International Research Journal of Pure & Applied Chemistry

21(15): 74-88, 2020; Article no.IRJPAC.61164
ISSN: 2231-3443, NLM ID: 101647669

Beneficial Effects of Biochar on Agriculture and Environments

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Authors' contributions

This work was carried out in collaboration among all authors. Author GY wrote the first draft of the manuscript. Authors RA and TI helped to correct and develop the manuscript. Authors SS and RSP managed the literature searches. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/IRJPAC/2020/v21i1530253
Editor(s):
(1) Dr. Wolfgang Linert, Vienna University of Technology, Austria.
Reviewers:
(1) Alexandre Ricardo Pereira Schuler, Federal de Pernambuco, Brasil.
(2) Mohd Hanif Bin Mohd Pisal, Universiti Malaysia Perlis (UniMAP), Malaysia.
Complete Peer review History: http://www.sdiarticle4.com/review-history/61164

Review Article

Received 04 July 2020
Accepted 10 September 2020
Published 22 September 2020

ABSTRACT

Crop residue management becomes the challenging issue to farmers for balancing between the economic and sustainable environment. Though burning is the easiest way of destroying the crop waste it not only causes drastic changes in green house gas but also large amount of nutrients are removed from soil by plants. Hence the technique which protects the environment along with enhancing soil quality is needed. Therefore pyrolysis of crop residue can become an alternate technique against past strategies. The heterogeneous characteristics of the biochar can be produced through the pyrolysis process and that would be employed as a soil amendment. The biochar application ameliorates the problems which persist in soil and enhance the crop production in environmentally sound way. And largely involved in the carbon sequestration thereby sustain the

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soil quality. However there is lack of information available on effects of long term application of biochar and durability of persistence in soil. Thus in those things made to review on brief account of biochar such as, biochar production, characteristics, impacts on soil properties, crop growth, reduction of green house gases and heavy metal remediation. Moreover, in this review discusses about what are all the challenges and future trust in the application of biochar. So, the deep understanding on biochar and its interaction with soil can bridge the gap prevailed in the scientific field and crop improvement.

Keywords: Biochar; crop residue; soil properties, crop production, carbon sequestration; environmental remediation.

1. INTRODUCTION

Biochar is kind of stable black carbon which can be acquired from pyrolysis of carbonaceous material under anaerobic condition. Now a day's it has been gaining greater attention worldwide due to their specific properties and versatile activities on agriculture and environment. Several definitions on biochar had been reported by several researchers. Of these, most standardized and accepted definition stated by the International Biochar Initiative (IBI) is "a solid material obtained from the thermochemical conversion of biomass in an oxygen-limited environment" [1]. Numerous researches are available about production and application of biochar. Eventually, researchers were tried to establish that pyrolysis was effective and energetic technique in bio-energy production [2]. The biochar production becomes an alternative strategy for utilization of agriculture waste into agriculture input. [3] reported that production of large quantities residues in agro-forestry could employed as an abundant source of biochar preparation and become solution to waste management [4]. Biochar application improves soil quality by enhancing water holding capacity, soil fertility and Nitrogen use efficiency of fertilizer [5] and employed for heavy metal remediation in polluted areas [6]. Added, [7] observed that biochar have potential to mitigation of climate change by locking and resist reemitting the carbon from soils. Growth of anthropogenic activities and industrialization leave contaminants viz., heavy metals, hormones, metalloids, pharmaceuticals, plasticizers, pesticides, personal care products and food additives into the environment that possess threats to environment and living things [8,9]. On this case, biochar is found to be a remediate for organic compounds and heavy-metal pollution [6,10]. Over a period of research explore more about the benefits of biochar application and act as an efficient tool to remove and reduce bioavailability of organic contaminants [11]. The researchers were documented well about remediation of heavy metals and metalloids contamination by biochar [6,12,13,14,15].

The increasing knowingness on biochar as well as advanced pyrolysis technology deliberately controls the biochar production which permits to create a biochar with specific properties [16]. While the poor or inadequate knowledge about biochar productions are facilitated to create an improper expression of result inference; eg. Increasing temperature results in greater surface area, lower yield, higher fixed carbon and lower oxygen content [17]. But higher pyrolysis temperatures result in lower CEC, lower ash contents, higher pH, EC, higher $CaCO_3$ equivalence and finally increase aromatic structure of biochar that will allow resistance to microbial decomposition and thereby enhance the carbon sequestration [7,18,19]. The main reason for obtaining inconsistent results in field experiment with biochar application are utilization of wide range of raw materials and different factors which can be manipulated in pyrolysis process. However, the ability to create a desirable properties in biochar, either by manipulating feedstock or pyrolysis, extends significant opportunity for applying biochar as a soil ameliorant and crop enhancer. Thus, a nutrient deficient or problematic soil can be matched with a biochar that is produced by a specific raw material and certain terms of pyrolysis help to amend that specific problem of soil [19]. The significance of biochar on agriculture and environment is given in Fig. 1. So far more characterization studies, field and green house trials, have been established to elucidate the impact of biochars and its specific properties on soils and crop growth. Hence this exploration endorse to understand well about potential risks of large-scale biochar application in agriculture and environmental remediation [20,21]. Therefore, to summarization about the development, production or application of biochar is highly important and predict its environmental behaviour in the future.

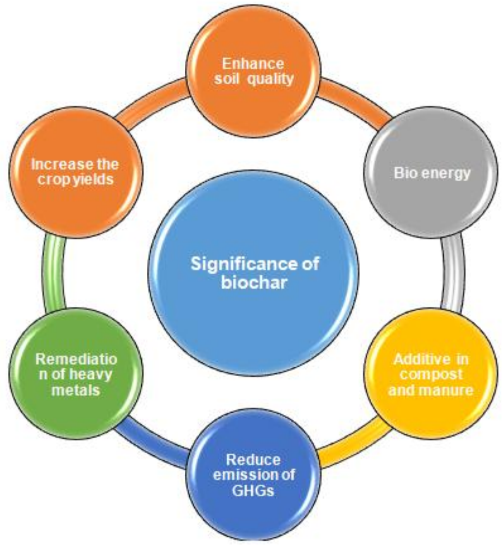

Fig. 1. Significance of biochar on agriculture and environments

2. BIOCHAR PRODUCTION

Biochar exhibits heterogeneous properties because of different raw material such as stalk, grain hulls, hard woods, manure and sludge that can be subjected to pyrolysis [22]. The biochar produced from agriculture waste is shown in Table 1. The process of pyrolysis in production of biochar can aid to remove the odour and wetness of the feedstock [23] and determines the properties of the biochar. Thus to obtain appropriate method in production of efficient biochar, different pyrolysis methods are practiced that including slow pyrolysis, intermediate pyrolysis, fast pyrolysis, hydropyrolysis, flash pyrolysis, microwave -assisted pyrolysis and vacuum pyrolysis [17,24]. While biochar productions through pyrolysis, bio-syngas and bio-oil are produced as by-products [24]. Moreover, different methods are available as pyrolysis to produce biochar includes gasification, flash carbonization, and hydrothermal carbonization [25]. The combine action of different raw material and different pyrolysis process produce profuse quantities of biochar with varied physicochemical properties. After the production of biochar, their properties need to be documented. Added, it is important to documentation of changes occurrence in biochar while storing [18].

2.1 Importance of Characterization

Biochar is formed from the carbonaceous material and characterisation is most important for acquiring good results in research. Xray diffraction (XRD), scanning electron microcopy (SEM), nitrogen adsorption isotherms, Fourier transform infrared spectrometry (FTIR), transmission electron microscopy (TEM), X-ray photoelectron spectroscopy (XPS), X-ray spectroscopy (EDS), scanning transmission electron microscopy (STEM) and nuclear magnetic resonance (NMR) are commonly used techniques for recognizing its morphology and complex chemical composition. Understanding well about biochar characteristics help to exploring new technologies for creating changes in agriculture. However, the versatile nature of biochar makes difficulties while verification and repeatability trail. Biochar properties can be influenced by the nature of raw material, pyrolysis process and the different variables within the process [19]. And the factors include pressure, heating temperature, heating speed, heating duration and post pyrolysis of the biochar etc., [17,19]. Thus manipulation of these factors can tend to produce biochar with specific characteristics such as surface area, adsorption capacity, pH, nutrient concentration, carbon percentage, chemical composition, physical characters and cation exchange capacity [26]. Pore numbers and size are considered the physical characteristics of the biochar [27]. The pyrolysis temperature increases with increased porosity of biochar. The biochar produced from wood materials at 300°C have 50% porosity where as pyrolysis at 850°C has 50% porosity in atmospheric pressure [28]. Similarly [29] recorded that the pore volume of wheat biochar at 400°C is 0.016 (cm^3g^{-1}) but pyrolysis at 600°C of the same wheat feedstock shows 0.034 (cm^3g^{-1}).Moreover the heating temperature of raw material influence the surface area of the biochar. For example pyrolysis of rice husk @ 350°C and 650°C having the surface area 32.7 (m^2g^{-1}) and 261.72 (m^2g^{-1}) respectively [30]. Another researcher mentioned that the surface area of wood biochar increased from 1(m^2g^{-1}) to 317 (m^2g^{-1}) by increasing the temperature from 350°C to 800°C [31].

2.2 Impacts of Biochar on Soil Properties

Biochar improvise the soil physical condition, such as texture, structure, bulk density, porosity and distribution of particle size [46]. A study conducted on effect of application of 40 t/ha of biochar to rice resulted in reduction of bulk density of soil from 0.1g cm^{-3} to 0.06 g cm^{-3} [37]. Exceeding of 1.7 g/cm^3 of soil bulk density reduce the soil aeration as well as hinder the plant root growth. But biochar amends these

Table 1. Biochar produced from agricultural sources

Source (feed stock)	Parts of the plant	Pyrolysis (°C)	Reference
Rice	Husk	550	[32]
		700	[33]
Wheat	Straw	550	
		350	[34]
		450	
		550	
		650	
Soybean	Stover	300	[35]
		700	
	Stalk	300	[36]
		700	
Cotton	Seed hulls	800	
		300	
Corn	Cob	400	[37]
		500	
	Stover	350	[36]
		600	
Peanut	Shell	300	[35]
		700	
Switch grass	Grass	500	[38]
		450	[39]
		800	
Rubber	Wood	300	[40]
		700	
Rapeseed	Seed	550	[41]
		500	
		450	
		400	
Rice	Husk	350	[42]
		450	
		550	
		650	
Kenaf	Stem	Gradual enhancement of room temperature to 400, 500 and 600	[43]
Cyprus	Cyprus saw dust impregnated with olive mill waste	Slow pyrolysis (500)	[44]
Acacia holosericea	Wood	Intermediate pyrolysis (500)	[45]

compaction by >10%. The porosity of biochar is estimated about 70-90% [47] and this biochar amendment enhances the soil porosity by 8.4% [48]. The increase in soil porosity and decreases in soil bulk density results in enhance the heat, water and gaseous movement in the soil [49,50] reported that biochar amendment in sandy soil, retain the water in the pores which present on the biochar thereby reduce the permeability of water and enhance the water retention capacity. Added, the effects of biochar on soil physical properties had comprehensively explained by [47]. They concluded that biochar amendment reduces 3-31% of soil bulk density, increases 14 -64% of porosity, 3-226% of wet aggregate stability, 4 - 130% of available water, reducing saturated hydraulic conductivity in coarse texture soil where as it is increased in fine textured soil and show moderate response to soil thermal properties. However, numerous factor that can able to influence the biochar impacts on physical properties of soil (Fig. 2).

Moreover application of biochar in soil affect their chemical properties by two ways i) supplying nutrients to soil ii) retaining the nutrients in pores or surface of the biochar. The chemical properties of soil are affected positively like an increase in pH, CEC and carbon content [51] and decrease the fertilizer leaching by release of nutrients slowly into soil which it retain [52]. The release of basic cation from biochar is the reason for increasing pH. Biochar is referred as organic fertilizer which contains C, N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu and Si. [53] explained about relationship between the large surface area and porous nature of biochar and increased nutrients and water retention. The biochar which is pyrolysed at higher temperature is highly suitable for amending K deficient soil [54]. Biochar application reduces inorganic N immobilization and volatilization of ammonia [23]. Biochar amendment enhances the nitrogen retention and use efficiency of nitrogen fertilization which will enhance the plant growth [55,56] reported that slow release of ammonia into soil would be noticed after the absorption of ammonia fertilizer. However, applying the biochar alone or biochar without fertilizer reduce the availability of nitrogen by sorption of nutrients. The biochar application express positive, neutral and sometimes negative impact on soil chemical properties. Thus prior amendment of biochar needs to understand the significant role of biochar on soil properties.

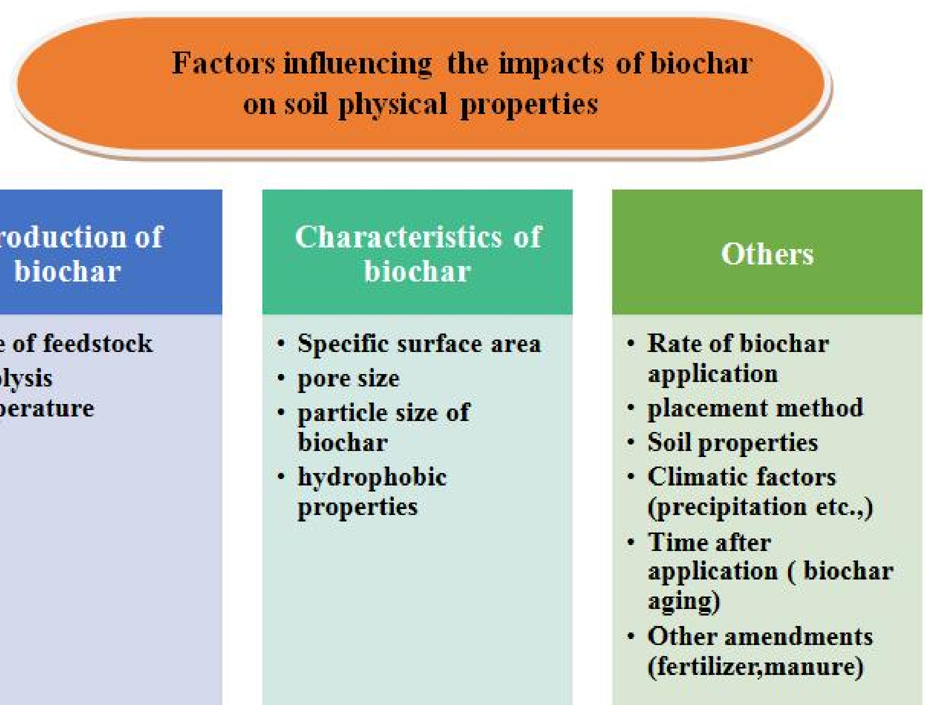

Fig. 2. Factors influencing the impacts of biochar on soil physical properties. Modified from [47]

However, only paucity of information available on how can biochar will creates changes in soil ecosystem and soil properties in long-term field experiment [23]. Thus this emerging field needs more investigation about the impact on soil microbiome, biogeochemical cycles and mechanism of long term application of biochar [22]. Biochar is recalcitrant material which resist to prone microbial decomposition [57]. However, the higher porosity of biochar provides additional niches to microbes [53]. The biochar adsorbs organic carbon and nutrients which are considered as a food source of microorganism and provide the habitat to microbiome [58]. The kind of biochar and soil type, application of biochar may reduces the changes within the structure and function of microbial community [59], have no effect on increase of microbial diversity and species richness [46,60]. Biochar increases bacterial abundance with decrease fungi abundance [61] and increases arbuscular mycorrhizal and ectomycorrhizal fungi colonization at plant root [62,63] found that addition of 10 t ha^{-1} of biochar with dairy manure increase the labile carbon pool, enzyme activities and total as well as bacterial phospho lipid fatty acid in eroded soil. Additionally, soil enzyme activity can also be affected by biochar through hamper and enhance the contact with SOM [64]. The biochar produced under different temperature at 200°C, 350°C and 500°C respectively and are applied into the calcareous soil at the rate of 1-2% w/w for 90 days incubation. The biochar amendment increase the organic carbon, microbial biomass carbon at 1.20 to 2.24 folds, microbial respiration at 1.21 to 2.23 folds, dehydrogenase activity at 1.47 to 2.30 folds and catalase activity at 1.80 to 2.93 folds. But the pyrolysis temperature and rate of application influence the biological properties of soil [65]. The different kinds of biochar have varied physical and chemical properties that conjunction with different soil ecosystem causes the varying level of microbial responses to amend of biochar in soils. [66] reported that combine application of biochar and manure enhancing the ammonia oxidizing bacterial community than other treatments and stated that altering the soil properties by amending the biochar enhance the microbial abundance in soil.

2.3 Biochar and Crop Production

Application of biochar in soil will become the affordable solution to farmers for amending the low nutrient deficiency soil, acidity, sodicity, salinity and some of physical constraints. Improvising the physical, chemical and biological properties of the soil through biochar application enhance the crop production which is graphically represented in Fig. 3.

Even though biochar have some negative effect, it can improvise the soil quality and crop production. The biochar produced from wood is applied at the rate of 0-16 t ha^{-1} increases the hydraulic conductivity of the soil and the yield even under low phosphorus deficient condition. Combined action of 4-8 t ha^{-1} of biochar with N fertilization can increase the yield under low N response condition [67]. In addition three years successive application of biochar to cotton plant at different level viz., 5 t ha^{-1}, 10 t ha^{-1}, 20 t ha^{-1} increases the lint yield (8.0–15.8% by 2013, 9.3–13.9% by 2014, and 9.2–21.9% by 2015) than the control [68]. Another researcher reported that application of biochar to wheat increases yield at 27 % than the non amended field in saline soil [69]. This biochar application not only increases yield in saline soil but also in acid soil it increases yield. The effect of biochar application for lettuce-cabbage-lettuce cropping sequence in acid soil reduces this toxicity effect of acidity and increases the plant biomass around 363 % [70] because of the Alkaline pH, high pyrolysis temperature and higher buffering capacity of the biochar tend to neutralize the acidity at partially or fully by precipitating the free Al^{3+} ions with carbonate, silicate and oxides which are present in the biochar [71]. One of the meta analysis reported that the biochar amendment doesn't show any significant effect on high CEC soil but it will highly helpful to improve low pH soil [72]. In the pot culture experiment, biochar-urea composite and urea fertilization alone applied and effect of these on leaching of nutrients and plant growth was observed. The result found that the leaching of NH_3-N was very low; the efficient nutrient retention on biochar enhanced the plant shoot growth at 14 % and root growth by 25% than the urea fertilizer alone [73].

2.4 Biochar and Greenhouse Gas Emissions

The biochar has been considered as one of the way to mitigate green house gas (GHG) emission from soil (Fig. 4). Occurrence of changes in the function and structure of soil micro biome by biochar application which is affected the C and N cycling, soil respiration and nitrous oxide flux. It tends to decrease the emissions of nitrous oxide [74] carbon dioxide [75] and methane [76]. Biochar induce to increase the abundance of microorganism which involved in nitrate reduction and biological N fixations in soil that can alter the N cycle [59]. Besides, microbial changes are considered as short term because biochar has small quantities of labile carbon [46]. One pot culture experiment was conducted to study the impact of biochar amendment on methane, nitrous oxide, nitrous oxide emission factor and crop yield. The result found that it reduces the emission of nitrous oxide and nitrous oxide –N factor and enhance the yield but it didn't show any influence on methane emission [77]. The effect of biochar with or without nitrogen application on net greenhouse gas intensity and balance under bio energy cropping system was evaluated and resulted that 72-80% of methane emission was reduced under biochar amended field [74]. Biochar has capability to change the soil C mineralization [78] and influence the C stabilized in soils [61]. Plants which absorb and fix the atmospheric carbon into their parts through photosynthesis employed as a feedstock to produce the biochar. The carbon presents in the plants still remain in the biochar but as an inert material. Hence it become one of the way to reduce the atmospheric carbon level [79]. It is supported by [80] and they stated that sequestration of atmospheric carbon in truck of oil palm is estimated around 2.57 tons of carbon per hectare at the age of 4 years , 22.33 t of C ha^{-1} in eighth year and 59.79 t of C ha^{-1} in fifteenth year. Thus utilization of high potential carbon sequesters plant in biochar production helps to sequestrate the carbon over a prolonged period of time and thereby reduces the climate fluctuations. Here some of the researchers listed out the percentage of carbon that persist in the biochar such as wheat straw (57.80% to 73.90%), corn straw (53.6 %) [81], 24.5% [82], peanut shell (58.40 % to 74.40 %), switch grass (60.5%) [38], waterweed (25.6 %) [83], corn cob (75 to 82%) [84], safflower seed (68.73% to 73.72%) [85] and Rape seed (57.95 - 67.29%) [41]. Thus application of these charred carbon into soil that can stabilize the carbon over a period of time because Soil is one of the largest sink for carbon. Soil carbon pool alone contributes 2500 GT of carbon to that of total carbon. Among the 2500 GT of carbon, 1500 GT of carbon belongs to organic form and remaining is in inorganic carbon 950 GT. additionally, 10–60 mg of C 10^{-4} m^{-2} of carbon can be sequestered in soil. The direct incorporation of crop residue which having low C:N ratio encourage the mineralization process very fastly through microbial community and results to enhance the carbon emission. Thus incorporation of crop residue based biochar that resist to microbial degradation enhances the carbon sequestration in soil. [86] reported that incorporation of wheat straw based biochar to maize for 5 months, increase 4.9 to 6.3 g kg^{-1} soil organic carbon in soil. Two years application of biochar in rice field enhances 12.6 to 12.8 g kg^{-1} of soil organic carbon [37]. Similarly several authors reported about enhanced carbon status by biochar amendments, i.e., 12.8 to 13.4 g kg^{-1} [87], 43 g kg^{-1} [88], 64% than control [5] and 76.29 % [89].

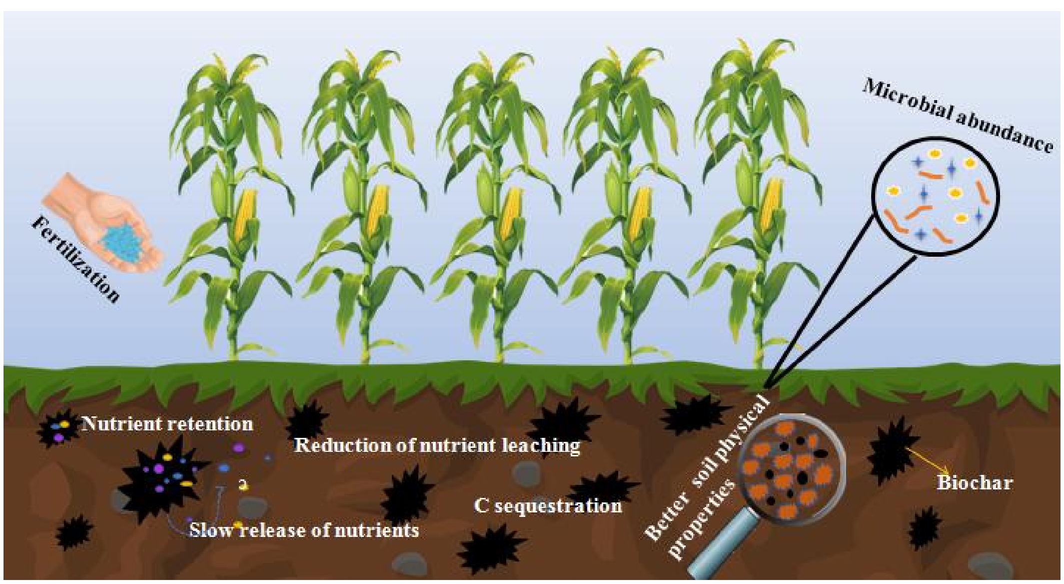

Fig. 3. Influence of soil properties by biochar application for enhancing crop production

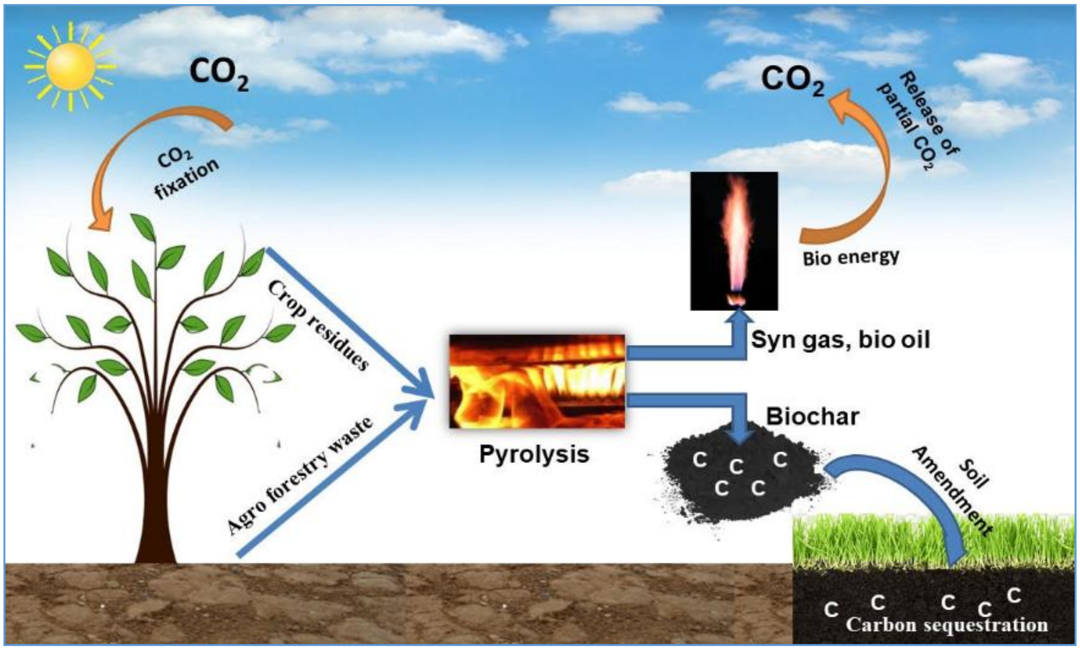

Fig. 4. Impacts of biochar amendment in soil carbon sequestration

2.5 Biochar and Environmental Remediation

Biochar are widely used in removal of organic pollutants in soil and the versatile properties of biochar like, microporosity, surface functional groups and high surface area make it an idealistic environmental remediation technique for organic and inorganic pollutants removal in both soil and water contaminated areas [90]. The organic and inorganic pollutants in the environment affect ability of microbes to break and decompose the pollutants that will enhance the longevity of these pollutants in the environmental ecosystem [91]. But unlike organic pollutants, biochar doesn't affect or inhibit the microbial decomposition of pollutants [92]. The biochar produced from different crop residues are utilized in removal of organic pollutants i.e., methyl blue could be removed at rate of 354 mg g^{-1} by sugarcane bagasse biochar [93], 31.25 mg g^{-1} by fruit bunch biochar [94], 2.36 mg/g by wheat straw biochar. Similarly methyl orange (3.24 mg g^{-1}) [95], phosphate (6 mg g^{-1}) [96] and nitrate (0.02 mg g^{-1}) are removed [97]. The graphic and semi quinone structure of the biochar to accept and donate e^- as well as free radicals are produced during the degrade and redox process of organic pollutant by biochar. Further the produced free radical degrade the organic pollutants [20]. Besides, organic pollutants removal through biochar highly depends on feedstock, residence time, heat treatment, reactor type and organic contaminants [98]. In addition these factors could be used for modifying specific properties of biochar. Thus while selecting the raw material and production of biochar, appropriate care should be needed for obtaining higher efficacy in organic pollutant removal. Not only the benefits of biochar on agriculture and environment are reported by several scientists, but also impacts of long term application of biochar in soil are identified [99,100,101]. Similarly biochar is utilized as a remediate agent to remove inorganic pollutants in contaminated environments. The biochar synthesised from water hyacinth employed as an absorbent for chromium ions which are present in the aqueous environment [102]. These inorganic pollutants can be adsorbed chemically or entrapped physically on biochar [103] but the effective removal is highly depends on surface functional group of the biochar. Moreover cation exchange, complexation, chelation, precipitation and cation bonding determine the efficient of the biochar [104,105]. In addition, alkalinity of biochar increases the soil pH and thereby stabilizes metals except arsenic [90]. In some metals, this alkalinity causes precipitation out of solution [103] and that can lower the metals bio availability to plants [106]. The biochar produced from rice straw could remove Al^{3+} at 450 µmol g^{-1} [107], Cd^{2+} at 6.34 mg g^{-1}, and As^{3+}

at 10.07 mg g^{-1} [108]. Similarly wood based biochar could remove Cu^{2+} by 15.5 mg g^{-1}, Pb^{2+} by 17.8 mg g^{-1}, Zn^{2+} by 1.5 mg g^{-1} and Ni^{2+} by 0.8 mg g^{-1} [109]. Although biochar can be utilized as a remediation tool, but still clarification are needed about longevity of metal immobilization and saturation point of biochar [92]. Owing to production of different biochar at varied temperatures shows difference responses to metals. For example, and an animal-derived biochar produced even under high pyrolysis temperature tends to be more effective [110]. To do efficient remediation in contaminated areas, feedstock and factors involved in the pyrolysis are in need of optimization. The economic feasibility of biochar application in large-scale [110] and successive rate of experimental trails [106] are needed to obtain better remediation. Finally, the combined action of biochar and phytoremediation needs to further exploration [111].

2.6 Potential Drawbacks of Biochar

Despite the biochar capability to amend soil problems, it also has some demerits.

i) While selecting the feedstock it needs greater attention because feedstock with low moisture content can create an issue. Added, to dry out the higher moisture content feedstock requires more time and cost of production
ii) Another important factor needs to be considered is initial characteristic is of feedstock which means the elemental concentration of feedstock is often magnitude the final product. If produced biochar has high ratio of oxygen-to-carbon ratio that will lower the aromatic structure and facilitate to ease degradation in soil. But these kinds of biochar are lower potential to sequestrate carbon compared to other recalcitrant biochar because of varied properties.
iii) Even sometimes the results may not show the significant effect to increases the crop yields by increase nutrient availability [18].
iv) The hazardous by products such as polycyclic aromatic hydrocarbons have possibility to be produced during the pyrolysis process [51].
v) Moreover very stable nature of the biochar cannot be easily removed from soil ecosystem [112].

3. FUTURE RESEARCH

Even though numerous researches have been established on biochar but still technical gaps are there that needs to be addressed.

Table 2. Technical gaps of biochar

Effects	i) Detailed and well establishment on persistence of biochar in soil is still unclear ii) Mostly short term application of biochar only reported by several scientists. Thus Assessment of long term effects of biochar application is needed. iii) Biochar are employed as one the way to reduce the green house gas formed from agricultural management practices. But still more improvement is needed towards on enhancement of efficiency in reduction of green house gases.
Removal of biochar	Some of the researchers are found that cannot remove biochar easily from soil. Thus find out the novel technique for removing the biochar is essential.
Mechanism	i) The comprehensive mechanism behind in the interaction between the biochar and soil physical, chemical and biological properties needed to explore more. ii) Mainly finding the interaction of biochar with soil micro and macro fauna and flora is still has gap to explore. iii) Interaction between several nutrients like absortion, desorption, retention, complexation and releasing pattern needs to be explored more.
Production with desired multiple properties	Now a days biochars are produced with specific properties needed to overcome a specific problem. Therefore production of biochar with several desired properties are needed to reclaim the multiple problem prevailed in the environment.

4. CONCLUSION

In this review, we concluded that the application of biochar not only enhance the soil properties but also reduce the green house gas emission as well as increase the crop production. In addition, it becomes more promising environmentally sound technology for managing agriculture crop residues over the crop burning. Addition of biochar along with the manure and fertilizer management ensures the crop production and soil quality. However still short term effects of biochar studies only carried out and yet to need to explore the long term effect of biochar amendment in soil, to develop the technology related to production of biochar with desired properties and to find out the depth in biogeo-cycle of biochar. The aforementioned future trust areas will brought out the biochar to feasible and large scale application level.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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