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Review

Biochar: an organic amendment to crops and an environmental solution

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Abstract: Biochar is a carbon-rich stable substance, defined as charred organic matter, produced during biomass thermochemical decomposition, and its application is currently considered as a mean of enhancing soil productivity, which is an important requirement for increasing crop yields whereas, simultaneously, it improves the quality of contaminated soil and water. However, depending on pedoclimatic conditions, its applicability exhibits negative aspects as well. It can also support biofuel production, therefore helping in reducing the demand for fossil fuels. Biochar is providing ecosystem services such as immobilization and transformation of contaminants and mitigation of climate change by sequestering carbon and reducing the release of greenhouse gases such as nitrous oxide and methane. It can further reduce waste as it could be produced from everything that contains biomass thereby assisting in waste management. Due to such wide-ranging applications, this review was conceptualized to emphasize the importance of biochar as an alternative to classic products used for energy, environmental and agricultural purposes. Based on the detailed information on the factors impacting biochar properties, the benefits and limitations of biochar, and the potential application guidelines for growers, this work aimed to help in partial achievement of multiple environmental goals and a practical recommendation to growers although its large-scale application is still controversial.

Keywords: biochar; organic amendment; environmental applications; agricultural benefits

1. Introduction

Biochar can be defined from a dual perspective: (i) as a "solid material" biochar, is a ground-up charcoal (black in color, highly porous, and finely grained, with light weight), for application to soil, which has been often considered as most valuable amendment or better described as a "soil conditioner" and (ii) as a "concept", is charred organic matter obtained from the carbonization and thermochemical conversion of biomass in an oxygen-limited environments [1–3]. Due to its inherent properties, a lot of scientific debate exists as to its application to soil such as increasing carbon (C) sequestration [4], improving soil physicochemical properties [5], reducing greenhouse gas (CO_2, N_2O, and CH_4) emissions from soil [6], thus ensuring ecological integrity and environmental sustainability. Biochar is deliberately used for industrial and agronomic applications. For example, it is being used in poultry industry against diseases and as an odor control agent, in livestock farming as a feed supplement, and in metalworking as a reducing agent [7]. In agriculture, it mainly serves as a valuable soil amendment for improving soil functions and soil fertility when being applied properly [8]. Biochar is derived from several thermal treatments of a variety of carbonaceous or biomass feedstocks. The thermal treatments may include carbonization, torrefaction, combustion, gasification and pyrolysis [9]. However, pyrolysis is the simplest and the most efficient one and is listed in the literature as the most preferred production method [10]. In practices, biochar can be made by typical open burning or oxidative (oxygen-rich) thermal decomposition of biomass. In an oxidative process of ash production, a lot of C volatilizes as carbon dioxide (CO_2), leaving behind primarily mineral components of the mass rich in potassium (K) and other salts [11]. Biochar is highly efficient in storing C in soils and retains large surface area being capable of holding and exchanging cations in soils [11]. Therefore, biochar is typically a desirable soil amendment. It is produced from a variety of feedstock including forest residues, agricultural residues, waste, and purpose grown biomass and the suitability of each feedstock for such an application is dependent on a number of physicochemical, environmental, and economic factors [12]. Reported physical and chemical properties (pH, ash content, elemental composition and stability) of biochar vary greatly originating from different feedstock and pyrolysis conditions [13]. It is well-known that both the biochar feedstock and production conditions can have important implications on how biochar amendments affect soil properties and their effectiveness for different management purposes. With such heterogeneity in feedstock material and pyrolysis conditions, it is difficult to identify the underlying mechanisms behind reported effects; however, it may provide a possible opportunity to "engineer" biochar with properties that are best suited to a particular soil type, hydrology, climate, land use, etc. Typically, mitigating climate change, energy production [14,15], waste management, reclaiming and restoring soil, and promoting soil fertility are some important complementary roles, which biochar can act in agriculture, horticulture and environmental management [4]. Owing to the wide ranging of applications, this mini review brings attention upon production methods, properties and applications of biochar showing that it can help in partial achievement of multiple environmental purposes and a practical recommendation to growers which might be a controversial issue explained by mainly improving soil quality under sustainable agricultural practices.

2. Biochar in the global attention

Biochar receives an increasing attention from many scientists and policy makers around the world and several countries (e.g. UK, New Zealand, and U.S.A.) are establishing "research centers" for exploring new possibilities in the terms of environmental protection and management [16]. Various environmental application of biochar include adsorption (for water pollutants and air pollutants), catalysis (for syngas upgrading, biodiesel production, and air pollutant treatment), and soil conditioning [10]. Two main reasons for the great interests on biochar are (1) the discovery that biochar-type substances are the explanation for the high amounts of organic C and maintainable fertility in the Amazonian Dark Earths known as "Terra Preta de Indio" and (2) its specific chemical and physical properties in combination with its specific chemical structure provides greater resistance to microbial decay compared to other types of soil organic matter [4,17,18]. However, the fundamental aspects, prospects and challenges for environmental applications are still discussed and are a matter of controversy, considering the rapid development of biochar materials [19]. An example is that in popular media biochar is sometimes referred to as a miracle cure or sometimes is portrayed as a potential environmental controversy [16]. The attention of the media and the public given to biochar can be illustrated by a Google™ search on "biochar" which yields around 3 million hits (last search was undertaken on 02/09/2020). The increasing attention in the introduction of biochar can also be illustrated by comparing the search volumes in Google Trends™ for "biochar", "terra preta" and "black earth" over the last years. An indication for the attention on biochar from the scientific community is provided by performing a search in the scientific literature search engines (i.e. Thompson's ISI Web of Science, Google Scholar™, Scopus™) where the number of those articles indexed for either "biochar" or "bio-char" is increasing proportionally compared to previous decade.

3. Short history of biochar

Biochar is actually an ancient technology as far as 8000 years ago for improving soil fertility for agriculture dating back to South America where biochar was used by farmers in the Amazon basin to remedy some of the worst (thin, infertile, acidic) soils into "terra preta", or patches of black soil that remain fertile today [20,21]. Archaeological surveys have confirmed that correlation exists between the conditions of the "terra preta" sites and the civilizations described back in the 16th Century. In Peru, Ecuador, West Africa, and Australia, similar applications of biochar by earlier civilizations are also found. The rediscovery of these lost civilizations is very interesting to the scientific community and probably more surprisingly, so is "terra preta" itself since observations revealed that even chemical fertilizers cannot maintain crop yields into a third consecutive growing season, yet these dark earths have retained their fertility for centuries [20] (Figure 1). Crops planted on "terra preta" can produce a yield up to four times greater than those planted on soil from similar parent material. Japanese horticulture has a custom of applying wood chars to soils to improve plant growth and performance. Traditional techniques for the addition of charcoal and ash to soils were probably performed with controlled burning of crop residues and/or local vegetation. Additionally, production methods include pit or mounds that are set on fire and then covered with soil to allow for slow smoldering [20]. It would be fair to say; even wood ash is particularly useful in reducing soil acidity and adding depleted nutrients such as calcium (Ca), K, and magnesium (Mg) to soils, which are poor in terms of mineral content.

Figure 1. Soil profiles showing "Normal Soil" (left) and "Terra preta" (right) (Photo adopted from: http://www.pronatura.org/).

4. Factors impacting biochar properties

Two main factors can affect physical and chemical biochar features (e.g. chemical composition, surface chemistry, and particle and pore size distribution), which in turn, determine its suitability of a given application, and its behavior/fate in the environment:

- Biochar production methods (i.e. pyrolysis conditions, characteristics of the carbonization process)
- Source of biochar (feedstock characteristics, raw biomass material from which the biochar was produced) [12,13,22].

4.1. Production methods

Different carbonization processes to produce biochar include pyrolysis, gasification, and hydrothermal [10]. Pyrolysis can be carried out in a furnace or a kiln, where oxygen-deficient conditions can be created. A simplified schematic representation of biochar production from pyrolysis and its application is compiled in Figure 2. Commonly, biochar is produced from biomass pyrolysis ["pyrolysis" = Greek word: breaking down (lysis) of a material by heat (pyro)] under a temperature range of 248–980 ℃ (480–1800 ℉) in no or limited oxygen conditions [13,23–26]. Pyrolysis chemically and physically alters the composition of biomass, which results in a highly porous, carbon-rich organic matter that transforms current agricultural waste into a variety of useful materials [27]. The yields of the pyrolysis products depend on feedstock, and pyrolysis processes (reaction temperature, heating rate, and residence time) [12,13,28]. The characteristics of biochar include its elemental composition (C, hydrogen [H], nitrogen [N], sulfur [S], and oxygen [O_2]), and surface characteristics (surface area, pore size, surface chemistry, etc.) [29]. Depending on the heating rate and exposure duration, heating process can be fast or slow [30]. Usually, biochar has very fine particles if the heating process is fast and relatively high (> 650 ℃ or >1200 ℉) temperature in a short time [31]. In contrast, a slow process and lower temperatures (450–650°C or 850–1200 ℉) produce larger biochar particles [13]. Higher production temperatures not only result in smaller but also more porous biochar particles that have a proportionally greater surface area and higher cation exchange capacity (CEC) and pH values [28,32]. Almost half of the C from woody biomass is preserved at lower temperatures (400–500°C or 750–950 ℉) [32]. However, at higher temperatures (> 700 ℃ or 1300 ℉), most of the biomass converts to syngas for energy production with only about 10–20% of the resulting residue as biochar [33]. Biochar yield decreased with increasing residence time at the same pyrolysis temperature [34]. Specific surface area and pore area increased with increasing residence time up to 2 h at 500–900 ℃ but decreased when the residence time exceeded 2 h [35].

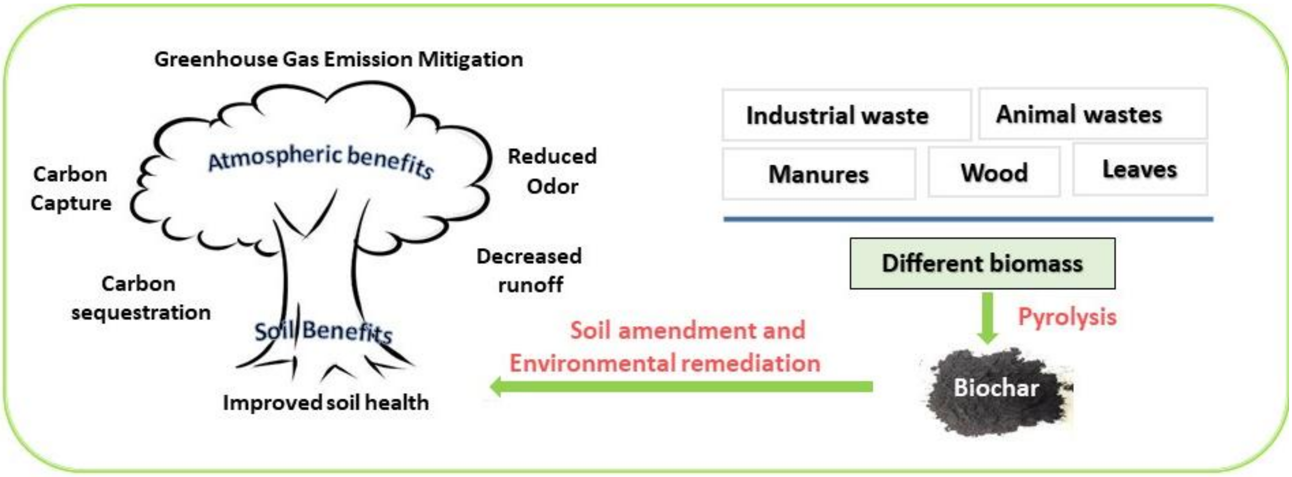

Figure 2. Simplified schematic illustration of biochar production from pyrolysis and its applications.

Gasification is a thermochemical partial oxidation process converting carbonaceous materials to gaseous products using gasification agents [10]. In a gasification process, gaseous compounds (H_2, CO, CO_2, N_2, etc.), liquid, and solid products are produced, and the yield of biochar is approximately 5–10% of the raw material biomass, which is lower than that of fast pyrolysis (15–20%) [36,37]. Another method to produce biochar is hydrothermal, and char produced from this process is often called hydrochar to be distinguished from the biochar produced from dry processes (pyrolysis and gasification). In hydrothermal process, biomass mixed with water is placed in a closed reactor and the temperature is raised after a certain time for stabilization [10]. The highest ratio of mass carbon produced per mass carbon feedstock is for hydrothermal (65–85%), in comparison with pyrolysis and gasification [9].

4.2. Source (feedstock) of biochar

The use of bio-wastes from agriculture, the food industry, and forestry are considered the main sources of feedstock for biochar production. Sources for biochar production include any type of plant or animal waste including tree cuttings, wood chips and pellets, shrubs, and grasses, agricultural residues (e.g., corn stalks, nut shells, rice hulls), manure, sewage sludge, poultry litter, excrement, and bones, etc. [13,28,38]. Biochar from food industry sources include bagasse, distiller grains, press cakes from the oil, juice, etc. [39]. Biomass can also be categorized into woody and non-woody biomass.

Woody biomass primarily comprises residues from forestry and trees and non-woody biomass consists of agricultural crops and residues, animal waste, urban and industrial solid waste [12]. Biochar produced from different materials may have different chemical properties even when the same manufacturing process is applied. For instance, biochar pH can vary from 4.6 to 9.3 depending on the initial source. It is also suggested that even within a biomass feedstock type, different composition may be the result of variable growing environmental conditions such as soil type, temperature and moisture content, as well as factors related to harvest time. Moreover, a risk associated to the use of bio-wastes (e.g. sewage sludge, municipal waste, chicken litter, etc.) for biochar production is the existence of hazardous components such as organic pollutants and heavy metals. As a fact, the total concentration of mineral nutrients of primary substance is increased during biochar production [40]. Since nutrient content can vary widely among different types of biochar, it can be considered as a nutrient source. For example, herbaceous biochars include more N than the ligneous biochars [41]. Normally, hardwood biochar has low total N, satisfactory levels of P, and high levels of K [42,43]. Biochars produced from corn and rice straw contain high level of P and K. While high level of P and Mg are typically found in the biochar produced from timber harvest residues [44–46]. Interestingly, biochar made from animal wastes has significant amounts of N [41].

5. Biochar benefits

Partially published studies on biochar benefit are listed in Table 1. A number of environmental applications of biochar include adsorption (for water pollutants and for air pollutants), catalysis (for syngas upgrading, for biodiesel production, and for air pollutant treatment) and as soil conditioner/amendment. As an amendment biochar not only isolates C in soil, but also improves the quality of the soil by neutralizing soil acidity, enhancing the CEC, and increasing the activity of soil microorganisms. The most important roles of biochar in agriculture are improving soil fertility and water-holding capacity, promoting crop yields, and enhancing pesticide degradation. Biochar benefits are listed in detail below:

- Although biochar includes some nutrients, these mineral contents are not enough to optimal growth of plants. Therefore, biochar is typically not considered as a fertilizer but a carrier for fertilizer [47].
- Increases fertilizer use efficiency and facilitate bioremediation of pesticide-polluted soils [8,48].
- Biochar utilization can promote nutrient availability in soils [49]. For example, alkaline pH helps increase nutrient (K, Ca, Mg) availability in low pH soils [8].
- Acidic soil might be modified by biochar with increasing soil pH and buffering capacity [50].
- Biochar can retain some nutrients, in some environment, preventing them to be lost to water body or air in the soil environment, which may reduce fertilizer application and protect the environment [4,29].
- Compared to soil particles, biochar have a high specific surface area. The pores of biochar hold water and nutrients and provide optimal conditions for beneficial microorganisms [51].
- Biochar can be beneficial to soil health and improves soil quality. Biochar application can potentially provide a low-cost alternative for reclamation of soils contaminated with heavy metals or organic pollutants [52,53].
- Retaining water in soil pores is another advantage of biochar. This can help plants to deal with adverse effects of water deficit [51,54].
- Biochar increases tolerance of plant against abiotic stress such as salinity and drought [54–56].

- Biochar may act in suppressing plant diseases. Fungal pathogen [57,58], bacterial infection [59] decreased after addition of biochar.
- Biochar does not denature soil enzymes and do not reduce soil enzyme activity in the long-term [60].
- The use of biochar as a soil amendment can also reduce the global warming gas emissions. Biochar production process does not create additional carbon dioxide (CO_2) gas emissions. In addition, biochar application helps lower the CO_2 concentration in agriculture, which is mainly responsible for mitigating global warming and climate change [61].

However, in some studies, the benefits of biochar are not found. Therefore, when making decision on biochar application, it is necessary to have a test firstly if conditions are allowed. An interdisciplinary research needs to be undertaken before making decision for biochar application, especially before policy is implemented. This is because biochar appears to have a wide range of implications and its irreversible effects on soil after its application. Policy should focus on the investments in fundamental scientific research in biochar application to soil. There must be a great body of scientific evidence for biochar site-specific application under a set of environmental conditions and biochar types (from different feedstock and/or pyrolysis conditions).

6. Inconsistencies and limitations in biochar application

Although many studies have indicated the positive effects of biochar on ecosystem, soil physical and chemical properties, and crop production, discrepancies about its application in fields remains. Depending on soil type, climate conditions and fertilizer management, crop responses to application of biochar might be different. Specifically, biochar amendment exhibited different impact on crop yields under tropical and temperate conditions. Owning to biochar nature, it appears to have greater benefits on coarse-textured soils than on fine-textured soils [62], which can restrict its application. Biochar application benefits more on the tropical soils, which are less fertile and acidic, via fertilization and liming effects, while its applicability is limited to temperate soils, which are more fertile and have higher pH values [63]. Biochar in long-term could inhibit native soil organic content mineralization [64,65]. As biochar can neutralize soil acidity and increase the soil quality and crop productivity through enhancing the alkaline nutrients availability for plants, greater response to biochar was mainly showed in acidic soils rather than calcareous soils [66,67]. In a meta-analysis review, no significant improvement was observed when biochar was added to alkaline soils with $pH > 7.5$ [68]. Sometimes, biochar application was reported not improving crop productions, e.g., wheat, faba bean, and rice [69–72]. Biochar caused negative effects on soil biota, which are associated with a mineralizable or labile fraction [73]. A decreased fungi/bacteria ratio in the presence of maple biochar at the rate of 5 ton ha^{-1} after 2 years was reported [74]. In agreement with this result, rice straw biochar decreased denitrifying bacteria abundance [75]. Other limitations and disadvantages of biochar include [16]:

- Removal of crop residues for biochar production as a feedstock potentially leads to the reduction of soil organic matter level in the fields.
- Health (e.g. dust exposure) and fire hazards need to be considered during production, transport, application and storage of biochar.
- During biochar application, soil compaction might be occurred.

- Biochar may include contaminants such as polycyclic aromatic hydrocarbons, heavy metals and dioxins.
- Interaction of biochar and other initial nutrients of soil is still unclear, hence, it might reduce the availability of nutrients.
- High biochar application rate affects earthworm survival negatively, and increases salt levels.
- Owning to sorption properties of biochar, efficiency of pesticides and herbicides might be reduced.

Table 1. Partially published studies on biochar benefit.

Biochar effect	References	Main findings
Slow release fertilizer	Mixed biochar with filtered liquid dairy manure [76].	Biochar promoted soil N and C storage but did not affect leaching losses of them.
Fertilizer carrier	Applied biochar with urea [47].	Biochar acted as a N “sponge”, gradually delivering N to the soil and plant.
Improve soil fertility	Used biochar (0.5% and 2% w/w) with NPK fertilizers in a moderately acidic soil [49].	Biochar increased soil pH, alleviated nutrient stress, and increased maize biomass production.
Microbial habitat	Reviewed the response of microbial communities to biochar-amended soil [77].	Biochar chemical and physical properties played significant roles in determining its effect on soil microbial community.
Water retention	Studied how and why biochar increase soil water retention capacity [78].	Biochar chemistry and pore morphology affected biochar-water interactions.
Alleviate abiotic stress	Investigated the interaction effects of abiotic stress on soybean productivity and water use efficiency under biochar addition [79].	Biochar addition alleviated the negative effects of abiotic stress on soybean productivity and water use efficiency.
Mitigate GHG fluxes	Conducted a laboratory incubation study to determine the effects of biochar on GHGs [80].	Biochar appeared to be an effective strategy to reduce GHG emissions, particularly in neutral to acidic soils with high N content.
Enhance plant nutrient uptake and pesticide degradation	Reviewed the potential benefits of biochar in agricultural soils [48].	Overall, the amendment of soil with biochar appears to enhance fertilizer use efficiency, soil fertility, and pesticide degradation and shows potential to improve soil health and crop yields, thus improving the sustainability of agriculture.

Notes: N: nitrogen; P: phosphorus; K: potassium; GHG: greenhouse gas.

7. Right rate, placement and size of biochar

Similar to 4R nutrient stewardship guidelines (right fertilizer source, right application time, right application rate, and right placement to crops) for fertilizer application in order to manage soil nutrients for achieving maximal crop productivity and minimal environmental impacts, a 4R stewardship guidelines (right source, right rate, right placement, and right cost) for applying biochar can be introduced. Up to now, however, there are no guidelines developed for farmers to apply biochar for its optimal agricultural and environmental benefits [81]. Below are briefly discussed some considerations with regard to the amount, way of application, source and cost of biochar application.

7.1. Application rate

There is a common myth among farmers and the public that "biochar is a miracle soil cure" and "once applied to soil, its effect will last forever". On the other hand, scientific results have constantly challenged these expectations discouraging users and affecting the broad adoption of biochar as a soil amendment. No one can exactly make a suggestion on biochar application rate, as there are reportedly contradictory results for biochar use. Some studies have used very high rates with success, while other studies reported a reduced plant growth by high application rates of biochar. Generally, the rates of biochar range from 0.5 ton acre^{-1} (1.1 ton ha^{-1}) to 150 tons acre^{-1} (330 ton ha^{-1}) in different parts of the world [82–84]. In fact, different plants show diverse responses to different biochar types and application rates. In many cases, the producers are recommended to use biochar at 20 tons acre^{-1} (40 ton ha^{-1} approximately). Additionally, since biochar is composed of very resistant C that can persist in the soil for a long time, repeated applications of biochar are not suggested. Other studies indicate that based on the kind of the biomass biochar produced the appropriate application rates (one time or cumulatively) are recommended at 2–5 mass % soil (1% is equivalent to 20 Mg ha^{-1}) for wood/crop residue biochar and at 1–3 mass % soil for manure-based biochar to achieve evident, long-term soil health improvement [22].

7.2. Application method

Biochar should be immediately and thoroughly mixed after application into the root zone with the top 15–20 cm (6–8 inches) of soil. To get maximum amending effects, biochar should not be spread on the soil because of small and light particles [16]. Subsurface application of biochar can be performed by tillage following broadcasting, band drilling, trenching, and localized holing. To prevent releasing biochar dust into the air and becoming airborne problem, avoid the application in windy-dry weather and do not plowing or rototilling dry soil with biochar. Thus, it should be tilled or disked into the soil [85]. Moreover, enough water content in soil is suitable to improve operation of biochar mixing with soil. Finally a combination of chemical fertilization and biochar is necessary to obtain maximum synergic beneficial effects for better crop growth.

7.3. Size of biochar

Biochar particle size is affected mainly by the source of feedstock and production conditions [86]. Wood-based feedstock generates coarser-textured biochar, whereas biochar from crop residues and manures are finer [3]. There are no strong references for biochar size and its effect on soil and plants.

Biochar is typically a rough mixture of carbon-rich particles/chunks ranging from dust size (less than 1 millimeter or 0.04 inches) to several centimeters [87]. It has been proven that small biochar particles fill with water faster, retain nutrients, and absorb pesticides better than larger size particles. Under normal field conditions, water, nutrients and other chemicals will not enter deep into large biochar particles. As a fact, smaller biochar particles have greater specific surface area per unit of mass. Bulk density, available water content, and water repellency decreased, and total porosity increased with an increase in biochar size from 500 to 2000 μm [88]. Large biochar particles (< 2 mm) with clay soil promote aggregation and macroporosity, and thereby increase saturated flow through the soil [89].

7.4. Cost of biochar

Biochar amendment could provide further worth by reducing costs of crop production and simultaneously providing significant environmental benefits. The efficiency of biochar is likely to be crop dependent as well as is dependent on biochar, soil and climate characteristics. Biochar may also increase financial profits of farmers by decreasing P and K fertilizer uses, limiting irrigation requirements, and reducing nutrient losses. Applications of biochar can provide beneficial effects over several growing seasons, which is varied in different crop. On the other hand, biochar application at large scale and high rates could be hardly profitable in conventional farming because of current price. It was reported that its cost reaches approximately US$ 250 t^{-1} (in April 2015) whereas, more recently its lowest price has been still unaffordable high (e.g., US$ 100 t^{-1} as the lowest price in 2018) [90]. In this regards, biochar availability and economic costs were the greatest barriers to the use of biochar, therefore, determination of optimum application rate of biochar is critical [91]. It should be noted that some beneficial effects with biochar application may be shown only in a long term, thus, it is wisdom to evaluate the expenses before its utilization. Therefore, it seems that biochar is more suitable for the high-value crops or in the regions where soil need to be reclaimed.

8. Conclusions and practical recommendations to farmers

Experimental evidence suggests that biochar application alters soil properties in a variable way (i.e., by modifying soil chemical, biological, and physical properties).

- Biochar ameliorates soil acidity with increasing soil pH and buffering capacity. When biochar is used as a soil amendment in acidic soils, it is important to know and account for the pH and salinity characteristics of the biochar applied.
- Biochar produced from forestry waste often have higher carbon content than from agricultural biomass and animal wastes. Moreover, the nitrogen content of biochar produced by algae is often higher than that produced from forestry biomass.
- Not only biochar itself contains nutrients, but also indirectly alters the soil nutrient content and availability.
- Biochar can increase water infiltration and hydraulic conductivity in fine-textured soils. In contrast, hydraulic conductivity is increased by biochar in coarse-textured soils.
- Surface broadcast application of biochar may increase erosion of particles both by wind (dust) and water. Use a disc to mix biochar into 10–20 cm of subsurface soil.
- For growers, the rate of biochar should be decided based on soil property, biochar property, crop type, and expenses, etc.

- A long-term evaluation should be conducted for understanding if a biochar, which is not effective in a short-term, can become effective with time.

Conflict of interest

The authors declare there is no conflict of interest.

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