	Sorption	R. Huang et al. (2018); H. Huang et al. (2018)
Sulphamethoxazole	Sugarcane bagasse	450–600	Water	Sorption	Ai et al. (2019)
Pentachlorophenol	Bamboo	600	Soil	Reduced leaching	Cai et al. (2020)
Simazine	Green waste	450	Water	Adsorption	Lee et al. (2020)
Dinitrobenzene	Pine needles	100–700	Water	Adsorption	Tong et al. (2019)
Trichloroethylene	Soybean stover	300–700	Water	Sorption	Huang et al. (2020)
Tylosin	softwood chips	850–900	Soil	Sorption	Li et al. (2020)
Pyrene	Saw dust	400–700	Water	Sorption	Bielská et al. (2017)
Humic acid, catechol	Softwood, grass	250–650	Water	Adsorption	Uttran et al. (2018)
p-Nitrotoluene (C)	Orange peel	250–700	Water	Adsorption	Liu et al. (2019b)
Naphthalene	Pine needles	100–700	Water	Adsorption	Hu et al. (2019)
Copper	Pecan shell	800	Water	Sorption	Zhou et al. (2017)
Copper	Green waste	550	Soil	Immobilization	Jones et al. (2016)
Mercury	Soybean stalk	700	Water	Precipitation	Tan et al. (2016)
Arsenic	Hard wood	400	Soil	Mobilization	Vithanage et al. (2017)
Chromium	Oakwood	450	Water	Sorption	Rajapaksha et al. (2018)
Copper and zinc	Hardwood	450	Water	Adsorption	Jiang et al. (2016)

studies a positive impact of biochar amendment on photosynthesis leading to a reduced generation of radical oxygen species. The application of 30 tons per ha of coconut husk and orange shell biochar increased *Brassica juncea* biomass (170%) and reduced copper concentration (51%) (Gonzaga et al., 2019). The effect of orange shell or coconut husk biochar was reflected by a high increase in gas exchange parameters (net photosynthesis, transpiration rate, stomatal conductance and water use efficiency) (Gonzaga et al., 2019). It also could be shown that biochar can be involved in the protection of the chloroplast ultrastructure hence foliar chlorophyll *a* (60%) and chlorophyll *b* (2 folds) improved due to biochar application in rice (Hafeez et al., 2019). Several studies focusing on metal-polluted soils reinforced the positive impact of biochar on photosynthesis due to a reduction of plant oxidative stress levels (Wang et al., 2018). Rice straw biochar reduced the cadmium bioavailability and decreased cadmium accumulation in shoots and roots, thus leading to lesser oxidative stress (Kamran et al., 2019). The oxidative stress was reduced through an increased enzymatic defence activity of guaiacol peroxidase, superoxide dismutase, ascorbate peroxidase and catalase (Fig. 2). In another study, rice straw biochar amendments lead to a decreased oxidative stress visualized by reduced electrolyte leakage, and a two-folds reduction of malondialdehyde and hydrogen peroxide after induction of catalase and superoxide dismutase activities (Mehmood et al., 2018). Biochar has a non-carbonized fraction (carboxyl, hydroxyl, phenolic surface functional groups) that bind effectively with contaminants which make it an excellent universal sorbent for contaminant (organic and inorganic) in the soil as well as water.

3.1.5. Heavy metal mobility in acidic soils

About 50% of the area of total arable land is occupied by soil having pH < 5.5. It has been shown that acid deposition, removal of farm products and aluminium-based fertilizers cause soil acidification with the effect of nutrients deficiencies, enhanced heavy metal toxicity and reduction in crop yield (Brantley et al., 2016; Lozano-Canales et al., 2019). Several techniques are currently in use to reduce soil acidity and to attain sustainable food production. One of these approaches is biochar amendment for soil improvement, due to its alkaline nature and high pH buffering capacity (Fig. 1 and Table 1 supplementary material). During feedstock pyrolysis, cations like calcium, potassium, magnesium, sodium and silicon are converted into carbonates and oxides (Guo et al., 2019). These salts react with the H^+ and monomeric aluminium species in acid soils, increasing soil pH and decreasing exchangeable acidity (Gezahegn et al., 2019; Guo et al., 2019). The soil pH buffer capacity is an important property in the amelioration of soil acidity. Application of manure biochar (3%) increased pH buffer capacity by 1.6 folds in Psammaquent-type, 2.4 folds in Plinthudult-type and 2.2 folds in Paleudalf-type of soils (Dai et al., 2014). However, manure-based biochar increased the pH buffer capacity more than lignocellulose-based biochar due to increases in cation exchange capacity in the soil (Dai et al., 2017). Low soil pH (< 5) leads to the solubilisation of Al, primarily to the phytotoxic form of Al^{3+} in soil solution (Rajpal and Basavarajappa, 2020). In acidic soil, aluminium toxicity is the primary limiting factor in acid soils for root growth and crop productivity. Free aluminium ions prevent root cell expansion, elongation, and division that limits water and nutrient uptake. Biochar decreases aluminium bioavailability and alleviates its toxicity in acid soil (de Almeida et al., 2020). Mixtures of biochar produced from rice, peanut and canola straws, reduced concentrations of total aluminium, monomeric aluminium and monomeric inorganic aluminium improve growth parameters, canola yield, seeds and straw production (Zhao et al., 2020). High biochar ash content (58%) correlates with the capacity to convert highly toxic aluminium cations into less toxic aluminium hydroxide in acid soil (Qian and Chen, 2014). High biochar surface areas and porosities offer more adsorption sites for aluminium and other metals bounding (Uchimiya et al., 2011) and chelation by organic hydroxyl and carboxyl groups (Qian et al., 2013). These studies suggested that biochar is a promising material for heavy metal remediation in contaminated soils and the plausible mechanisms are highlighted in Fig. 3.

3.1.6. Soil organic contaminants

Organic contaminants such as organochlorine pesticides, polybrominated diphenyl ethers, halo hydrocarbon and polycyclic aromatic hydrocarbons are commonly found in the environment due to industrial activities or farming practices which are very toxic to humans and animals (Zhang et al., 2017a). These pollutants enter plants through roots and leaves and can lead to serious damage to the plant cell ultrastructure, biosynthesis of proteins, amino acids, nucleic acids, lipids, hormones and DNA stability (Hellström, 2004). To reduce the bioavailability and leachability of organic pollutants in soils, biochar can be used effectively to ameliorate these pollutants through various physicochemical reactions (Zhang et al., 2013). In a previous study, Yang et al. (2006), the bioavailability of diuron was reduced by applying 0.1% biochar. Graber et al. (2012) showed that biochar amendments were able to reduce sulfentrazone and S-metolachlor bioavailability. Song et al. (2012) observed that wheat straw biochar leads to 42 times higher sorption of hexachlorobenzene than the control soil. Thus, it is concluded that biochar has the potential to reduce the bioavailability and efficacy of organic pollutants (Tables 2 and 3).

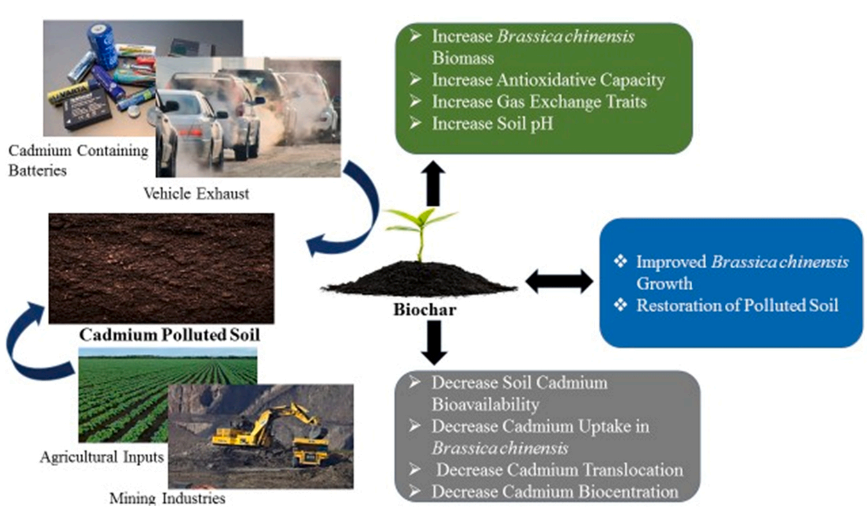

Fig. 2. The effects of biochar addition on soil properties and cadmium phytotoxicity in *Brassica chinensis* cultivated in soils with high levels of cadmium.

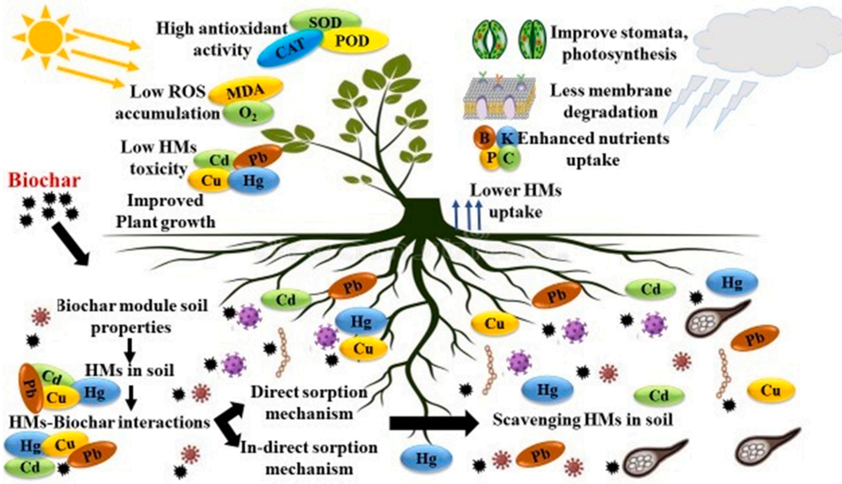

Fig. 3. The effects of biochar amendments on the plausible mechanisms of trace elements' movements in rhizosphere: their interactive effects upon ion flux interactions and elemental sequestration (ranging from free movement, adsorption, absorption and assimilation).

3.1.7. Climatic and environmental perturbations

Many climatic factors affect crop productivity through their combined impacts upon plant growth and soil properties; for a summary, see Fig. 4 (Palanivelu et al., 2020). Intensive agronomic practices such as chemical fertilization, tillage and understory straw removal would reduce field soil carbon storage and affecting the microbiome diversity. The application of biochar to both natural and arable soils is a plausible sustainable management practice which sustain soil organic carbon and its associated microbiome thereby maintaining or even improving plant productivity (Sundberg et al., 2020; Feizi and Razavi, 2020). El-Naggar et al. (2018) increased organic carbon by about 76% upon the biochar application in sandy soil. A combination of straw with biochar lead to an increase in the decomposition of organic matter, and the CO_2 flux was also enhanced. This combination also increased macro-aggregates percentages which promoted C sequestration (R. Huang et al., 2018; H. Huang et al., 2018). Yang et al. (2017) significantly reduce the soil CO_2 emissions under maize stover-derived biochar addition. Singh and Cowie (2014) stimulate native soil organic carbon mineralization in the low-carbon clayey soil by *E. saligna* wood biochar but this effect decreases with time, which may be due to the depletion of labile soil organic carbon. Li et al. (2018) concluded that biochar reduces soil heterotrophic respiration, increasing soil organic carbon and decreasing carbon-degrading microbial activity. Zhang et al. (2017) applied 8 ton/ha of wheat straw-derived biochar, leading to a 34–80% increase in soil organic carbon, 19–47% microbial biomass carbon and 8–38% microbial biomass nitrogen. Hamer et al. (2004) reported that the decomposition rate of corn straw biochar was 0.9%, rye straw biochar was 0.7% and wood biochar was 0.3%. Wang et al. (2014) significantly increased soil organic carbon storage in a Chinese chestnut plantation by applying 5 tons/ha biochar.

Soil carbon dioxide emissions (soil respiration) are the primary mechanism of carbon loss from ecosystems and contributing negatively to climate change (Wang et al., 2019). Global warming potential per unit mass of methane and nitrous oxide gases are 25 and 198 times higher respectively than that of CO_2 (Xu and Shang, 2016). Approximately 50 tons/ha of rice husk biochar decreased 73% N_2O emissions during 60

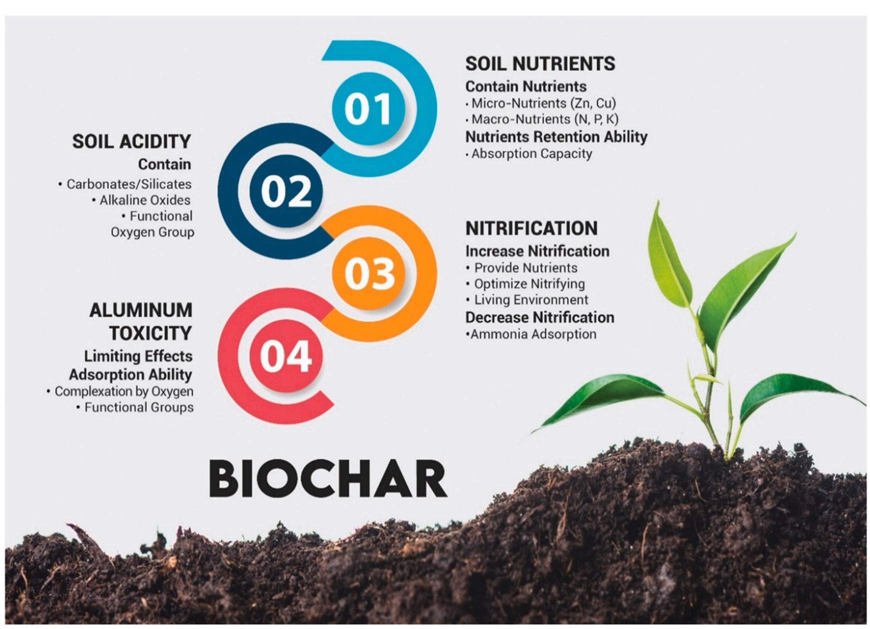

Fig. 4. Plausible mechanisms of biochar amendments in ameliorating soil acidification and aluminium toxicity, and regulating nutrient cycling and nitrification in soils.

days in paddy soil and without an increase in CO_2 emissions (Wang et al., 2011). Pig manure-derived biochar was reported to decrease carbon mineralization (Gascó et al., 2016). Biochar has a positive effect in reducing total CO_2 emissions, increasing microbial biomass or soil moisture and promoting soil organic carbon sequestration (Ge et al., 2019). Combining steel slag and biochar reduced total CO_2 emissions by 42–60% and increased soil carbon stock in paddy fields (M. Wang et al., 2020; H. Wang et al., 2020). Interestingly, the combined application of biochar and nitrogen fertilizer increases soil fertility and decreases soil CO_2 emissions in bamboo plantations (Ge et al., 2020). About 30 tons/ha of biochar reduced CO_2 emissions by 32% (Sun et al., 2014). Peanut shell biochar reduced the total CO_2 emissions of soil by 33% while wheat straw biochar reduced by 90.25% (M. Wang et al., 2020; H. Wang et al., 2020). Straw-derived biochar decreased CH_4 emissions by 20–51% annually (Wang et al., 2019). Cottonseed husk biochar reduced CH_4 emission by 69% in the peanut copping system (Tan et al., 2019). Oak biochar showed the potential to reduce N_2O emissions by 27–67% and CH_4 emissions by 24–42% in rice fields (Shaukat et al., 2019). In another study, adding willow wood biochar led to a reduction of N_2O emissions by 50–90% in lime soil (Ameloot et al., 2016). At an application rate of 30 tons/ha pine biochar, the amendment significantly increased N_2O emissions by 48% while 30 tons/ha peanut shell biochar enhanced emissions (131%) in sandy loam soil (Lan et al., 2019). Conversely, biochar amendment decreased N_2O emission by 39% in nitrate-rich degraded soil (Jiang et al., 2020). The application of 50 g/kg rice straw biochar increased soil denitrification rates by 13–26% and reduced N_2O emissions by 442–809% (Su et al., 2019). Rice-straw-derived biochar decreased soil N_2O emissions by 35% (Yuan et al., 2020). Corn residue-derived biochar reduced total CO_2 emission by 18–25%, CH_4 emission by 124% and total N_2O emission by 71–110% in sandy loam soil (Yang et al., 2020b). Overall, biochar application generally increased soil methane and carbon dioxide emissions by an average of 15% and 16%; and lowering soil nitrous oxide emissions by an average of 38% (Zhang et al., 2020b). Nevertheless, more in-depth research is needed to understand the multi-faceted biochar, soil type and gas emissions interactions.

3.2. Limitations of using biochar amendments

While biochar could serve as a major source of carbon sink and effective soil improvement agent, it also has several limitations (Table 4). Top dressing of biochar leads to the loss of soil by erosion (Liu et al., 2019). The application of biochar may cause soil compaction under inappropriate conditions. However, these soil-related issues could be resolved with proper planning and integrated management (e.g. slope design, contour engineering, proportion of waste rocks to substrates, etc) on sites. Several contaminants like heavy metals, metalloids and dioxins are present in biochar which might have harmful impacts on soil properties and plant health (Kavitha et al., 2018). Due to various reasons (e.g. branches were harvested from trees growing in high Cd soils), these contaminants are present in feedstock used to produce biochar. Thus, good quality feedstock (with little or no contaminants) or a low pyrolysis temperature of less than 500∘C could reduce the contamination issues (T. Liu et al., 2020; H. Liu et al., 2020a). Health and safety measures are needs to be considered during biochar production, transportation, application and storage to reduce occupational health and fire hazards (Xu et al., 2019). Biochar pore size distribution alters soil physical properties like water retention, habitat and aeration. High biochar application of approximately 67 tons per ha would increased soil pH and salt levels which might later affect earthworms' survivorship (Shi et al., 2019). The carbon storage capacity of biochar in soils is less understood at present. Moving forward, it is envisaged that the soil carbon sequestration capacity after biochar addition is dependent upon many environmental, economic and social factors (Zhang et al., 2019c).

Large processing plants are able to process 23,000 tons of biomass per day, which required high-capacity biomass handling, transportation and storage infrastructures. Operationally, the hard cellulosic structure in the biomass posed challenging processing throughput problems resulting in higher production costs (Maroušek et al., 2019). If biochar is not produced according to the environmental guidelines, it can create various environmental issues: excessive deforestation, greenhouse gas emissions and local health problems (McCarl et al., 2009). Seed germination, productivity and associated microbiome are influenced by the presence of volatile organic compounds (pyrazines, pyridines, pyrroles and furans) and polyaromatic hydrocarbons in biochar (Pandey et al., 2020). Biochar adsorbs pesticides and herbicides, leading to a reduction in their efficacy. During pyrolysis, phytotoxic and carcinogenic compounds are released, heavy metals might be transformed into less toxic forms, and pathogens are eliminated under some conditions; these pyrolysis-linked transformation is dependent on the type of feedstock, type of residue in feedstock, and pyrolysis parameters (Tripathi et al., 2020). Conversely, nutrients in biomass (mainly nitrogen and sulphur), might be lost during continuous pyrolysis (Ndirangu et al., 2019; Paz-Ferreiro et al., 2018). The use of biochar can lead to an increase in greenhouse gas emissions (mainly nitrous oxide). In terms of air quality consideration, the ash content in biochar is a source of dust particulates and when not managed adequately, it can cause respiratory diseases. For certain soil and crop types, the addition of biochar can further increase the soil pH and impairing the productivity of certain species with a narrow range of optimal soil pH. When nutrient circularity is poorly managed in certain communities, long-term crop residues usage in biochar production could disturb local nutrient cycling loops and reduce soil health (Ashiq and Vithanage, 2020; Wang et al., 2020b).

Table 4
Drawbacks of biochar application in soil.

Biochar	Pyrolysis Condition	Soil Type	Effects	References
Wood-derived	550 °C for 1 hr	Sandy loam clay	No significant changes were observed in microbial biomass and organic carbon	Espinosa et al. (2020)
Birch Charcoal	475 °C for 4 hr	Sandy slit soil	Carbon dioxide and nitrous oxide gas emission increases	Shen et al. (2019)
Wood-derived	500 °C for 40 min	sandy loam calcareous	No heavy microbial colonization	McCormack et al. (2019)
Rice husk	350–500 °C	sandy loam	Biochar was mobile in poor sandy soils (0.3 m in 4 years)	Beusch et al. (2019)
Wheat straw	450 °C	Paddy soil	Methane and nitrous gas emission increase in paddy fields	Jiang et al. (2019)
Wood-derived	350–500 °C for 1 hr	Arsenic contaminated soil	Increased arsenic and copper 30 folds sorption after the biochar addition	Rechberger et al. (2019)
Hard wood-derived	600 °C for 24 hr	Sandy loam clay	Reduced biodegradability of simazine	Zhang et al. (2019d)

4. Synergistic enhancement of biochar properties

Biochar is widely used as an amendment to promote soil aggregation stability, reduce erosion susceptibility, optimize the air-soil water balance, improve hydraulic conductivity and nutrients/water retention ability (Lee et al., 2019). The general effects of plants receiving biochar amendments are shown in Fig. 5. Compost is known to contain organic

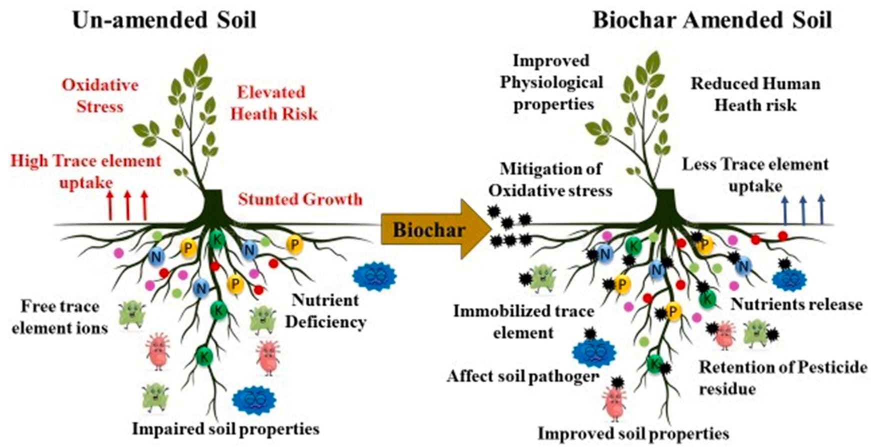

Fig. 5. The salient characteristics of plants growing in un-amended (control) and biochar-amended soil.

nutrients, useful microbes, degradation products and microbial metabolites; with generally positive effects on the physico-chemical and biological properties of soil as well as the associated plant productivity (Alshankiti and Gill, 2016; Stamatiadis et al., 1999). These benefits can be further improved through the addition of beneficial microorganisms as well as other additives including humic acids (Canellas and Olivares, 2014). A further effect of soil improver could be an interaction with biochar to prevent its stability, function and efficacy in the soil by decreasing oxidation and degradation of biochar (Palansooriya et al., 2019). Besides, biochar stability is directly related to the feedstock type and production conditions while inversely related to the presence of saprophytic organisms like fungi. However, as compared to other organic soil amendments within soils high stability of biochar confirms its potential for large soil productivity (Lehmann and Joseph, 2015). The further chapter will give insight into the synergistic effects of various soil improvements with biochar.

4.1. Pre-treatment of biochar before pyrolysis

Additives to the feedstock before pyrolysis can have an impact on the biochar properties (Lehmann and Joseph, 2009). Alkali or iron can break down lignocellulosic compounds and increase the biochar yield such as the addition of mineral ash (Edye et al., 1993; Feng and Zhu, 2018). Adding of wood ash to biochar leads to an increase in soil electrical conductivity, the ratio of charge density/unit surface area of organic matter, the cation exchange capacity due to surface oxidation and the surface area for cation absorption (Amonette and Joseph, 2012; Tomczyk et al., 2020). Sewage sludge biochar has a high content of heavy metals, alkaline pH, lower carbon content and higher ash contents (Pandey et al., 2020). The addition of phosphoric acid to the feedstock can be used to enhance functional groups, reduce pH and producing a slow-release phosphate fertilizer (Peng et al., 2017). Interestingly, adding some phosphate rock had a positive effect on Pb removal capacity (Gao et al., 2018). Supplementation with iron ameliorates iron deficiency by producing biochar with magnetic characteristics to remove toxic heavy metals from the soil. Biochar characteristics such as the concentration of acidic functionalities (particularly the phenolic species), the degree of aromatic condensation, and the pore volume can be tailored by infiltrating the biomass with suitable iron salts and clay minerals before pyrolysis (Rawal et al., 2016). There are several studies about the post-treatment of biochar (Xiang et al., 2020; Palniandy et al., 2019), often with similar additions as discussed earlier for pre-treatment. These studies show that post-treatment with steam, air, or chemical methods alters biochar properties like pH, organic C, adsorption capacity, specific surface area, porosity or ash content (Klasson et al., 2014).

4.2. Addition of biochar and compost mixtures

Incorporating biochar and compost together as a mixture into the soil has a significant effect on the sorption-desorption of metals in soil and can positively affect soil fertility, water status, and plant growth (Agegnehu et al., 2016; Abideen et al., 2021). Recent literature highlighted that the combination of biochar with compost adjusts soil carbon-nitrogen ratio, reduces heavy metal mobility or nitrous oxide emission, improves nitrogen retention, and changes microbial composition (Agegnehu et al., 2017; Antonangelo et al., 2021). Biochar can also be co-composted with pre-composted materials to charge the biochar surfaces with various elements. For instance, composted biochar with iron grit improved the growth of *Salix viminalis* (three folds) and soil fertility by reducing acidity, metal mobility and toxicity in arsenic and lead-contaminated soil (Lebrun et al., 2020). *Chenopodium quinoa* yield was increased by up to 305% with the application of co-composted biochar into sandy and nutrient poor soil, compared to the control (Kammann et al., 2015). Total N losses over 42 days of co-composted biochar were reduced by 64% (Hua et al., 2009). Peanut shell-derived biochar with compost enhanced the yield of *Chrysanthemum coronarium* by 16%– 107% and these improvements were accompanied by favourable water holding capacity soil organic matter, electrical conductivity and nutrient availability (Liu et al., 2019c). Applying wheat straw biochar-poultry manure compost mixture with a diluted pyroligneous solution increased maize grain yield, leaf area index, and leaf sap NPK, and reduced leaf electrolyte leakage (Lashari et al., 2015). Luo et al. (2017) studied the growth effect of *Sesbania canabina* and *Kosteletzkya virginica* after receiving 1.5% biochar and compost amendments; these plants recorded enhancement in growth rate by 20% respectively as compared to the controls while root length and tips increased by 1.5%. The application of biochar poultry manure compost at 12 t/ha increased wheat yield by 38% compared to the control (Lashari et al., 2013). Biochar with manure compost alleviated the salt stress of maize by promoting microbial community and antioxidant enzymes (Lu et al., 2015). There were also remarkable suppression effects on greenhouse gas emissions: biochar and compost application reduced greenhouse gas emissions from bananas (Bass et al., 2016). Sarkhot et al. (2012) reported that carbon and nitrogen storage can be optimized by applying biochar with dairy manure effluent, leading to a 75% reduction in net nitrification, a 229% reduction in net ammonification and a 68% reduction in cumulative CO_2 fluxes.

4.3. Addition of biochar and humic acid

Humic acid (HA) is a component of organic matter, soluble in water at higher soil pH values and can remain undisturbed for centuries under certain circumstances (Duarte et al., 2008). It has positive effects on soil physical and biological conditions such as aggregation, aeration, permeability, cation exchange capacity, nutrient transport and availability, root initiation and growth and shoot development (Zhao et al., 2019b; Pal, 1992). The combined application of biochar and humic acid could improve key physiological markers (relative water content, leaf osmotic potential, electron transport rate for photosynthesis) in maize undergoing drought stress (Haider et al., 2015). One of the known characteristics of HA seems to be its ability to reduce the contaminant mobility such as heavy metals or pesticides in the environment (Duarte et al., 2008), to interact with oxides, hydroxides, and to improve nutrient availability and uptake (N, S, P), especially under nutrient deficiency conditions (Trevisan et al., 2010). These properties were enhanced and supplemented in combination with biochar amendment. The combination of biochar 20% and HA 0.7% significantly increased growth parameters, uptake of total nitrogen, phosphorus and potassium and total chlorophyll in *Calathea insignis* (Zhang et al., 2014).

Rock phosphate enriched with compost, biochar, humic acid and *Alcaligenes* sp. increased growth grains yield, stover yield, soil organic carbon and potassium content in maize (Hussain et al., 2019). Using biochar and humic acid enhanced the plant growth, morphological parameters and the acquisition of macro- and micro-elements of *Calendula officinalis* from the soil (Karimi et al., 2020). Even under salt stress, the joint application of potassium humic acid casuarina tree plant biochar enhanced the growth of *Solanum melongena*, soil K^+, soil physio-biochemical characteristics, and the balance of osmoprotectants and antioxidants; with reduction of nitrate and cadmium uptake (Rady et al., 2018). Biochar, HA and compost enhanced the availability of nutrients and synthesis of chlorophyll in salt-treated barley plants (Rekaby et al., 2020). Biochar and HA also had an impact on heavy metal toxicity; a combination of 5.0% sawdust charcoal, 7.5% wheat straw charcoal and 2.5% biological HA with additional pig manure increased yield in *Brassica campestris* by 19%– 34% while concomitantly reducing the accumulation of cadmium, copper and lead (Zhou et al., 2018). The joint application of biochar and humic acid had a significant impact on the activity of pH-dependent pesticides. In particular, the HA had a high affinity to polar, ionic pesticides of high water solubility, while biochar, due to its moderately hydrophobic character, preferentially attracts non-ionic pesticides of low water solubility (Ćwieląg-Piasecka et al., 2018). Due to these complex interactions, consideration should be given to recommending the precise dosage during the application of pesticides.

4.4. Addition of biochar and nanoparticles

Nanomaterials are defined as natural, incidental or manufactured materials containing particles, in an unbound state or as an aggregate or agglomerate, where ≥ 50% of the number size distribution is within the size range of 1–100 nm (Cornelis et al., 2014). Besides sustainable practices such as phytoremediation, manufactured nanoparticles are recommended as an effective agent for the remediation of heavy metal-contaminated soils, because of their capacity for metal stabilization (Feizi et al., 2018; Alomar et al., 2016). Nano-scale zero-valent iron is commonly used for the treatment of various environmental contaminants (Sun et al., 2020). There is an impressive number of papers focusing on the synergistic effects of biochar and nanoparticles. The addition of biochar to nanoparticles prevents toxicity in barley, tobacco, onion, wheat, and spinach and improves plant growth and development (Abdel Latef et al., 2018; Khan, 2016). Cerium oxide nanoparticles (500 mg/l) with biochar induce *Triticum aestivum* growth by stimulating photosynthesis, transpiration and stomatal conductance. Biochar reduced the phytotoxic effect of cerium under these conditions by nine folds (Ali et al., 2019). Zinc oxide nanoparticles sprayed on *Zea mays* leaves grown with 1% biochar improved the height of maize plants, leaf number, dry biomass and chlorophyll, while reducing cadmium, electrolyte leakage, malondialdehyde and hydrogen peroxide contents (Rizwan et al., 2019). Bashir et al. (2020) also applied zinc oxide nanoparticles with biochar and compost in wheat cultures to enhance plant growth, yield and chlorophyll and to remediate cadmium from soil. Iron nanoparticles (30 mg/l) with 1% biochar increased the dry biomass of rice (Fig. 6), chlorophyll and gas exchange in cadmium-contaminated soils (Wu et al., 2018a). Wu et al. (2018b) found a significant increase in the plant biomass and the effective antioxidant activity of *Brassica chinensis* grown in soils contaminated with polybrominated diphenyl ethers (industrial product) after the combined amendment of biochar with nickel and iron nanoparticles.

4.5. Addition of biochar and phytohormones

Phytohormones govern all aspects of development and form the integral chemical signalling systems regulating responses and adaptations to nutrients and environmental perturbations. The influence of salinity and biochar increased phytohormones in bean plants in terms of increased polyamines, abscisic acid (ABA), 1-aminocyclopropane-1-carboxylic acid, jasmonic acid and salicylic acid which is linked with the decrease of sodium uptake (Farhangi-Abriz and Torabian, 2018). Overall, when co-applied with certain groups of phytohormones, biochar alleviated the negative effects of salt stress on bean seedlings by reducing Na^+, endogenous stress hormones (e.g. ABA), and the improvement of growth hormones like cytokinins and auxins (Farhangi-Abriz and Torabian, 2018). Seeds of *Brassica juncea* are treated with 10 μmol/L salicylic acids under salinity. Salicylic acid reduced salinity stress by alleviating the antioxidant system (Yusuf et al., 2008). In *Zea mays Phoenix dactylifer* and *Triticum aestivum* biochar with melatonin and phosphorus enhanced leaf gas exchange by 3–20%, osmolyte accumulation, α-amylase activity and antioxidant enzyme by 2–7%, 29%, 9–55% (Alharby and Fahad, 2020). Melatonin mediates physiological processes in plants; melatonin-treated plants have enhanced photosynthetic rate and total chlorophyll and reduced oxidative damage by salt stress through ant oxidative enzymes (Faraq et al., 2020). Melatonin spray increased soybean height, leaf size and the number of pods and seeds under salt and drought stress (Wei et al., 2015). In addition, some studies observed a higher release of ethylene due to biochar applications. The rates of ethylene production varied with different biochar concentrations (Spokas et al., 2010; Ding et al., 2018). Based on the available evidence, the source of ethylene is likely to be derived from biochar; most biochars exhibiting ethylene production even without soil or microbial inoculums (Spokas et al., 2010; Elsiddig et al., 2021). Our study suggested that the combined application of ascorbic acid (ASA) and biochar at appropriate amounts and concentrations on sorghum seedlings may be helpful in salt tolerance and stimulating greater antioxidant enzymatic activity to overcome the unfavourable saline conditions (Elsiddig et al., 2021). The results showed that the provision of biochar of ca. 12.5 tons/ha improved the growth and yield of true shallot seed plants (number of plants/clumps, number of bulbs/clumps, number of bulbs splitting, bulbs diameter, and dry weight of bulb/clump) (Firmansyah et al., 2021).

4.6. Addition of biochar and microbes (bacteria or fungi)

An extensive number of soil bacteria, mycorrhizal fungi and free-living saprotrophs can promote plant growth by biodegradation, synergistic interactions (N_2 fixation), production of volatiles like acetoin, stimulating the synthesis of phytohormone-like compounds and interfering with plant gene expression (Jambon et al., 2018). They are also known for their removal capacity for organic and inorganic pollutants, and their ability to induce plant systemic resistance and improve stress resilience (H. Liu et al., 2020; T. Liu et al., 2020b; Mohamed and Paleologos, 2017; Pieterse et al., 2014). Plant growth-promoting bacteria facilitate plants growth undergoing stress by various direct and indirect mechanisms including secreting metabolites (citric, lactic, gluconic), phytohormones, enhancing soil enzyme activities, improving the availability of nutrients (such as phosphate), promoting mineral uptake or

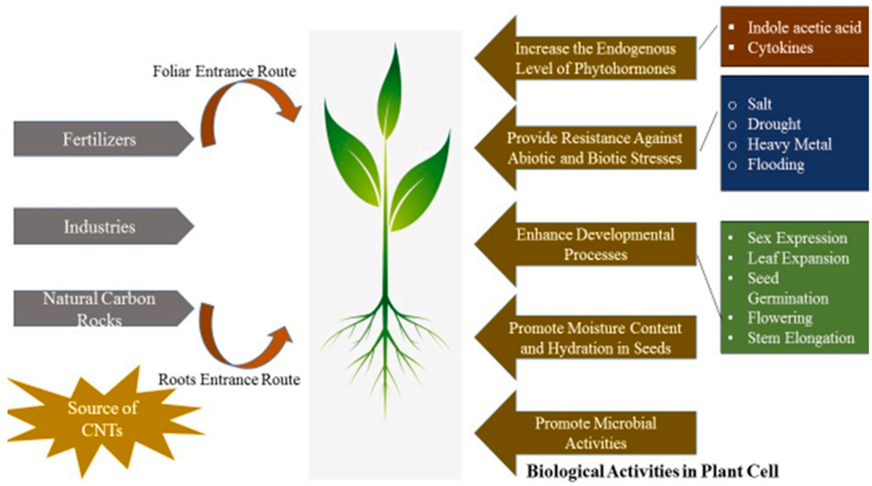

Fig. 6. Effect of nanoparticles on plant growth dynamics triggers by different growth stimulating agents.

stimulating the expression of salinity responsive genes (Gupta et al., 2020; Sani and Yong, 2022). Biochar provides a favourable microhabitat, which changes the microbial community structure (Solaiman et al., 2010). Biochar can enhance the properties of soil microbes by the formation of suited surface areas and soil aggregates, adsorption and remediation of pollutants and the facilitation of electron transfer between microbial cells and soil organic matter (Zhu et al., 2017). *Eupatorium adenophorum* co-composted biochar improves maize biomass by 243% (Pandit et al., 2020). A combination of biochar, compost, and arbuscular mycorrhizal fungi resulted in the highest plant cover, which enhanced grassland restoration (Ohsowski et al., 2018). Biochar (2%) with *Funneliformis mosseae* and *Pseudomonas* sp. influenced root morphology, grain yield promoted root colonization and improved nutrient uptake in *Apium graveolens* (Ning et al., 2019). In *Quinoa*, biochar with compost and *Thiobacillus thiooxidans* improved the bioavailability and translocation of essential nutrients from the soil to plant the plant biomass (Ramzani et al., 2017). In kidney beans, rice straw-derived biochar with rhizobia increased root and shoot biomass, nodulation and nutrient uptake (Ghazi, 2017). The combination of woody biochar with *Bradyrhizobium* sp. enhanced plant growth, nitrogen and phosphorus concentration, and nodulation of *Lupinus angustifolius* (Egamberdieva et al., 2017). Hydrocarbon biochar with *Bradyrhizobium* sp. promoted growth, yield and pod formation of *L. angustifolius* under irrigated and rain-fed conditions (Egamberdieva et al., 2020).

However, studies also show that biochar's pyrogenic organic matter and heavy metals may induce toxicity to soil microorganisms (Gibson et al., 2016). In contrast to this statement can biochar and microbes interact in detoxification and the promotion of stress resistance? Seneviratne et al. (2017) proved the synergetic effects of woody biochar (1%, 2%, 4% and 5%) and *Bradyrhizobium japonicum* on *Vigna mungo* under heavy metal stress. Alam et al. (2019) enhanced the antioxidant defenses of mung bean in arsenic-contaminated soil by the treatment of biochar (cow dung, sawdust, and rice husk) with mycorrhiza and selenium. The combination of biochar, compost and arbuscular mycorrhizal fungi enhanced remediation and grassland restoration (Ohsowski et al., 2018). The results of soil microcosm experiments showed that the removal efficiencies of total hydrocarbons (TPH) were significantly higher in petroleum-contaminated soils amended with biochar than in soils without (Quin et al., 2013). Arbuscular mycorrhizal fungi can improve plant growth, and nutrient uptake, and provide resistance or tolerance against stress to host plants in exchange for photosynthetic carbohydrates (Govindarajulu et al., 2005). The combination of biochar and bacteria (*Burkholderia phytofirmans* and *Enterobacter* sp) mitigated the adverse effects of salinity by reducing the Na^+ uptake in the xylem and maintaining nutrient homeostasis in maize (Akhtar et al., 2015). Similar results were shown at salinity stress of maize by (Fazal and Bano, 2016), showing that the combination of biochar, fertilizer and *Pseudomonas* sp. kept high soil moisture and enhanced nutrient availability leading to a reduced tissue Na^+, higher membrane integrity, a stimulation of proline synthesis and peroxidase activity to overcome oxidative stress. Corn growth was also significantly increased under salinity by a combined amendment of shrimp waste biochar (1%) with *Funneliformis mosseae* (Kazemi et al., 2019). The combination of biochar with compost and *Pseudomonas fluorescens* alleviated water deficit stress in cucumber and led to significant increases in *Pseudomonas fluorescens* population, in plant shoot length, shoot biomass, root length, root biomass chlorophyll, relative tissue water contents and membrane integrity (Nadeem et al., 2017). Hashem et al. (2019) improved under drought stress the plant growth, shoot and root length, leaf area, number of branches, relative water content and membrane stability index but also nitrogen fixation in *Cicer arietinum* by the application of *Conocarpus erectus* biochar in combination with the inoculation of *Claroideoglomus etunicatum*, *Rhizophagus irregularis*, and *Funneliformis mosseae*.

5. Concluding remarks

Biochar application to soil is a promising strategy to reduce soil degradation, improve soil health and play an intrinsic role in supporting plant growth and survival. Many suitable feedstocks under different pyrolysis conditions can be used for biochar production, resulting in biochar products with a broad range of physicochemical properties. The physicochemical composition of biochar, including surface chemistry, particle size and pore size, and these could ultimately affect plant performance, especially under drought and saline conditions. Biochar is a good and plausible solution for resolving existing soil ecosystem problems due to its intrinsic physical and biological characteristics. Soil quality can be improved by adding biochar owing to its influences on soil structure, texture, porosity, particle size distribution and density, nutrient availability, electrical conductivity, and cation exchange capacity. In addition, the highly porous network of biochar provides conducive refugia for soil microorganisms. The strategic incorporation of biochar with humic acid, compost, microbes and other amendments can improve soil fertility and plant health across different cultivation scenarios. Additionally, biochar can ameliorate many unfavourable soil environmental situation like excessive metal contamination and the deacidification of acidic soil. Additional efforts need to be directed towards the selective utilization of biochar in an effective and environmentally friendly for the reclamation of degraded and saline lands especially in arid zones. A more in-depth understanding of the multi-faceted biochar-plant physiology and soil biochemical interactions would open new research avenues as potential ways towards large scale and sustainable commercial applications.

6. Future prospects and directions

Since the Palaeolithic era, biochar has always been associated with human civilization and food production. There remains many unanswered questions about the quality and microscopic characteristics (physical and biological aspects) of biochar in the soil and adjacent rhizosphere. To deepen our understanding about biochar, advanced, multi-disciplinary and novel methodology are required to boost our fundamental knowledge in the field of soil management, crop production, carbon sequestration, emission reduction and pollution control. These environmental concerns and future research directions on proposed issues are highlighted in Figure II (supplementary material). It is a matter of time when biochar enters the future carbon trading markets since it is a widely used soil amendment in many land-related activities globally like agriculture, forestry and the ecological restoration of degraded soil.

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.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ecoenv.2022.114408.

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