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Dr. Smita Agrawal
Department of Horticulture, Rajmata Vijayaraje Scindia Krishi Vishwavidyalaya, Race Course Road, near Mela Grounds, Gwalior, Madhya Pradesh, India

Syed Shaheem Muzafer
Department of Social Science, Indira Gandhi National Open University, Maidan Garhi, and IGNOU Road, New Delhi, India

Corresponding Author:
Dr. Smita Agrawal
Department of Horticulture, Rajmata Vijayaraje Scindia Krishi Vishwavidyalaya, Race Course Road, near Mela Grounds, Gwalior, Madhya Pradesh, India

Greening carbon production: Biochar as an eco-friendly alternative for sustainable environmental solutions

Dr. Smita Agrawal and Syed Shaheem Muzafer

Abstract

Addressing the potential ecological disaster resulting from existing environmental damage and global warming requires exploring alternatives to traditional carbon manufacturing methods involving coal and petrochemicals. A promising solution lies in the conversion of renewable resources, specifically biomass. To minimize energy consumption and pollutant emissions, there is a need for efficient processes that derive carbon from renewable sources. Biochar, a carbon-rich substance derived from various organic waste feedstocks like municipal sewage sludge and agricultural waste, emerges as a noteworthy option. Its unique qualities, such as high carbon content, cation exchange capacity, specific surface area, and stable structure, make biochar a subject of increasing interest. Its low thermal conductivity, high porosity, renewability, stability, and bulk density further contribute to its suitability in various applications. Notably, biochar not only enhances seed quality and efficiency but also indirectly increases organic carbon levels in the soil, garnering widespread acceptance as a sustainable carbon material. This review comprehensively explores the synthesis, characterization, modification, and diverse applications of biochar.

Keywords: Biochar, environmental pollution, carbon particle, renewable resource, priming

Introduction

One of the greatest concerns facing the world in the twenty-first century is climate change, which is a result of different anthropogenic activities [1]. Due to the widespread use of synthetic fertilizers, particularly in developing nations, to increase crop yields, agriculture accounts for a significant portion of the emissions of non-CO_2 greenhouse gases (NO_2 and CH_4). Agricultural land use changes with high intensities have the potential to worsen soil acidification [2] and the destruction of soil organic carbon (SOC), among other environmental issues. It is vital that sustainable management techniques be created in order to lower greenhouse gas emissions, enhance soil quality, and increase agricultural output [3] In this context, the use of bio char (BC) as a cost-effective strategy to reduce the negative effects of climate change and to protect the integrity of the soil has received a lot of attention [4]. This is due to the spike in interest in climate-smart agriculture.

In the past ten years, interest in biochar, the carbonaceous byproduct of pyrolyzing organic materials in low oxygen environments, has grown. Biochar is used to increase soil carbon (C) sequestration, remediate soil, reduce greenhouse gas emissions, and enhance crop yields and soil fertility [5] BC is produced by pyrolyzing a variety of biomass materials, such as plants, agricultural wastes, rice husks, animal manure, bones, straw remnants, woody material, and grasses, at high temperatures and pressures (between 300 and 700 °C) and in the absence of oxygen [6]. Biochar typically consists of nutrient-rich ash, moisture, unstable matter, and stable matter. About 50% of the carbon in pyrolyzed feedstock BC's original biomass is accumulated [7] Biochar was first recommended as a soil amendment to retain carbon in the soil, hence enhancing carbon sequestration, because the carbon component in it is relatively stable [8]. Biochar, however, has benefits beyond carbon sequestration. It can be applied as a soil amendment to enhance the physical, chemical, and biological characteristics of the soil, boosting its health and productivity [9]. Through so-called "priming effects" (PEs), BC amendment alters native SOM mineralization, which eventually affects the rate of SOC mineralization. PEs can have a beneficial effect (such as speeding up the breakdown of soil organic matter, or SOM), a negative effect (such as slowing down SOM decomposition), or no effect at all.

Additionally, with time, the impact of BC-induced PEs on SOC mineralization may change. For instance, a prior study noted that enhanced C mineralization (15%) after BC amendment as evidence of a positive PE over a relatively short period of time [10]. Using thermochemical methods like pyrolysis, biochar can be created from a variety of carbon-based biowaste sources, including woody biomass, crop residues, animal litter, composts, and biosolids [11]. Organic matter is broken down during pyrolysis, an anoxic thermochemical process, yielding solid biochar, condensable bio-oil, and non-condensable syngas (or charcoal). Three sequential reactions take place during the pyrolysis of biomass: (i) the removal of moisture; (ii) the depolymerization and fragmentation of lignocellulosic materials along with the removal of CO_2 and bonded water; and (iii) the re-condensation and re-polymerization that results in cracking and charring [12] Various physicochemical properties, such as surface area, pore size distribution, particle size, carbon speciation and structure, functional groups, cation exchange capacity, hydrophilicity/hydrophobicity, and ash content, are imparted to the biochar products depending on the pyrolysis conditions (temperature, residence time, heating rate, pressure, and methods). Not only that, but by adjusting the pyrolytic conditions and procedures, the yield of gases, bio-oil, and biochar may be specifically targeted [13].

One requirement for increasing plant germination and productivity is seed quality, which is accomplished through seed management strategies [14]. The controlled dehydration of seeds to a degree that allows for an increase in the speed and uniformity of germination under unfavourable temperature conditions has become one of the most important strategies for improving seed quality in recent years. In recent years, sustainable agriculture has grown, allowing us to supply organic and nutrient-rich goods. Biochar was utilised as the priming material in this line since it is rich in carbon. One requirement for increasing plant germination and productivity is seed quality, which is accomplished through seed management strategies [15]. The controlled dehydration of seeds to a degree that allows for an increase in the speed and uniformity of germination under unfavourable temperature conditions has become one of the most important strategies for improving seed quality in recent years [16]. In recent years, sustainable agriculture has grown, allowing us to supply organic and nutrient-rich goods. Biochar was utilised as the priming material in this line since it is rich in carbon. Pyrolysis is the method used to produce biochar. The current review focuses on the uses of biochar in a variety of industries, such as agriculture (for example, storing carbon), energy (for example, capturing and storing GHG), the environment (for example, soil and wastewater remediation), the animal industry (for example, animal feeds), the construction industry (for example, concrete mixes), and the materials industry (e.g. catalysts and air-filters).

Synthesis of Biochar

Biochar is created when biomass is heated over 350 °C without the presence of oxygen. Pyrolysis is the thermochemical process by which the bio material is transformed into biochar. For the creation of biochar, a variety of organic materials are employed, such as plant leftovers, animal carcasses, wood, manure, biosolids, food wastes, industrial biowaste, and municipal wastes [17]. According to reports, the pyrolysis process preserves one-third of the biomass carbon as the end char material while also generating combustible bio-oil and non-condensable gases during the heat reaction [18]. Biochar, the pyrolysis product, has a remarkable larger specific surface area and porosity, as well as persistence against biological degradation, than the initial biomass due to the selective removal of organic molecules and structural alterations of the original carbon frame work [19]. Three sequential reactions take place during the pyrolysis of biomass: (i) the removal of moisture; (ii) the depolymerization and fragmentation of lignocellulosic materials along with the removal of CO_2 and bonded water; and (iii) the re-condensation and re-polymerization that results in cracking and charring [20]. Based upon the pyrolysis conditions (temperature, residence time, heating rate, pressure, and methods), various physicochemical properties (e.g. surface area, pore size distribution, particle size, carbon speciation and structure, functional groups, cation exchange capacity, hydrophilicity/hydrophobicity, ash content) are imparted to the biochar products. Not only that, the yield of gases, bio-oil, and biochar can be custom-targeted by varying the pyrolytic conditions and methods (21 Wang *et al*., 2020) [3].

The pyrolytic process is frequently divided into slow (0.1- 10 °C s1), rapid (10- 200 °C s1), and flash (>1000 °C s1) modes based on the heating rate of the biomass used. These modes produce biochar yields in the following order: slow (25-50%) > fast (15-25%) > flash (5- 15%). Slow, fast, and flash pyrolytic modes' respective residence times are: >5 min to several hours, 10-25, and flash pyrolytic modes are: >5 min to several hours, 10-25 [22]. The distribution of the final product is very diverse as a result of the pyrolysis reaction's interaction with a number of process factors and the biomass's rather variable composition. The requirement for fossil fuels can be decreased by using biochar to store carbon in biomass and bio-oil and syngas to produce liquid fuel and chemicals with added value. Therefore, when building and operating a pyrolysis unit, a whole system energy balancing perspective should be taken into account in order to achieve the most energy- and cost-efficient operation and product production. Mango wood was used to prepare biochar, according to a recent assessment, and this method can be applied to create other carbon-based materials. The material was poured into a vertical kiln after it had air dried. 30 minutes of pyrolysis at 500 °C without oxygen were performed. After being pulverised, the biochar was put through a sieve (2 mm). Biochar had a pH of 9.9, an electrical conductivity of 1.0 dS m1, a cation exchange capacity of 21.7 cmol /kg, and a specific surface area of 23.5 m2/ g. Additionally, the biochar included total N (5.9 g /kg), total P (14.43 g/ kg), total K (1.5 g/ kg), organic carbon (67.2 g /kg), calcium (0.0016 g/ kg), chlorine (1.44 g/ kg), and hydrogen carbonate (0.85 g/ kg) [23].

Characteristics of Biochar

Biochar characterization methods

For agricultural or environmental applications, it is crucial to identify and quantify the biochar's approximate, ultimate, physicochemical, surface, and structural properties. With the necessary modifications, conventional methods used for other environmental samples like soil, sediments, plants, and solid waste are used to measure the proximate, ultimate, and physicochemical properties of biochar, including pH, electrical conductivity, bulk density, and elemental composition [24, 25]. Advanced analytical technologies like ICP MS can be used to detect chemical elements, while HPLC or GC with LC-MS can be used to quantify aromatic compounds in the bulk matrix of biochar. Recently, a number of crucial sophisticated spectroscopic techniques have seen increased application for characterising the surface of bio char. An approach frequently utilised to examine the chemical functionality and mineralogy of biochar or materials derived from biochar is Raman spectroscopy. The most used surface examination method is thought to be X-ray photoelectron spectroscopy (XPS). This method produces results that average over the entire surface and is a standard surface-sensitive spectroscopic method [26]. Char and biomass polymers are analyzed and characterized using nuclear magnetic resonance (NMR) techniques. Nuclear magnetic resonance spectroscopy using 13C-cross-polarisation magic-angle spinning (13C-CPMAS NMR) can be used to monitor the chemical changes in plant biomass following pyrolysis in great detail. Characterization of the surface functional groups of biochar is done using Fourier-transformed infrared spectroscopy (FTIR). The present proximal, ultimate, physicochemical, surface, and structural analyses of biochar were assessed critically, and it was concluded that choosing the right methodologies is essential for reliably and consistently determining the attributes of biochar [27].

Chemical Characterization

[28] found that when the temperature rose from 450 to 850 °C, the C content in rubber wood sawdust-derived biochar increased from 44 to 97 wt.%. C and other elements on the surface may, however, be lost as volatile matter if the pyrolytic temperature is sufficiently high (i.e. >900 °C) [29]. The majority of the carbon in biochar has refractory characteristics, which limits its ability to sequester carbon. The H/C or O/C ratios are impacted by the pyrolytic temperature. These ratios offer a precise indicator of the degree of pyrolysis and oxidative change in biochar [30, 31]. H/C and O/C ratios decreased when pyrolytic temperature rose from 300 to 700 °C when oil-palm-empty fruit bunches were used. In biochar, trace elements can also be discovered. For instance, biochar made from freshwater and saltwater macro algae contained high concentrations of As, Co, Pb, Hg, Cd, and Zn among other trace metals. Engineered or designed biochar may contain nanoscale components. Oak sawdust-derived biochar with nanoscale-zero valent iron assistance demonstrated improved nitrobenzene elimination effectiveness in aqueous medium. Pb2+, Cd2+, Cr6+, Cu2+, Ni2+, and Zn2+ were only a few of the trace elements that were eliminated when biochar made with the help of magnetic nanoscale zero valent iron was created from reed plants.

Physical Characterization

An increase in surface area causes a chemical reaction to proceed more quickly [33, 32]. The primary determinant of bio char's surface area is the pyrolytic temperature. Surface areas of 120 and 460 m^2 /g for biochar generated at 400 and 900 °C, respectively, were reported by [34]. High pyrolytic temperature-produced biochar has also been found to have increased organic chemical sorption [35]. Used rice husks to create a biochar with a high specific surface area, which they subsequently mixed with iron oxide. In comparison to iron oxide modified sand, the synthesised biochar-iron oxide showed an adsorption about 2.5 orders of magnitude higher. An essential characteristic of biochar is its volatile content, which affects its porosity and pore structure and reveals the presence of organic compounds [36]. Demonstrated a declining tendency of volatile-matter concentration with increasing temperature from 350 to 650 °C, from 55.4 to 14.8% over time. This pattern was attributable to the breakdown of hemicelluloses and cellulose. Because biochar contains less volatile matter, soil microbes have less access to organic matter, which negatively affects soil health.

Diverse Application of Biochar

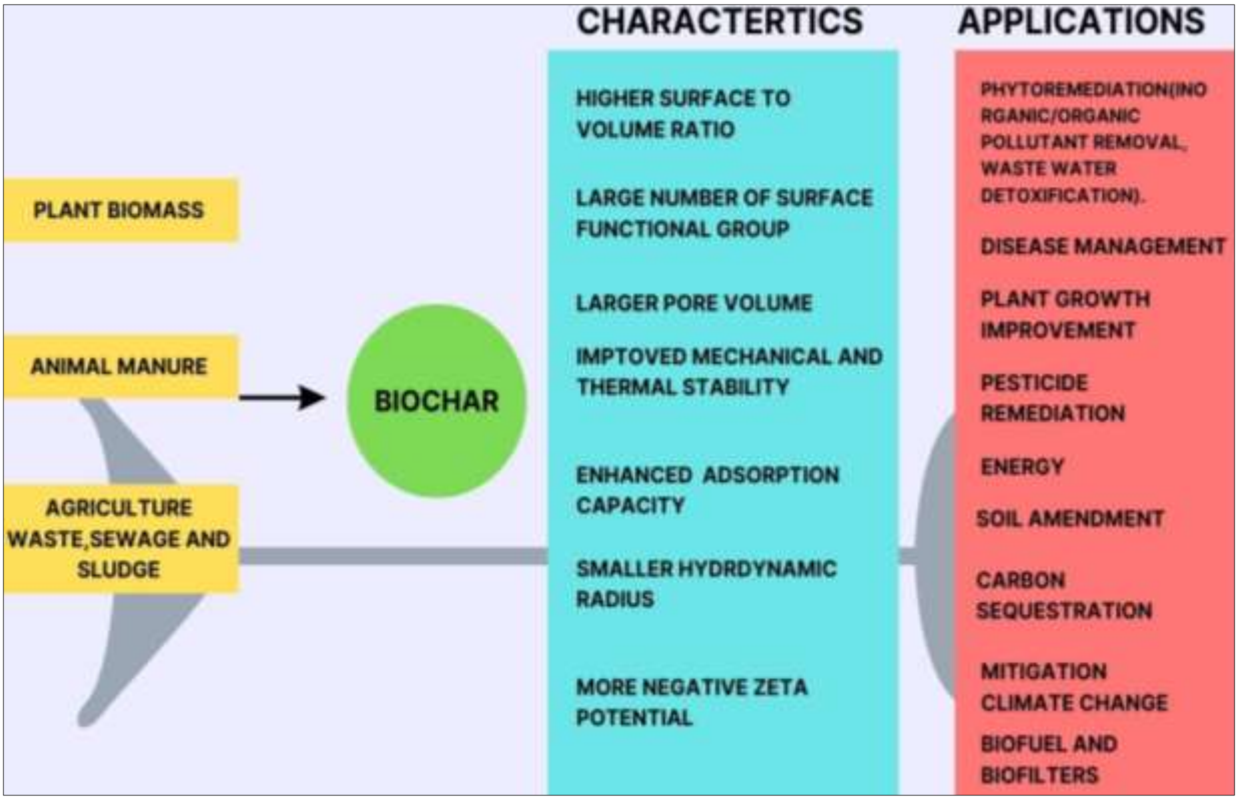

Fig 1: Application of Biochar

Mechanism

In the soil, biochar is subject to a number of natural ageing processes. Full mineralization, or the conversion of biochar to H2O and CO_2, either by biotic or abiotic processes, is slow since biochar's carbon content is largely resistant, with reported half lifetimes in the range of 1000 years [37]. Even while the ageing processes that lead to altered qualities are somewhat quicker, they are nevertheless difficult to spot in the field. Observation times can be drastically cut down using artificially accelerated ageing techniques that imitate natural ageing mechanisms. Figure 1 presents implications for artificially accelerated ageing techniques together with the most pertinent biological ageing mechanisms. In places that are seasonally frozen, biochar ageing can result from natural rainfall or freeze-thaw occurrences. This causes mechanical fragmentation, surface oxidation, dissolved organic matter (DOM) release, and mineral dissolution (i.e., decreased ash content). Through experiments, chemical oxidation, freeze-thaw cycling, and wet-dry cycling, these environmental processes can all be sped up. While biochar adsorption of root exudates may result in acidity and mineral dissolution, soil mineral interaction with biochar might lead to pore obstruction and increased biochar mineral concentration. Chemical manipulation can experimentally speed up these processes. The labile carbon content of biochar can be oxidized and released through biological and photochemical processes, which can be experimentally sped up by microbial inoculation and UV light, respectively. The subsections below address the precise methods that cause biochar to age.

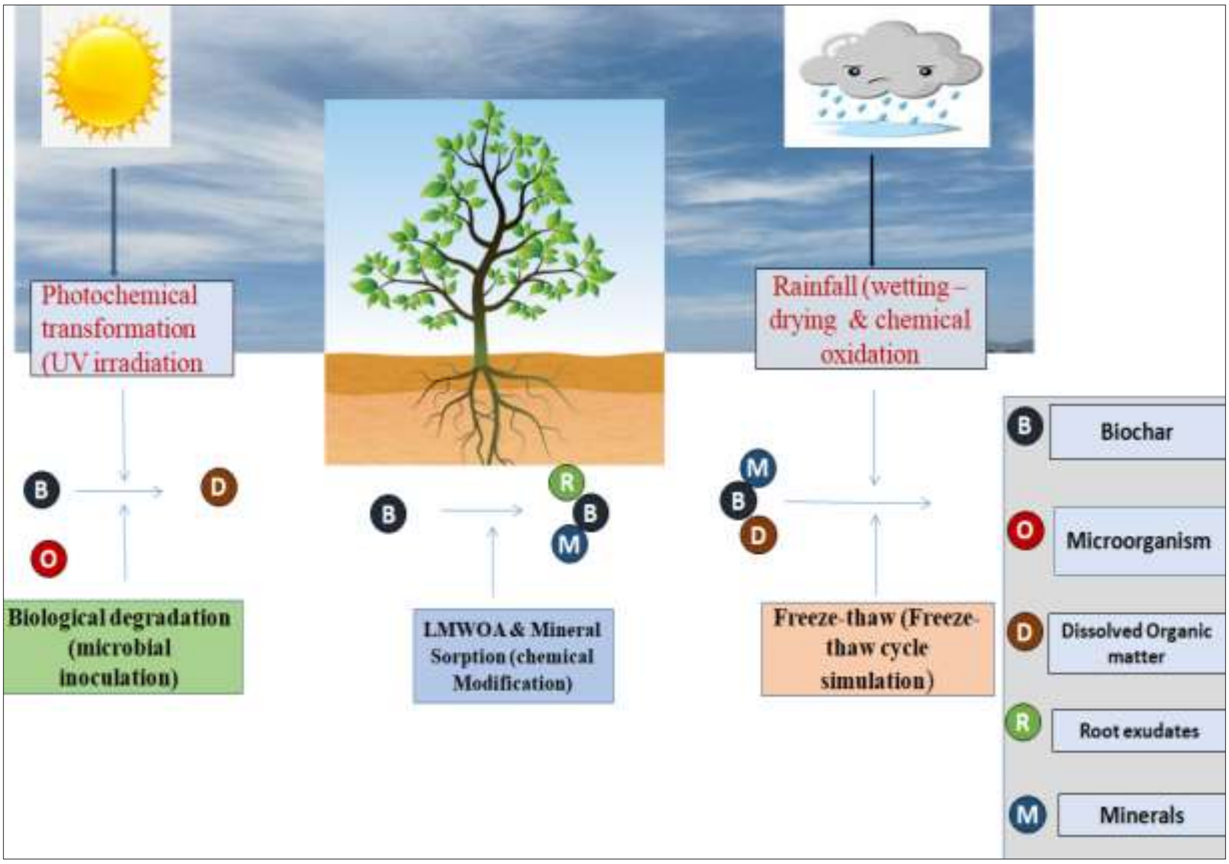

Fig 2: Biochar field aging mechanisms and implications for artificial accelerated aging shown in parentheses.

Dissolution

Mineral component dissolution (deashing) is a significant ageing process with agronomic repercussions. There are two steps of mineral oxidation in biochar [38].

Stage 1: Initial rapid element detachment induced by ion exchange, submicrometer particle dissolution, and preferential dissolution at crystal imperfections.

Stage 2: pH-dependent zero-order reaction.

Numerous natural or man-made occurrences, such as the addition of H+, will lower soil pH levels, increasing the amount of minerals released from biochar (Figure 1). The main cause of the acidity of the soil is rainfall. Due to dissolved CO_2, rainfall often has a pH of 5.6 or less (i.e., carbonic acid). When it comes to acid rain, dissolved air pollutants like NOX and SO2 cause soil pH to be significantly lower (pH 4) and introduce higher levels of H+ [39].

Fragmentation

Mechanical decay is a significant, but frequently disregarded, ageing factor. The main factors for biochar physical fragmentation and disintegration in the field are rainfall and freeze-thaw cycles (Figure 1). Graphite sheets may bulge as a result of water sorbed in charcoal during periods of rainfall. water molecules' expansion and contraction during freeze-thaw cycles. Biochar will tend to shatter at relatively low strain under mechanical stress, in contrast to more elastic raw biomass. Small biochar particles can form in this fashion and are known as dissolved black carbon. There is no discernible change in the elemental makeup or other chemical properties [40].

Interactions with Soil Minerals

Minerals in the soil can interact with biochar through adsorption processes and adhere to the charcoal surface after biochar has been applied to the soil (Figure 1). The creation of biochar-mineral complexes improves long-term carbon sequestration, and the adsorption of soil minerals onto biochar can protect it against oxidation and decomposition processes. The production of surface complexes like Fe-O-C or integration into interior pores allows soil minerals including kaolinite, montmorillonite, iron oxides, and aluminium oxides to adhere firmly to biochar surfaces and increase oxidation resistance [41].

Biological Degradation

The biochar's well-designed porous structure provides a sizable microbial habitat niche [43, 42]. It has long been known that biochars exposed to hundreds of years of natural ageing experience substantial colonisation [44], but it is still unclear whether soil organisms will successfully colonise biochar in a relatively short amount of time (i.e., several years). Due to a paucity of labile carbon, the wood biochar remained sparsely populated after three years of outdoor age. (2013) [45]. In contrast, grass biochars take 90 days of short incubation before they can be utilised as a substrate and are both quickly colonized [46]. While it may take hundreds to thousands of years for microorganisms to completely mineralize biochar (to H_2O and CO_2) [47], changes in biochar properties may also occur as a result of microbial colonisation and degradation after several years of field application. Due to the addition of additional oxygen-containing functional groups and DOM release, soil microbes are crucial for biochar surface oxidation and labile carbon loss (Figure 1).

Abiotic Oxidation

A lot of research imply that abiotic oxidation plays the primary role in the oxidation of biochar, which can happen either abiotically or biotically [48] Numerous methods have been found to cause abiotic biochar oxidation. Additional oxygen-containing functional groups, such as hydroxyl, carbonyl, and carboxyl, may be introduced to the surface of biochar via atmospheric oxygen-induced oxidation. At room temperature, this mild oxidation process proceeds slowly [49]. For instance, the percentage of oxygen-containing functional groups might only rise by 2% after 2 months of air ageing of sludge biochar (measured using the Boehm titration method at 45 °C). Rainfall events can also result in biochar oxidation owing to the dissolved oxygen and nitrogen oxides in rainwater [50]. A lot of research imply that abiotic oxidation plays the primary role in the oxidation of biochar, which can happen either abiotically or biotically [48] Numerous methods have been found to cause abiotic biochar oxidation. Additional oxygen-containing functional groups, such as hydroxyl, carbonyl, and carboxyl, may be introduced to the surface of biochar via atmospheric oxygen-induced oxidation. At room temperature, this mild oxidation process proceeds slowly [49]. For instance, the percentage of oxygen-containing functional groups might only rise by 2% after 2 months of air ageing of sludge biochar (measured using the Boehm titration method at 45 °C).

Table 1: Biochar impacts on soil, plant and environmental factor

Statement	Description	Reference
Increasing crop production	Numerous studies found that crop yields rose normally for a short period of time (1-2 years), but in some situations there were also unfavourable effects.	[53]
Increasing arbuscular mycorrhizal colonization linked to increase in crop product	This impact may be brought on by changes to the soil's physical characteristics, indirect effects on mycorrhizae caused by effects on other soil microbes, interference with plant-fungus signaling, detoxification of allelochemicals on biochar, and the creation of refuge from fungi grazers.	[54]
Acting as microbial habitats	Increased nutrient availability in soils appears to have an impact on how much biochar boosts soil microbial activity and biomass.	[55]
Increasing earthworm abundance and activity	There is evidence that some biochar-amended soils are preferred by earthworms to non-biochar-amended soils.	[56]
Liming effect	When the initial pH is low, biochar application results in a rise in soil pH according to various field investigations. However, on alkaline soils, the results may differ.	[57]
Increasing soil cation exchange capacity (CEC)	The effectiveness and duration of this CEC increase after adding biochar to soil need to be investigated. Biochar raises the CEC of soil.	[58]
Influencing N cycle	The effects of adding biochar on soil hydrology and related microbial processes, the mechanisms of which are largely unknown, determine N_2O emissions.	[59]
Decreasing soil microbial biomass and N mineralisation	With the addition of biochar, the activity of the microbial community declines due to lower soil organic matter breakdown and N mineralization, which may have been brought on by the decreased microbial biomass C	[60]
Priming effect	There is conflicting evidence of a potential priming effect, which only applies to short-term and extremely small samples of biochar and specific types of soil.	[61]
Decomposition of biochar enhanced by agricultural management practices	Agricultural management techniques (such as ploughing, sowing, and planting) may affect (accelerate) the breakdown of biochar in the soil, hence possibly lowering its capacity to store carbon.	[62]
Reducing greenhouse gas emissions	Agricultural systems' N_2O and CH_4 emissions are reduced by biochar, which can also act as a carbon storage in the soil.	[63]
Risk of contamination Contaminants	(such as PAHs, heavy metals, and dioxins) that may be in biochar have negative effects on soil characteristics, microorganisms, and their functions.	[64].
Increasing soil sorption capacity of trace contaminants	Increased soil sorption of pesticides, herbicides, and polycyclic aromatic hydrocarbons (PAHs) by biochars affects the toxicity, movement, and destiny of these contaminants.	[65]
Influencing soil salinity	Biochars absorb salts and lessen the effects of salt stress on plants, proving that biochars can be used to lessen the impacts of salinity in agricultural soils.	[66]
Influencing soil organic matter	dynamics Although some pertinent processes are acknowledged, it is still not well understood how combinations of soil, climate, and management factors affect these processes.	[67]

Implications of Biochar Interactions with Soils for Agricultural Productivity

Management of Saline

Because osmotic imbalances and oxidative stress reduce plant growth, salinization of soils is a developing concern [68]. Due to improved retention and decreased ammonia volatilization, the management of saline soils with appropriate rates of biochar has a mitigating effect on nitrogen leaching [69]. The capacity of biochar to modify soil physicochemical properties plays a significant role in microbial colonisation. This has been shown to increase the number of ammonia-oxidizing bacteria in alkaline soils and reduce N leaching [70]. In their research [71], shown that the application of biochar in conjunction with efficient microbes reduced the effect of saline stress on the growth of *S. cannabin* by enhancing the fertility and nutrient content of the soil. The fact that biochar affects soil physicochemical properties to enhance colonisation by Arbuscular mycorrhizal fungus (AMF) is the reason for the growing interest in the co-application of biochar and microorganisms for plant growth [72]. According to experimental data, this combination can reduce the effects of drought on plant development by enhancing the WHC [73]. Salt-induced stress is mitigated in various ways by biochar. Biochar surfaces may interact mechanically with soil components like ions, minerals, and organic materials. Because it might offer ionic salt exchange sites, biochar is hence likely to be able to buffer soil salt. Since it is not apparent how well biochar surfaces would work to lessen salt stress when the ions are kept in the ion-exchange sites, our understanding of how biochar surfaces could alter soil ionic salts is not entirely comprehensive. Additionally, basic cations (Ca2+, Mg2+, and K+) that could lessen salt stress are frequently present in biochar. When biochar is created from manures or grasses, it has a high mineral content. However, using biochar frequently could lead to salt stress since it adds salts and tiny organic molecules. The fact that biochar is porous and hence carries a lot of SSA is one of its most crucial characteristics. This substantial SSA enhances soil water retention while buffering salts (Figure 2). It is uncertain whether the water held in the pore would aid plant water intake because the pores of the biochar are so small.

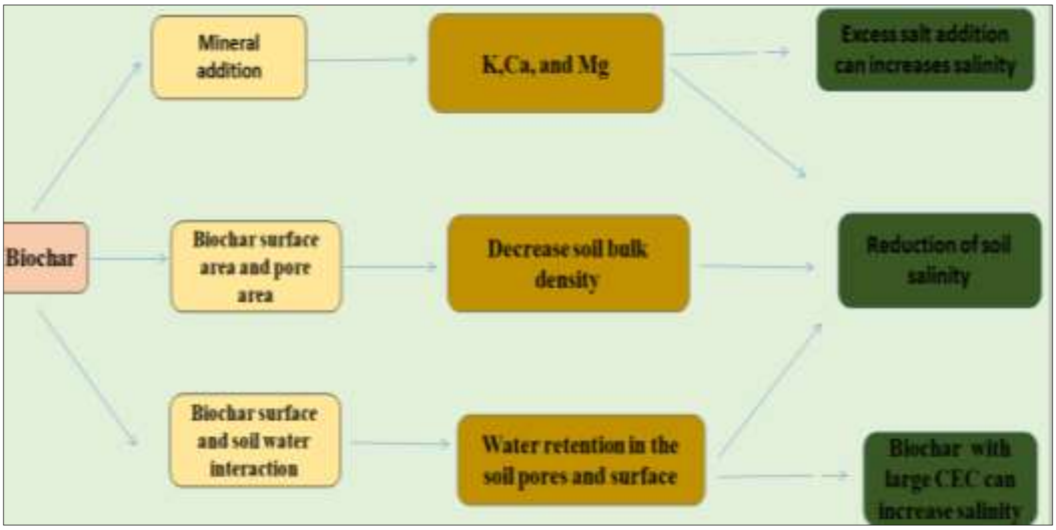

Fig 3: Role of Biochar in the remediation of saline soil

Management of Polluted Soils

Recent years have seen a substantial rise in the application of biochar for pollution cleanup due to the wealth of literature attesting to its adaptability [74, 75]. As was already said, adding biochar as a soil amendment material raises the pH, CEC, and OM content of the soil. Biochar indirectly increases soils' capacity to retain contaminants such heavy metals [76], dyes [77], antibiotics [78], and others through enhancing these characteristics. Because both organic and inorganic contaminants are widely available to plants and other life forms at low soil pH, their potential for toxicity is greatly increased [79]. By increasing the electrostatic adsorption of cationic pollutants, adding more organic units for complexation with or degradation of pollutants, converting pollutants to less harmful forms, precipitating pollutants as non-toxic salts, etc., adding biochar to polluted soils enhances pollutant retention. According to research by [80, 81], heavy metals like lead (Pb) immobilize in contaminated soils according to the stated mechanisms and precipitate less dangerous Pb5 (PO4) 3Cl, Pb3 (CO3) 2 (OH) 2, and Pb (OH). Greater soil contaminant immobilization directly contributes to decreased bioavailability. For instance, adding biochar to paddy soil dramatically reduced the uptake of heavy metals (Cr, Ni, Cu, Pb, Zn, and Cd) by the above- and below-ground sections of rice. Similar to this, adding charcoal to maize plants grown in Pb-toxic soil increased certain growth characteristics [82]. lowered plants' absorption of organic contaminants [83].

Mitigation of Greenhouse Gas Emission

However, if it is not trapped, usually half of the biomass's initial carbon can be released. Pyrolysis and biochar, however, are regarded as carbon-negative technologies since they can also reduce carbon footprint in a number of other ways. First, because biochar carbon is stubborn, adding it to soils helps reduce climate change. Since biochar carbon is stable, it can be kept in the soil for a very long time—possibly millennia. By speeding up the process of organo-mineral complexation (described in the preceding section), it can encourage the stabilization of other carbon forms in the soil and lower CO_2 emissions [84]. Studies have revealed that biochar alters the emission of greenhouse gases (GHGs) from soils in a variety of ways, including (a) changes to the dynamics of soil nutrients, (b) changes to soil pH, EC, and Eh, and (c) changes to crop production. A one-year field experiment, for instance, shown that adding NPK fertilizer to agricultural soils can raise N_2O emissions. However, adding biochar made from wood waste to the same soil considerably reduced N_2O emission and improved storage [85]. The modifying impact of biochar on GHG emission depends on the kind and ageing conditions of the biochar, the soil type, the water-filled pore space, and its capacity to affect the composition of the soil microbial community [86]. However, biochars have the potential to function as an effective adsorbent for dissolved organic carbon, gaseous ozone, NO_3^- [87], NH_4^+ [88], and other nutrients [89]. As a result, the amount of these compounds may be understated whether estimated through the extraction from biochar-amended soils or through analysis of the emitted gases.

Conclusion and future prospects

Water and soil contamination is an increasingly prevalent global issue. Using sustainable and renewable methods to eliminate pollutants in water and soil has become the pursuit of researchers. Thus, there is a demand for novel, efficient techniques and materials to eradicate organic and inorganic pollutants from nature, including heavy metal ions, dyes, antibiotics, and pesticides. Applying biochar to elevate the quality of soil and water by removing contaminants has been regarded as a feasible green strategy that is cost-effective. The performance characteristics of biochar are affected by the type of feedstock materials, residence time and pyrolysis temperature. Applying biochar to contaminated water and soil has been verified to be effective as a tool to remediate soil and water systems. The immobilization or mobilization mechanisms of heavy metal ions include reduction, complexation, electrostatic attraction, precipitation reactions, and cation exchange. The interactions are often multifaceted and depend on both biochar and soil properties. Therefore, both biochar and soil properties should be considered for harvesting the benefits of biochars. Specifically, a matrix of biochar versus soil properties can be developed for guiding the decision-makers for large-scale biochar applications. Despite the increasing number of research with biochar in the recent decade, there are few field studies with biochar. Long-term field studies are required to verify results from short-term laboratory studies so that benefits of biochar application (e.g., climate change mitigation, immobilization of pollutants, inhibition of acidification, etc.) would be harvested at a larger scale. The specific recommendations are-

- **The need for technological maturity:** Long-term studies are required to understand the future of the currently applied biochar. Few studies have attempted to examine the future role of biochar using artificial conditions. However, real field conditions may differ and thus, the need for long-term field studies.
- **Accreditation of biochar:** Given thousands of studies reporting diverse results, it is difficult for practitioners to use biochar and, if so, determine which of the types to use. Therefore, an international body can be formed to accredit the quality of biochar. A generalized guideline can be prepared for preparing, testing, and applying biochars for achieving a target, while equal importance needs to be paid for the long-term effects of biochar because the role of currently applied biochar may be reversed in the future.
- **Biochar-based composites:** Development and application of biochar-based composite and fertilizers can be one of the new dimensions of biochar research since there is a higher chance of obtaining biochar-nutrient/contaminants interactions than their direct application to soils. However, detailed studies are required before advocating any large-scale application.
- **Cost-effective biochar production:** Research is needed to tailor technologies that can help to produce biochar at a low cost. One of the big challenges is that many large biochar production companies are struggling to sustain their business. Efforts are to be made to harvest all possible benefits, including recycling energy. Moreover, obtaining a sustainable source of biomass is needed. The use of waste biomass (municipal waste) can be an option for that. However, suitable technologies are required for handling diverse biomass.
- The elimination mechanisms of different contaminants by biochar should be in-depth investigated using theoretical calculation and molecular simulation technology, which is helpful to understand the contribution of different functional groups on the binding of pollutants. Theoretical calculation and molecular dynamics simulation can supply information that cannot be available in spectroscopic analysis, such as the structure, bond distance, binding energy of adsorption system. This information is useful for deeply understanding the reaction mechanisms between pollutants and different functional groups, which is important for the preparation of biochar and surface grafting of specific functional groups on material surfaces to improve the binding of contaminants, especially for the selective elimination of contaminants in multi-contaminant environments.

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