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Exploring Nano-Biochar: an Emerging Therapy for Soil Health

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BIOCHAR (BC), a carbon-rich material, is created by thermally decomposing agricultural solid waste in an oxygen-limited setting. Biochar converted into Nano biochar (nano-BC) by applying processes. In this process, the physical and chemical properties of this valuable material are enhanced, and waste management, energy production, soil remediation, and pollution emissions are decreased more profitably. Nano-BC can remove contaminants like heavy metals, organic compounds, and inorganic compounds from wastewater. This review provides a comprehensive overview of the properties and characterization of biochar and nano-modified biochar, and use of nano-modified biochar in environmental clean-up. As well as this review also discussed nano-modified biochar role to enhanced phytoremediation of emerging contaminants.

Keywords: soil health, heavy metal, biochar, phytoremediation.

1. Introduction

Recently, biochar (BC) has been widely used as a soil amendment and produced on a massive scale globally. Biochar is the result of the thermochemical conversion of biomasses that lack oxygen or have limited oxygen availability. Biochar-based applications are relatively new in dealing with soil pollution and climate change (Luo et al., 2020; Bassouny and Abbas, 2019; Faizan et al., 2024). BC has been used in a variety of fields, including agriculture, biotechnology, and environmental cleanup. Biochar having size ranging from several mm to cm is included as “Bulk-BC” are frequently used for agricultural and environmental protection. Biochar is a dense organic material that is recovered after pyrolysis of plant or animal biomass (Tomczyk et al., 2020), which has garnered increased attention from different sectors around the world. According to environmental experts Liu et al.(2013), biochar has the potential to mitigate climate change through its carbon sequestration properties. Because of its widespread availability, inexpensive cost, porous structure, and surface functional groups, biochar is acknowledged as a significant adsorbent for eliminating organic pollutants and heavy metals (HM) from wastewater (Cao et al., 2009; Howladar et al., 2025; Sultan et al., 2025). For the purpose of using biomass, the process of producing biochar is more economically appealing than incineration because it simultaneously produces fuel gas and bio-oil. When using biochar as an adsorbent, its ability to absorb pollutants is still less than that of common adsorbents like activated carbon. Many attempts have been made to alter biochar to give it unique porous structures and surface characteristics in an attempt to increase its adsorption capacity (Kah et al., 2017).

Advancement in nanotechnology have been undertaken on the generation of nano-biochar (nano-BC) for soil and agricultural applications in a sustainable fashion (Gao and Wu, 2014; Sultan et al., 2024). There are two methods for manufacturing nano-modified biochar with improved functionalities: modifying the raw biomass before converting it into biochar by procedures such as pyrolysis, calcination, or coprecipitation, and directly altering previously generated biochar (Ahuja et al., 2022). Surface alterations with metal precursors, nanoparticles, and organic-inorganic polymers create biochar nanohybrids. The properties of these nano-modified BC are controlled by the feedstock type, pyrolysis temperature, biochar-to-metal nanoparticle ratio, and pyrolytic reaction medium. Modifications aim to optimize biochar output by adjusting temperature, heating rate, and residence time based on

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feedstock properties (Maˇsek et al., 2013). Nano-modified biochars exhibit a wide range of specific surface area (SSA) values, from 5.58 to 1736 m2/g, due to their tiny particle sizes. According to research, the SSA of nano-modified biochar increases with higher pyrolysis temperatures. Some argue that increasing the pyrolysis temperature has no effect on the SSA of nano-modified biochars and may even reduce it. Variations in the materials used to make nano-modified biochars could explain these disparities. Post-pyrolysis treatments like chemical regeneration or physical modification improve the durability and efficacy of nano-modified BC for environmental applications. Chemical regeneration is crucial for reactivating BC, particularly for adsorbing heavy metals and organic contaminants such as dyes and antibiotics. To absorb these contaminants, the technique commonly uses solvents and chemical reagents. The efficiency of regeneration varies based on the kind of pollutants and the solvent employed for organic and inorganic adsorbents. Recent research has shown that nano-modified biochar is useful remediators for affected soils, improving the chemical and physical properties of the soil, increasing nutrient availability and content, increasing soil fertility, and controlling the structure and activity of the microbial community (Gao et al., 2024).

The comparison between biochar and nano-biochar with highlighting the key aspects such as their properties, applications, and benefits are incorporated in table 1. In this review, the agricultural and environmental friendly properties of nano BC and nano-modified BC synthesis, properties and their characterization are highlighted. The present article has made an attempt to display latest data on the effect of nano BC/ nano-modified BC in environmental cleanup and phytoremediation of contaminants to improve soil health for sustainable agriculture is also discussed.

Table 1. Comparison between biochar and nano-biochar.

S.No.	Aspect	Biochar	Nano-biochar
1	Definition	Biochar is a carbon-rich material produced by the pyrolysis of biomass under low-oxygen conditions	Nano-biochar is biochar modified or processed to nanoscale size, often enhanced with nanoparticles or surface modifications
2	Size	Micrometer scale (larger particles)	Nanometer scale (<100 nm), very fine particles
3	Surface area	Relatively low surface area (specific surface area around 10-100 m²/g)	High specific surface area due to the nanoscale size (can exceed 500 m²/g)
4	Porocity	Moderate to high porosity	Very high porosity due to the small particle size and larger surface area
5	Production method	Pyrolysis of biomass (wood, agricultural waste, etc.)	Modified pyrolysis or additional techniques like ball-milling, acid treatment, or chemical activation to produce nanoparticles
6	Surface chemistry	Surface functional groups such as carboxyl, hydroxyl, and phenolic groups.	Enhanced functional groups, often modified with metals or other nanoparticles to improve reactivity
7	Stability	Stable and durable under environmental conditions, but its effectiveness depends on the feedstock.	Similar to biochar, but nanoscale biochar might degrade faster under certain conditions due to increased surface reactivity.
8	Application	Soil amendment, water filtration, carbon sequestration, waste management, and as a fertilizer.	Similar applications but also enhanced in areas like drug delivery, environmental remediation, and enhanced catalytic activity due to the increased surface area and reactivity.
9	Carbon sequestration	Effective in carbon storage over long periods (decades to centuries).	Also effective for carbon sequestration but more research is needed on the long-term stability of nano-biochar.
10	Environmental impacts	Reduces greenhouse gas emissions, improves soil health, enhances water retention, and promotes microbial activity.	Potentially higher reactivity, which may lead to faster degradation of contaminants but could also cause leaching of nanoparticles into the environment.
11	Cost	Relatively low cost (depends on feedstock and production method).	Generally more expensive due to additional processing steps required to produce nanoscale biochar.
12	Reference	Lehmann and Joseph, 2015	Liu et al., 2019

2. Synthesis of nano BC and nano-modified BC

Biochar is produced through the high-temperature pyrolysis of common biomass waste in a hypoxic environment. Additionally, it is highly compatible with microorganisms, has a broad range of raw material sources, a strong adsorption capacity, a large specific surface area, and low preparation costs (Li et al., 2020). Carbonate, which is derived from mineral components, is present in biochar (Almutairi et al., 2023). The ratio of the biochar's preparation and pyrolysis temperatures to its total carbonate content is direct. Alkaline compounds in biochar primarily exist as carbonate, according to research. In addition, oxygen-containing functional groups like -COO-(-COOH) and -O-(-OH) are abundant on the surface of biochar and combine with H^+ to form organic anions, another class of alkaline compounds in biochar (Singh and Vijayan, 2023). The alkalinity of biochar is determined by its biomass feedstocks (Sarfaraz et al., 2020). Compared to biochar made from non-legumes, biochar made from legumes has a higher alkaline content (Xu, 2016). Moreover, biochar's high specific surface area and capacity to function as a buffer for both acidic and alkaline substances are ascribed to its exceptional adsorption abilities, hydrophobicity or hydrophobicity, and abundance of oxygen-containing functional groups on its surface (Yuan et al., 2023). Remediation of contaminated soils is one area of great interest in the application of biochar in environmental protection. Farming and environmental domains are seeing a growing use of biochar, which is acknowledged as an eco-friendly modifier. Applications of biochar have been shown to improve crop productivity, minimize soil contamination, promote plant growth and development, revitalise nutrient-deficient soil, and improve soil nutrient utilisation (Khan et al., 2024). Biochar has the ability to change the bulk density, pH, porosity, water and nutrient holding capacity, and surface area of soil, among other physical and chemical properties (Yadav et al., 2023). Utilising biochar as a soil fertiliser can enhance soil nutrition (An et al., 2022) and promote plant development in environments that are stressed by salt (Yuan et al., 2023). Certain mineral nutrients, including C, N, P, K, and Mg, are present in biochar. Biochar has the ability to change the physical and structural properties of soil, including bulk density, CEC, water and nutrient holding capacity (Gao et al., 2024). It provides soil microorganisms with a "shelter" due to its porous structure, which protects them from external threats, affects the quantity and activity of microbes, and promotes the cycling of nutrients. Biochar strengthens the stability of the aggregate structure of the soil, increases the capacity of the soil to retain carbon, and promotes plant growth and development (Gao et al., 2024).

The most promising modification method produces mineral-modified biochar by adding minerals to its surface, which combines the benefits of both minerals and biochar (Tan et al., 2016; Sizmur et al., 2017). By moving and stabilizing minerals, biochar can serve as a carrier for minerals in composite materials and offer some porous structure for heavy metal adsorption. In contrast, the large surface area and size-quantization effect of the minerals in the composites, especially the nano-sized minerals—show excellent selectivity and activity for heavy metal adsorption (Hua et al., 2012). When it comes to effectively adsorbing various pollutants from aqueous solutions, biochar modified with nanoparticles performs significantly better than regular biochar (Zhang and Gao, 2013). Mineral nanoparticles can be added to virgin biochar by depositing minerals or nanocrystals onto its surface. Compared to commercial activated carbon, ZnO-GAC had a removal efficiency on Pb(II) that was 5.1 times higher (Kikuchi et al., 2006). In a two-step process, they created magnetic biochar/ZnS composites by first producing biochar from rice husk by slow pyrolysis at 400 °C for five hours. Subsequently, they injected zinc chloride and thiourea continuously at 180 °C into a polyol solution to deposit zinc sulphide on the biochar. A ten-fold increase in Pb(II) adsorption capacity was observed in magnetic biochar/ZnS composites when contrasted with magnetic biochar control (Yan et al, 2015). Despite the good adsorption capacities of these composites made by loading minerals—particularly zinc minerals—their practical application was limited by their difficult preparation process and relatively weak mineral-biochar adhesion strength. Additionally, soaking biomass feedstocks in a metal salt solution during the catalytic pyrolysis of biomass with metal salts is an intriguing method to lower activation energy and enhance the quality of the bio-oil produced (Wang et al., 2015) (Fig. 1). Mineral-modified biochar can be produced with a number of benefits through the direct pyrolysis of biomass that has been loaded with metal salts: (1) Biochar production and mineral formation, even at nanoscale, occur concurrently; (2) Scale-up is facilitated by the single pyrolysis step in the entire synthetic process; and (3) Metal salts may catalyse the pyrolysis of biomass in order to increase the porous structure of biochar (Fig. 1).

While a number of investigations have demonstrated some encouraging outcomes through direct pyrolysis of biomass that has been treated with zinc nitrate ($Zn(NO_3)_2$) or potassium permanganate (KMnO) (Gan et al., 2015; Wang et al., 2015). The resulting modified biochar's porous structure and mineral phase fell well short of expectations because of the loading of metal salts and the selection of pyrolysis conditions. Pyrolysis of biomass contaminated with heavy metals can also produce biochar modified with nano minerals. Biochar from contaminated biomass can be a win-win solution when compared to biochar obtained by impregnation or biochar after modification because, without the need for additional chemical reagents, it recycles contaminated biomass into useful materials (Mosa et al., 2018). Biochar is produced by oxygen-free pyrolysing biological materials to produce a highly aromatic, stable, and insoluble carbon-rich product (Xiao et al., 2018). Heavy metals and antibiotics can be absorbed by biochar, which has the potential to remove ARG-contaminated soil (Ngigi et al., 2019). By absorbing or eliminating MGE carriers, biochar can alter the makeup of microbial communities, reducing or eliminating ARGs' ability to move horizontally across bacteria. The origin of the material, the pyrolysis procedure, and the amount of addition all affect how well biochar inhibits ARGs (Liu et al., 2022). It's unclear, though, if different particle sizes will have a different inhibitory effect on ARGs when using biochar. Particularly, there has been a lot of research done on nano-biochar, or biochar the size of nanoparticles. Compared to regular biochar, nano-biochar has a number of noteworthy differences, qualities like a greater surface area, more developed micropores, higher oxygen-containing functional group concentrations, and a more potent capacity to absorb heavy metals and mineral elements (Pratap et al., 2021). In addition to increasing nutrients and creating favourable environments for microbial growth, nano-modified biochar also encourages microbial activity and reproduction in soil (Sun et al., 2021). Research indicates a robust association between ARGs and the bacterial makeup of soil, whereby alterations in the bacterial community function as the primary intermediaries of ARG fluctuations (Liao et al., 2018). According to Bulgarelli et al. (2012), soil microorganisms can also colonies plant roots and transform into root endophytic bacteria. ARGs can travel to other soil microorganisms, including root endophytic bacteria, and subsequently to plant shoots. Compared to fertilizers and composts, biochar usually has a high alkalinity and a stable fixed carbon structure. The high pH value and large surface area of biochar with functional groups aid in the effective fixation of cadmium (Cd) in soil (Beesley et al., 2010). Numerous scholars have carried out in-depth investigations into the production and alteration of biochar in substantial amounts. Adsorption of Cd by the soil is influenced by the biochar's surface functional groups (Uchimiya et al., 2011; Alyemeni et al., 2016). In addition, there are differences in the properties of biochar made with various raw materials and temperatures. For instance, pyrolysis at 350 to 550 °C was successful in producing wheat straw biochar (WSB) (Liu et al., 2012).

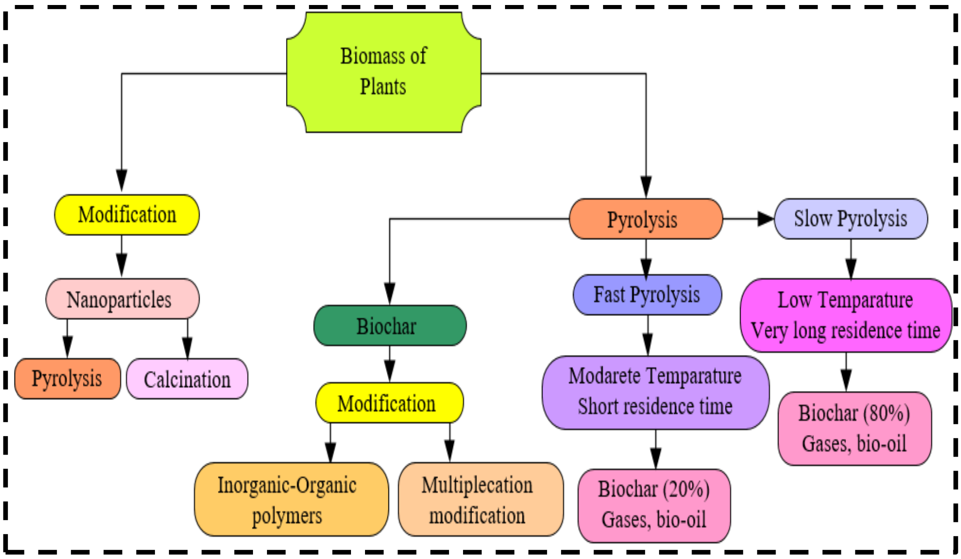

Fig. 1. Various methods of biomass and biochar modification

3. Distinctive properties of nano-BC and their characterization

In addition to the sorption mechanism, improvements in BC modification are known to exist. These include loading with nanoparticles, organic functional groups, reluctant, minerals, and biomaterials; activation with an alkaline solution to enhance sorption capacity is one of them. When comparing chemical and physical methods for BC modification, physical methods are known to be more cost-effective and environmentally friendly (Amalina et al., 2023). It enhances BC's physico-chemical characteristics, such as porosity and permeability, through manageable steps. Ball milling, magnetization, microwave irradiation, and vapour/gas activation are common physical modification techniques for BC. By enhancing BC's qualities, these techniques raise the caliber of the soil. Ball milling, for example, reduces the particle size while increasing surface area and adsorption capacity by breaking down intact BC into small powders (Fig. 2).

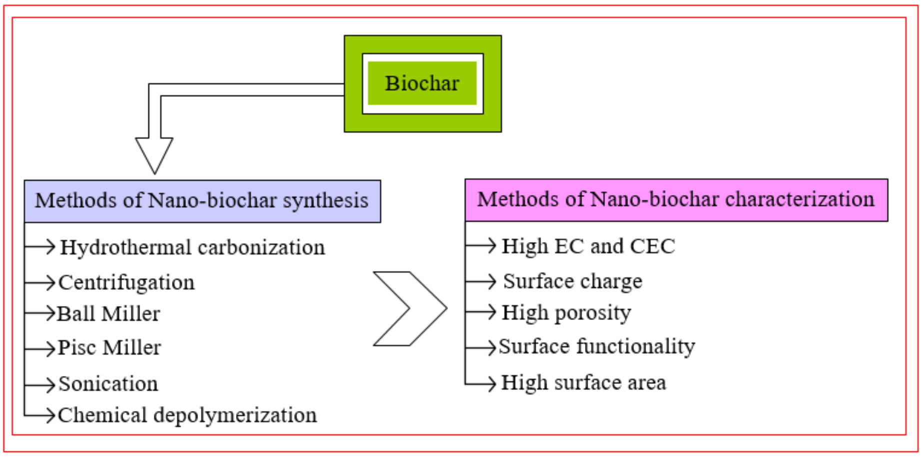

Fig. 2. The various processes for producing nano-biochar and characterizing techniques

Two types of ball milling exist: physical ball milling and chemical ball milling. While chemical ball milling alters the microporous structure and functional groups, physical ball milling greatly affects the surface area and particle size of BC (Islam et al., 2021). An external magnetic field can make it simple to recover the magnetic BC produced by chemical ball milling (Yi et al., 2020). Superior environmental remediation results from the magnetization process, which increases BC's catalytic activity and surface charge. Microwave irradiation is a newly developed technique for BC modification that involves rapidly raising the temperature of BC to 200–300 C through microwave heating. The surface area and sorption capacity of the microwave-modified BC are higher for many pollutants with hydraulic functional groups. The combined effects of vapour activation and microwave irradiation greatly enhance BC's physico-chemical characteristics, such as its CEC and water-holding capacity (Lee et al., 2020). In addition to improving porosity and increasing BC's surface area, gas/steam activation removes residues that have partially burned and become trapped in the porous structure. Through surface reactions, this BC modification process activates hydrogen and carbon dioxide (Wang et al., 2019). Consequently, it shows greater methane and nitrogen dioxide adsorption capacity when compared to pristine BC (Li et al., 2020). To sum up, BCs can be physically modified by ball milling to increase their surface area, adsorption capacity, and microporous structure. They can also be modified by microwave irradiation to improve their surface area and sorption capacity against a variety of pollutants. The final step in improving BCs' physico-chemical characteristics, adsorption capacity against different gases, porosity, and surface area over their original state is gas/steam activation.

Enhancing the functionalities of biochar (surface area, pore volume, functional groups, etc.) will increase its adsorption capacity. Crushing biochar into smaller particles to create nanobiocoal is one method of enhancing functional groups. The particle size of biochar is substantially larger than 50 mm, according to published research. Particle size also appears to have little bearing on the adsorption of heavy metals from contaminated soils and wastewater, according to research (Murtaza et al., 2022). Furthermore, a major obstacle to the potential application of nanocoal as HM adsorbents is thought to be its low yield during production. Recent research publications have focused on the synthesis of nano-biochar, or nano-BC, for use in agriculture and the environment (Rajput et al., 2022; Alam and Faizan, 2024). When carbonization occurs, 'dissolved' or 'nano-BC,' or micro-sized BC with a size of 1 µm–1 nm, are produced. In terms of elemental composition, polar and aromatic structure, graphitic structure, cation exchange capacity, crystalline form, temperature-dependent dispersibility, pH, pore size, specific surface area, stability, and zeta potential, bulk-BC and nano-BC differ from one another (Ramanayaka et al., 2020). Colloidal and nano-BC exhibit a multitude of properties that enhance their adsorption and immobilisation capabilities (Mahmoud et al., 2022). Recently, the ability to remove harmful substances from water bodies through nano-BC-assisted adsorption has made remediation and "C" sequestration possible (Xia et al., 2022). Furthermore, because of its higher surface-to-volume ratio, high porosity, and surface functionality, all of which are advantageous for immobilising enzymes—nano-BC can function as a nanocatalyst in bioremediation (Naghdi et al., 2018). The ability of nano-BC to remove various pollutants is determined by its chemical and physical properties, which are affected by the feedstock, production process, and temperature during pyrolysis, and additional pre- or post-treatment methods (Xia et al., 2022). Because of these unique properties and applications, nano-BC creates new opportunities for a long-term, reasonably priced, and environmentally friendly method of reducing environmental pollution. As a result, current information on methods for producing and characterizing nano-BC and its use in the control of environmentally dangerous pollutants is provided in this review. Moreover, a thorough evaluation of the potential for pollutant removal assisted by nano-BC is provided for future research. When choosing nano-BC for a wide range of applications, its distinct qualities are crucial. Plant-derived nano-BCs bind organic pollutants and heavy metals more firmly and cooperatively due to their high oxygen surface functionality and large aromatic cluster size. Aluminosilicate, sulphate, and carbonate groups are abundant in nano-BC made from municipal waste, and they facilitate co-precipitation and heavy metal complexation (Song et al., 2019). In a similar vein, the effectiveness of nano-BC as a nano adsorbent and nano catalyst is dependent on porosity as well as the type and degree of functional groups. The graphitic and amorphous character of BC can affect the production, properties, morphological diversity, and wear resistance of nano-BC (Anupama and Khare, 2021). Higher bulk density, carbon content, and extractable cations are obtained from the synthesis of nano-BC using bulk-BC generated at high temperature (Nath et al., 2019). Comparatively speaking, nano-BC derived from coconut fibres has a higher carbon content (90–94%) than nano-BC derived from sewage sludge (4%). According to Wang et al. (2013), nano-BC typically contains less aromatic and carbonized carbon and more ash than macro-BC. The pyrolysis duration and operating temperature have an impact on the created nano-BC's characteristics. According to Zhou et al. (2017), large particle synthesis is the outcome of raising the pyrolysis temperature. Consequently, the nano-BC's solid density rises, leading to an increase in its size. Similarly, longer pyrolysis times result in smaller particles that form denser bulk fractal structures faster than less dense disordered carbon (Nath et al., 2019). At lower temperatures (300-400°C), the surface areas of nano-BC synthesized are smaller (5.6-47.2 m^2g^{-1}), whereas those synthesized at higher temperatures (450-600°C) are larger (342-430 m^2g^{-1}) because of the formation of surface porosity and de-volatilization of biomass (Ramanayaka et al., 2020). The nano-charged BC surface charge is described by the zeta potential, which also maintains the nano-BC colloidal solution's effectiveness (Fig. 3). Higher zeta potential indicates greater dispersion and reduced particle aggregation. Since nano-BC's zeta potential is greater than bulk-BC's (19.4 to 87 mv), it is possible that nano-BC has more dispersion and colloidal stability.

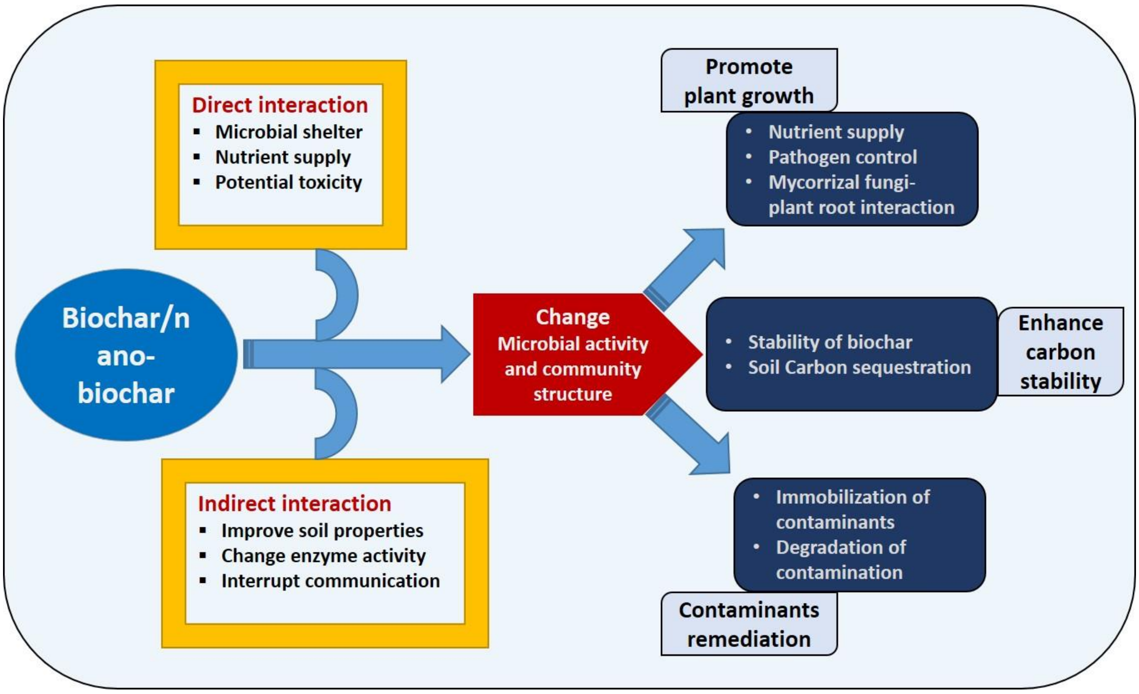

Fig. 3. The proposed mechanism of biochar and nano-biochar

4. The use of nano-biochar in environmental clean up

Throughout the past ten years, BC has been utilised to enhance soil and plant health, clean up contaminated water and soils, reduce greenhouse gas emissions and fertiliser needs, enhance soil remediation, and act as an industrial catalyst. By thermo-chemically converting biomass in an oxygen-constrained environment, BC is created (Das et al., 2021). But because the detrimental effects of BC on human health and the environment are still largely unexplored, two potential risks must be addressed. It is necessary to investigate two aspects: the first is the greater use of hazardous chemicals in the manufacturing process; the second is the poisons released from adsorbents based on biochar. Various toxic substances, such as furans, dioxins, and polycyclic aromatic hydrocarbons (PAHs), are produced during partial or incomplete pyrolysis or pyrolysis under oxidised conditions (Buss et al., 2016). Nevertheless, research indicates that pyrolysis of fully dried biomass can lower

PAH release because the moisture in the biomass partially burns the organic compounds that are created during pyrolysis (Dunnigan etal.,2018). Corrosive pollutants, such as different components utilised in the manufacturing process or acids or alkali used to activate the adsorbent, are what cause environmental degradation. BCs also show phyto- and cytotoxic qualities (Yang et al., 2019). It is not ruled out that during the production and application of BNHs, their nano counterparts may inadvertently be released into the environment, which could result in a potential risk of nanotoxicity (although it is anticipated that the risk will be lower than with just nanoparticles). Acritical aspect of safer, greener, and more environmentally friendly chemistry has been the synthesis of nanoparticles, an essential component of BNHs that are directly used to modify BC. This topic has acquired attention recently. During the chemical production process, the environmentally friendly synthesis of nano adsorbents from different crops and their wastes offers a great substitute for expensive and dangerous chemicals. For an ecosystem to be safe, BNH stability in the face of nanotoxicity is crucial. Long-term research on the physicochemical interactions of BNHs with the environment is therefore essential. Given the potential harm that BC and nano-hybrid research may cause, it is imperative that mitigation strategies be developed as they continue to grow. To create safer BNHs, it is necessary to look into environmental and health hazards. The dust emissions and possibly hazardous characteristics of biochar were documented by Gelardi et al. They claimed that BC's high porosity and low density were what led to its atmospheric dispersion (Gelardi et al., 2019).

Because of their enhanced surface functionalities, increased adsorption capacity, and larger surface area and active sites, BC-based nano-adsorbents (BNHs) have attracted a lot of attention over the last five years. Given these benefits, research has been done on the efficiency of BNHs for improved adsorption qualities, different preparation techniques, and associated adsorption mechanisms (Ahuja et al., 2022). The various surface morphologies, sizes, adsorption capacities, and underlying mechanisms demonstrated the critical roles played by the kind of biomass feedstock, the preparation technique, and the doped metal precursor. Whilst pristine and modified BC is commonly used for wastewater treatment, further research in this field is still needed to close certain gaps in the literature. Convincing enhanced HM adsorption potentials are revealed by BNHs. Unfortunately, their application is still restricted because some unresolved eco-safety issues prevent their use in open, dynamic niches and ecosystems. It's also unclear how the type of raw material will affect the morphology, chemical makeup, and surface functional characteristics of BC. Factors such as the selection of less costly raw materials, optimal production techniques, and distinct production conditions can also significantly impact the characteristics of the resulting BC. In order to optimise adsorption variables and BC feedstock properties, researchers have recently begun to employ artificial intelligence and machine learning (Lakshmi et al., 2021). It is crucial to ascertain the stability of BC, nanoparticles, and their hybrids before developing effective formulas. By modifying BC with nano-metals, metal oxides, or metal hydroxides, its functional qualities should be enhanced. Since the size of the nanoparticles used to modify BC is a critical factor in enhancing the functional qualities of biochar, there may be an impact on the adsorption of heavy metal ions. However, it not only demonstrated efficient removal of heavy metals but also contributed to a decrease in nanotoxicity.

When applied to soil, nano-BC significantly increased microbial activity, including Actinobacteria and Bacteroidetes biomass, and decreased Proteobacteria activity, which was mostly found in contaminated soil (Liu et al., 2021). In another study, the bacterial population's size and the quantity of microbial taxa were greatly enhanced by the application of calcium-based magnetic BC, which also caused a change in the population's composition (Wu et al., 2021). Moreover, except for low alkaline phosphatase activity and Bacteroidetes abundance, soil enzyme activity was elevated by Fe-Mn modified BC (Lin et al., 2019). Firmicutes and Proteobacteria population increased in comparison to control and BC addition alone. Gram-negative bacteria proliferated and gram-positive/gram-negative bacteria modifications were observed when BC aged with Cd. Micro flora and gram-positive bacteria declined. Another study found that the presence of nano-zerovalent iron increased the number of bacterial species known to produce nitrogen, specifically Gemmatimanas and Sphingomonas, and enhanced nitrogen conversion and metabolism (Liu et al., 2021). Along with Fusarium, it also strengthened the composite fungal community structure. Further research revealed that BC modified with sulphur (S) (1%) and S-Fe (1%) (Wu et al., 2019), BC modified with rhamnolipid (2%) (Zhen et al., 2019), BC modified with Fe (2%) (Moradi and Karimi, 2021), and BC modified with iron-zinc oxide composite (3%) (Yang et al., 2021) all resulted in increased microbial activity (bacteria and fungi). Additionally, they found that adding 5% coconut husk to BC enhanced the population of fungi, bacteria, and soil enzymes, including dehydrogenase, urease, and acid phosphatase (Liu et al., 2018). However, invertase did not significantly change. Moreover, discovered that the quantity of soil enzymes rose with the addition of Fe-Mn modified BC (2 percent). As an additional illustration, compared to pristine BC, Fe-Mn-Ce modified BC (2%) increased S-POD, S-UE, S-CAT, and S-AKP/ALP activity (Lin et al., 2019). In particular, the Oxalobacteraceae and Gemmatimonadaceae families had higher abundances due to the altered microbial activities (Zhang et al., 2020). The population of microorganisms, in particular proteobacteria, acidobacteria, gemmatimonadetes, and S-CAT, S-UE, S-POD, and S-AKP/ALP activity, was found to be enhanced by adding Fe-Mn-La modified BC (2 weight percent) to soil (Lin et al., 2021). Furthermore, S-CAT and UE activity were reported to decrease with iron-modified BC (3%)

treatment (Wen et al. 2021), on the other hand, found that Fe-Mn BC (2%) reduced phosphatase activity (85) but had no discernible effect on UE and CAT activities. Extensive research is needed to fully understand how modified BC application, which significantly improves soil quality, affects soil microbes and enzymes. In brief, modified BCs were found to be beneficial for microbial communities, microbial diversity, and microbial co-occurrence networks. These modifications are supposed to enhance the survival behaviour of soil and the function of the soil ecosystem, especially with regard to the cycling of nutrients and carbon, which will eventually improve the structure and quality of the soil.

Table 2. Various techniques for creating nano-biochar and its various applications.

Feedstock	Methodology	Application	Improvement effect	References
Microcrystalline cellulose	Carbonization and in situ precipitation	Phenol removal using photocatalyst Removal of (Cd (II)), glyphosate, oxytetracycline, and Cr (VI)	90 minutes to remove 99.8% of the phenol	Zhang et al. (2020)
Oil palm	FeCl3-pretreated biomass was pyrolysed, carbonised, and then sulfonated at 500°C.	Acid catalyst	Much greater catalytic activity than commercial catalysts for esterification	Jenie et al. (2020)
Wheat	Impregnation	Nanofertilizer	Nitrate, potassium, phosphate, and sodium release slowly	Khan et al. (2021)
Hydrochar made from leftover orange peels	Carbonization by hydrothermal means	Electrochemical sensor	Finding nitrites and sulfites in wastewater	Ferlazzo et al. (2023)
Cynara scolymus leaves	Amberlite cation exchanger (ACE) IR-120 surface modification and mild milling	Nanobiosorbent	The percentages of Pb2+ removed (91.74-59.18%) and methylene blue removed (96.27-99.14%)	Mahmoud et al. (2023)
Cynara scolymus	Altered Nano-BC derived from Cynara scolymus using an amberlite cation exchanger (ACE) IR-120	Adsorption	Methylene blue removal rates range from 96.27% to 99.51%.	Mahmoud et al. (2023)
Mulberry	Nano-BC produced from mulberry waste	Adsorption	A tetracycline removal rate of 103.7%	Yu et al. (2023)

5. Nano-modified biochar enhanced phytoremediation of emerging contaminants

New pollutants harm biodiversity, ecosystems, and human health, necessitating extensive mitigation strategies. Higher trophic levels, including humans, may be impacted by some persistent organic pollutants (POPs) and per- and polyfluoroalkyl substances (PFAS), which have the capacity to biomagnify throughout the food chain. Pollutants that result contaminate soil and water, endangering human health, habitat quality, and ecosystem function (Kumar et al., 2023). Eutrophication and drinking water pollution can be caused by the discharge of wastewater, industrial activities, and agricultural runoff contaminating surface and groundwater with nutrients, organic compounds, heavy metals, and pesticides. Ecological and ecosystem processes allow emerging pollutants to have an indirect impact on the environment. Drugs and personal hygiene items disturb the microbial ecosystems in soil and water, which has an impact on the decomposition, cycling of nutrients, and other functions of the ecosystem. Persistent organic pollutants (POPs) can be transported by microplastics, and environmental pollutants can be concentrated and adsorbent by heavy metals, which increases their bioavailability and toxicity (Mishra et al., 2022). The interdependence of human and natural systems is emphasized by the ecological effects of emerging pollutants, which also highlight the need of implementing sustainable practices, safeguarding the environment, and actively controlling pollution (Souza et al., 2022).

Certain heavy metals and bioaccumulative per- and polyfluoroalkyl substances (PFAS) can become biomagnetic as they move up the food chain, increasing the levels of contamination in apex predators. There may be an impact on species interactions, ecosystem dynamics, biodiversity, and community structure. The ensuing pollutants interfere with energy flow, primary production, nutrient cycling, and ecosystem resilience, endangering ecosystem health and resilience (Azzouz et al., 2023). Because human and environmental systems are interdependent, the ecological effects of new pollutants underscore the need for proactive pollution control, biodiversity preservation, and ecosystem resilience (da Silva et al., 2023). The process of cleaning up soil contamination is difficult and requires careful consideration of the contaminants, the location, and the desired outcomes. Treatments for soil contamination include physical, biological, chemical, and phytoremediation methods (Sánchez-Castro et al., 2023). One often used remediation method involves excavating contaminated soil and transporting it to a treatment or disposal site.

The best way to remove highly contaminated soil and source materials is through excavation. These materials may include heavy metals, petroleum compounds, and industrial wastes. Excavation is costly and disruptive, though, and it needs to be carefully planned and managed to minimize environmental effects and dispose of contaminated soil appropriately. By using chemicals or water to wash contaminated soil, pollutants are eliminated. By eliminating pesticides, heavy metals, and organic compounds from soil particles, soil washing can produce cleaner soil that can be disposed of or reused (Li et al., 2023). On the other hand, soil washing may result in sludge and wastewater contamination that needs to be cleaned up and disposed of, raising the expense and difficulty of the cleanup process. Chemicals are used in chemical remediation to immobilize, break down, or cleanse contaminated soil. The Fenton reagent and ozone injection can be used to convert organic pollutants into less hazardous or non-toxic molecules. Environmental damage is lessened by in situ chemical reduction (ISCR) and zero valent iron (ZVI) treatment, which reduce the mobility and bioavailability of heavy metals and metalloids in soil. For chemical cleanup solutions to be effective over the long term and prevent side effects, strict management and monitoring may be necessary. In biological remediation, pollutants in the soil are broken down, metabolised, or immobilized by plants, fungi, and microbes. According to Fang and Naidu (2023), biostimulator and biological augmentation promote the growth and activity of soil microorganisms, facilitating their breakdown of complex and organic toxins. Two plant-based phytoremediation methods that improve soil quality are phyto-stabilization and phyto-extraction. They both reduce pollutant concentrations. Even though it can take longer and requires site-specific conditions, biological remediation is affordable, safe for the environment, and sustainable. The goals, site conditions, and type of contamination all affect how to treat it. Including chemical treatment and bioremediation, phytoremediation demonstrates different methods of cleaning up soil contamination. In physical, chemical, and biological processes, it offers a summary of methods to lessen the negative effects of soil contaminants on the environment. When pollutants are removed from the environment, a range of physico-chemical factors affect how biogeochemical nano-BC behaves. When nano-BC contains a high concentration of cationic surface groups, its ability to exchange ions with toxic metal ions is improved. Greater aromatic group concentration on the nano-BC surface leads to improved π-π interaction with organic contaminants. According to Filipinas et al. (2021), the zeta potential can be used to determine the sorption of pollutants because of nano-BC's electrokinetic properties, suspension stability, and aggregation capacity. The temperature at which BC is pyrolyzed determines the surface functionality as well. It has been discovered that a lower temperature produces a greater number of surface functional groups, stronger colloidal stability, and a higher zeta potential (Xu et al., 2020). Specifically, valence, hydration area, electronegative structure, and hydrolytic constant are the main factors that determine how well nano-BC removes metal ions. Pb2+ had a sorption rate of nano-BC that was significantly higher than Cd^{2+} under the same treatment conditions (Zhang et al., 2022).

The different sorption rates were attributed by the authors to variations in the properties of the metals (hydrolytic constant, hydration area), as well as their affinity for binding sites. The molecular weight, aromaticity, hydrophobicity, and polarity of the groups that comprise organic pollutants influence their interaction with nano-BC. The sorption of carbonaceous compounds by highly hydrophobic compounds typically proceeds slowly (Choi et al., 2014). Due to its high hydrophobicity, galaxide demonstrates strong sorption to ball-milled nano-BC (Zhang et al., 2019). The pH, root exudates, dissolved organic matter, coexisting pollutants, and soil microbes are additional environmental factors that impact the remediation of pollutants with the help of nano-BC. The surface functional groups of nano-BC undergo protonation in low pH environments, leading to the production of H^+. Owing to sorption site competition between cationic and H^+ pollutants, this reduces the sorption capacity of nano-BC (Mahmoud et al., 2023). According to Wang et al. (2017), p-nitrophenol's sorption on nano-BC was enhanced when lead and p-nitrophenol were present together. According to Mukherjee et al. (2022), soil microbes in soil systems may benefit from the carbon of nano-BC as a food source, which will increase their metabolism and pollutant degradation efficiency. Plants in contaminated soils may also release root exudates, which could alter nano-BC's physical and chemical characteristics and reduce its capacity to absorb pollutants (Li et al., 2019). Because of their large surface area, small pore sizes, and surface functionality, nano- and colloidal BC have much higher pollutant removal efficiency than pure BC (Ramanayaka et al., 2020b). Nevertheless, using natural nano-BC in environmental applications has a number of disadvantages, including limited uptake, accumulation, high agglomeration, low yield and stability, toxic nature, and recovery (Liu et al., 2018).

The stability and suitability of nano-BC for pollutant removal in various environmental matrices is increased when it is functionalized with the right redox functional groups. Still in their early stages, these studies require a broad understanding to be applied in situ. By examining the connections between feedstock types, pyrolytic parameters, oxygenic surface functional groups, and BC structure, potential molecular mechanisms of pollutant removal via electrochemical reaction pathways can be deduced (Amusat et al., 2021). There needs to be development of large-scale nano-BC production techniques in order to achieve high nano-BC yields for a range of applications. Green and biogenic ways of generating nano-BC should be looked into in order to reduce the likelihood of chemical cross-contamination during wastewater treatment. Although nano-BC has outperformed bulk-BC, further investigation is required to compare the performance of nano-BC to that of other nanomaterials and carbon-based nanocomposites (Rajput et al., 2022). Different ecosystems may be at risk of cross-contamination due to nano-BC's greater contaminant adsorption and mobility. Numerous organisms may be more vulnerable to the risks associated with nanoparticles due to the high distribution of nano-BC in natural aquatic systems (Freixa et al., 2018). An analysis of the respiratory system's toxic impact has revealed a reduced risk to human health (Dong et al., 2019).

In terms of broad applicability compared to pure and bulk-BC, nano-BC is a novel and promising substitute for carbon-based nanomaterials (Fig. 4). Nano-BC exhibits remarkable physicochemical properties because surface modification is simple and its surface functionality is high. Typically, centrifugation, carbonization, ball milling, ultrasonication, and hand grinders are used in its production. While ultrasonication is less environmentally friendly and requires more energy, ball milling is a cost-effective, sustainable, and green method. Prior to selecting nano-BC production for commercial synthesis, however, each process must undergo eco-toxicity assessment, life cycle assessment, and process optimization. Nano-BC's comparatively small size provides optimized surface areas, which may make it useful for environmental remediation. Hazardous organic and inorganic pollutants from a range of environmental matrices are significantly decreased when comparing nano-BC to bulk-BC. As a detoxifier, nano-BC is essential for waste management, decreasing soil erosion, and retaining soil nutrients. Microorganisms, biocatalysts, and enzyme immobilisation can all be carried by Nano-BC thanks to its surface properties. Nano-BC also functions as a biosensor for the detection and tracking of hazardous pollutants, making it a good substitute for chemical electrodes in certain situations. Furthermore, microorganisms on nano-BC have a place to live thanks to the large surface area. Consequently, discovering how they interact at the molecular and genetic level may lead to the development of novel applications for hybrid remediation techniques. On the other hand, there is a large amount of information lacking regarding the physicochemical properties and parameters of nano-BC synthesis using various techniques. The process parameter must be optimized for yield and the desired qualities (porosity, surface area, functionality, and binding sites).

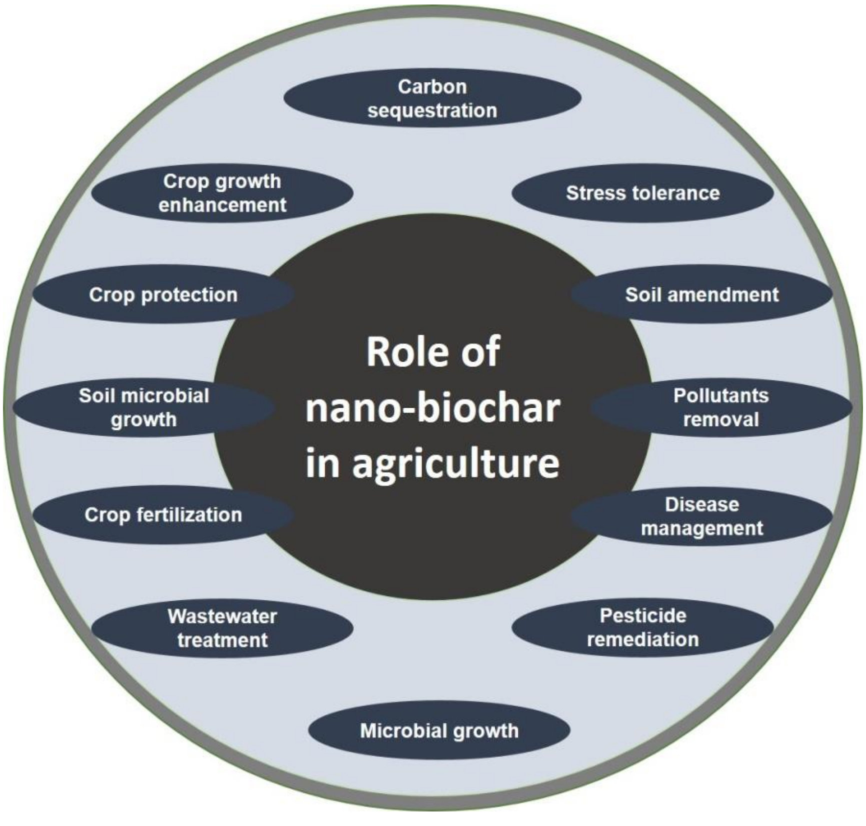

Fig. 4. Role of nano-biochar in agriculture

Numerous uses for nano-modified biochar have been studied recently, including as a catalyst, a carbon black substitute, a carrier for biomolecules, and a means of eliminating different pollutants like agrochemicals and medications (Goswami et al., 2022). Nano-modified biochar has outstanding adsorptive qualities that enable it to absorb a variety of contaminants. Furthermore, biochar that has been modified by nanotechnology may act as a catalyst to promote the breakdown of organic materials (Yang et al., 2017; Faizan et al., 2023). Significant environmental risks affecting ecosystems and public health are posed by heavy metal pollution. Because of its high surface area, remarkable reactivity, and ion exchange capacity, nano-modified biochar has been successfully used to remove heavy metals from systems. These metals include copper, Cd, chromium, arsenic, mercury, and lead (He et al., 2019). Some of these heavy metals are known to have toxic acute and long-term effects on human health, even though they are not necessary. Although certain elements are necessary in trace amounts for human health, others can become dangerous when their concentrations rise above recommended thresholds (Zheng et al., 2021). Consequently, studies on agriculture and the environment need to employ efficient heavy metal removal techniques like stabilization, microbial remediation, and electrochemical approaches. Numerous factors influence how effective nano-modified biochar is, such as dosage, original concentration of heavy metals, additional ion content, and pH. The mechanisms involved in removal processes include adsorption, exchange, co-precipitation, reduction, precipitation, ion and oxidation. Heavy metals have been found to be removed from nanomodified biochar in numerous research investigations. The information obtained to assess the efficiency of nano-modified biochar in removing heavy metals was analysed using several models, including Temkin, Freundlich, Langmuir-Freundlich, Langmuir, and Sips. Furthermore, the rate of heavy metal removal was calculated using models incorporating Elovich, intraparticle diffusion, first order kinetics, and second order kinetics. In a study, the benefits of both biochar and iron oxides were combined in one magnetic biochar, which effectively removed multiple metal (loid) contaminants from soil (Wan et al., 2020). The Fe_3O_4-modified biochar not only removed exchangeable and soluble metal (loid) fractions, but it also directly adsorbed solid fractions.

Zhu et al. (2019) investigated the removal of Cd(II) from aqueous solution using a novel porous biochar activated with K2CO3, grafted with nano-zerovalent iron and nano-α-hydroxy-iron oxide. A pseudo second-order kinetic model proved to be the most effective in explaining the adsorption of Cd(II) to this composite, suggesting that chemisorptions is the primary process involved. Adsorption rates of the composite were remarkably fast for Cd(II). The composites' maximum Cd (II) adsorption capacities were determined to be 26.43 mg/g and 22.37 mg/g, respectively. In contrast to other materials, these composites showed better efficiency in the removal of Cd(II). Ni (II), an illustration of a model pollutant, was eliminated using nano-modified biochar produced by ball milling. According to the results, this nano-modified biochar that was ball-milled was superior to pure biochar at eliminating Ni (II). Additionally, it outperformed a number of commercial sorbents (such as Chlorella sorokiniana, natural bentonite, Na-montmorillonite, and activated carbon) with rapid adsorption rates and exceptional Ni(II) adsorption capacity. More surface area and more acidic functional groups were among the superior chemical and physical properties of ball-milled nano-modified biochar when compared to pure biochar. Therefore, it was more effective than pure biochar at removing impurities.

Many different environmental factors, the stability and effectiveness of heavy metal removal using nano-modified biochar are influenced by various factors, including soil minerals, feedstock, and temperature during pyrolysis, content of nanoparticles, loading of the biochar, additives, etc. The degree of immobilisation of heavy metals in biochar loaded with polymetallic nanoparticles, for instance, varies depending on the nanoparticle to biochar ratio (Zhang et al., 2020). Additionally, there was a strong adsorption of organic pollutants by the nano-modified biochar. Pesticides, antibiotics, chemicals that cause cancer and persistent organic pollutants are among the organic pollutants that can be eliminated by utilising catalyst, reluctant, and adsorbent properties of nano-modified biochar. Because of their potent catalytic, reducing, and adsorptive qualities, these applications have relevance in agricultural and environmental settings. Persistent organic pollutants (POPs) that cause cancer, like polybrominated diphenyl ethers (PBDEs), and polycyclic aromatic hydrocarbons (PAHs), have been found to have the ability to enter the food chain. These may be harmful to human health as well as the environment because of their carcinogenic qualities (Lian et al., 2022). Therefore, using biochar that has been altered by nanotechnology to remove these pollutants from the environment can be a useful tool. In order to eliminate decabromodiphenyl ether (BDE209) and activate persulfate (PS) in soil, For instance, biochar supported nano-zerovalent iron (biochar-nZVI) was produced using a liquid phase reduction technique (Li et al., 2019). The data showed that BDE209 was reduced by 82.06% in 4 hours at a molar ratio of 3:1 PS/biochar-nZVI, pH 3 and 40◦C.

The impact of different sizes of biochar (sub-millimeter, micron, and nanoscale) made from maize straw and rice husk on diethyl phthalate (DEP) adsorption was investigated in this study (Ma et al., 2019). The results showed that biochar has a greater ability to adsorb DEP at smaller particle sizes, with nanoscale biochar having the highest adsorption capacity. Because of its improved pore structure and increased specific surface area, nanoscale biochar showed higher adsorption. This suggests that the primary cause of the DEP adsorption of nanoscale biochar is the filling of pores, as opposed to the H bonding and π-π EDA interactions seen in larger-sized biochar. Furthermore, the ability of nanoscale biochar to adsorb DEP was greatly diminished when the starting pH was lowered from 9 to 3. This was a result of the acidic environment reducing the nanoscale biochar's surface charge and facilitating the particles' easier agglomeration. Worldwide usage of phthalate esters (PAEs) as plasticizers in plastic products raises the possibility of benzene carboxylic group bioaccumulation. Eliminating PAEs from sediment and soil environments is crucial (Xu et al., 2021). As compared to biochar treatments, FM-biochar treatments produced better results, indicating that FM-biochar is a useful technique for lowering the bioavailability of PAEs in wheat grains. Pine-derived biochar's ability to absorb specific organic micro pollutants (OMPs) may be enhanced by the addition of various alkali and alkaline earth metals (AAEMs), such as Na, K, Ca, and Mg (Bentley et al., 2022). The rate of OMP adsorption was higher than that of untreated biochar and nearly equal to that of commercial activated carbon at pH 11, which showed the biggest improvement. The biochar's micropores' surface area was significantly expanded by this treatment. This demonstrates how some pretreatments can improve the performance of biochar in water treatment applications. As an adsorbent, it was found that using nano-modified biochar could remove organic pollutants and heavy metals. Knowing how pollutants interact with nano-modified biochar is necessary to link enhancement to the engineering design of these materials (Ambaye et al., 2021). The pollutant removal efficiency is greatly impacted by variables like pH and material dosage. More research is required to determine whether organic compounds and heavy metals can be removed from contaminated environments using nano-modified biochar (Table 3).

Table 3. Role of nano-biochar on soil health.

S.No.	Aspect	Effect of nano-biochar on soil health	References
1	Soil structure	Improves soil porosity, leading to better aeration, root penetration, and water infiltration	Li et al. (2019)
2	Soil fertility	Enhances nutrient retention (N, P, K) and availability, thus improving overall soil fertility and plant growth	Zhang et al. (2017)
3	Water retention	Increases water holding capacity, reducing water stress on plants, especially in drought conditions	Ahmad et al. (2014; El Refaey et al., 2022)
4	Soil pH	Can help buffer soil pH, making it more suitable for plant growth in acidic or alkaline soils	Zhou et al. (2018)
5	Microbial activity	Promotes beneficial microbial populations, improving soil health and biological diversity	Zhang et al. (2017)
6	Soil organic carbon	Enhances soil carbon content, aiding in long-term carbon sequestration and improving soil quality	Lehmann et al. (2011)
7	Heavy metal immobilization	Nano-biochar can adsorb and immobilize heavy metals, reducing their bioavailability and preventing toxicity	Tan et al. (2015)
8	Soil erosion control	By improving soil structure and water retention, nano-biochar helps reduce soil erosion, particularly in sandy soils	Lehmann et al. (2011)
9	Soil-microelement availability	Increases the availability of trace elements (e.g., iron, manganese) essential for plant growth	Li et al. (2019)
10	Soil amendment	Enhances the effectiveness of other soil amendments and fertilizers, reducing the need for chemical inputs	Ahmad et al. (2014)

6. Conclusions

In this review we have thoroughly examined the function of BC and nano-modified BC in promoting soil health for sustainable farming methods. We also discussed the use of nano-modified BC in environmental cleanup and phytoremediation. Mechanistic strategies for removing soil toxicity using nano-modified BC are revealed in this review. To fully understand the mechanism of action, more research is required in the future.

Declarations

Ethics approval and consent to participate

Consent for publication: The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

Availability of data and material: Not applicable.

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