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# Contaminate Remediation with Biochar and Nanobiochar Focusing on Food Waste Biochar: A Review

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POLLUTION creates world-wide environmental and human health concerns. Biochar (BC) and nanobiochar (NBC) may be used in the production of smart materials that may revolutionize remediation research. BC's ability to adsorb pollutants makes it an attractive cost-effective soil treatment option. To improve BC properties and composition, it is activated and modified by regulating pyrolysis or with the addition of various compounds such as metal nanoparticles (NPs), magnetite, and nano zero-valent iron. In comparison to BC, NBC has a superior capacity to adsorb contaminants and nutrients, making it a suitable waste management option. Food waste represents one-third of the food produced globally and is a promising potential source of BC. In this review, some trends are identified and assessed, such as production of BC by biomass pyrolysis. Applications in soil and water remediation and their mechanisms are also discussed. The production of BC and NBC from low-cost materials, compared to expensive traditional remediation, provides inexpensive, meaningful treatment options for a range of contaminants in soil and water. We concluded that BC and NBC have high potential to remove contaminants in soil and water due to their distinctive characteristics.

**Keywords:** Soil remediation; Water remediation; Nanoparticles; Biochar; Nanobiochar; Food Waste utilization. Abbreviations: BC; biochar; NBC: nanobiochar; AC: activated carbon; NMs: nanomaterials; FW: food waste; GHGs: greenhouse gases; HMs: heavy metals; NPs: nanoparticles; nZVI: nano zero valent iron; SSA: specific surface area; CEC: cation exchange capacity; NMBC: nano-metallic biochar; FGs: functional groups.

## 1. Introduction

The contamination of soil is a major environmental problem. Soil contamination is frequently caused by the excessive release of herbicides, pesticides, antibiotics, and fertilizers into the environment and can pose serious health hazards to humans (Brevik et al., 2020). Policymakers and scientists have searched for new strategies to deal with pollution in soil and water (Zama et al., 2018). Vitrification, mechanical separation, pyrometallurgical separation, electrokinetics, phytoremediation, biochemical reactions, and washing and flushing are some of the methods that may be used to remediate contaminated soils (Chakraborty et al., 2019). Adsorption is used more than any other method of remediation since it is efficient, cost-effective, and ecofriendly (Pandey et al., 2021).

There are a number of disadvantages to the above-mentioned methods, such as the release of toxic gases during vitrification, need for pretreatment

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during pyrometallurgical separation, toxic byproducts generation during pyrometallurgical procedures, and the inability to take up large amounts of contamination with phytoremediation. These approaches may also result in contaminant-rich wastes. All these downsides mean that new techniques are needed (Chakraborty et al., 2019). This has motivated some researchers to look into the use of widely available biochar (BC) resources as a potential way to mitigate soil and water pollution (Zama et al., 2018, Elbasiouny et al., 2021b, Elbasiouny et al., 2023). Remediation procedures are increasingly focused on environmentally acceptable in-situ treatments, such as bioremediation and phyto-stabilization, which are frequently supported by the inclusion of soil amendments (Zeng et al., 2015).

Biochar has garnered more interest as a material to use during smart remediation than other adsorbent materials including activated carbon (AC) owing to its low production cost, distinctive features, and carbon negativity (Ramanayaka et al. 2020). Biochar is highly cost-effective, simple to manufacture, has long-term stability in soil and possible recalcitrance, is easily available, and represents a simple way to dispose of organic waste (Ogbonnaya et al., 2014)., Biochar as an organic amendment is a relatively stable (i.e., not easily biodegradable) (Khalil, et al., 2023). Biochar is a carbon-rich charcoal (containing up to 80% C) made by slow biomass pyrolysis (or thermochemical organic material breakdown at high temperatures between 300° - 700 or 800°C) in the presence of no or little oxygen. Feedstock may include plant or animal products (Bassouny and Abbas, 2019, Phares et al., 2020; Elbasiouny et al., 2021a, Elbehiry et al., 2022, Jiang et al., 2023). The properties of BC are determined by the composition of the feedstock, pyrolysis temperature, and heating duration (Ogbonnaya et al., 2014; Mohan et al., 2018). The properties of BC include a negative surface charge and huge surface area, which allows remediation of contaminated soils. Biochar use in soil enhances the availability of nutrients, increases microbial activities, soil organic matter, and water holding capacity, and improves crop production. Biochar is able to adsorb large amounts of pollutants and make them inaccessible to organisms (Koul et al., 2018). BC has been shown to be capable of immobilizing metal(loid)s in the environment, thereby reducing their bioaccumulation (Zand et al., 2020).

Carbon nanomaterials (NMs) have recently emerged as important tools in fields such as energy, agriculture, and the environment, especially in phytoremediation of pollutants such as organic chemicals and heavy metals (HMs). Improved nanostructures, such as nanobiochar (NBC), have brought possible new answers to a variety of contemporary challenges. The BC and nano-biotechnology may result in the production of NBC and BC nanocomposites which might change remediation approaches in a variety of disciplines (Chausali et al., 2021). However, only a few studies have evaluated designed NBC for remediation. While these studies used a variety of NBCs, they were limited in regard~~s~~ to the pollutants they covered, including phenanthrene, carbamazepine, As, and Ni (Ramanayaka et al. 2020). NBC is a nanosized BC with improved physical and chemical characteristics (Chausali et al., 2021). Its application to a range of contamination issues is promising; however, research on NBC is in the early stages (Anupaman et al. 2021). NBC offers several benefits including improved bioremediation of organic pollutants, wastewater treatment, and many other applications. Because of its economic effectiveness, sustainability, and environmentally friendly nature, it may become the ideal alternative to traditional techniques. In comparison to BC, NBC has superior capacity to adsorb contaminants and nutrients, as well as mobility in soil, giving it advantages as a waste management option (Chausali et al., 2021).

Global population expansion and the corresponding demand for food has resulted in approximately 1.3 - 1.6 billion tons of food waste (FW) annually (Xing et al., 2021; Li et al., 2022). This is 30 – 45 % of municipal solid waste (MSW) and approximately 35% of consumed food (Li et al., 2022; Zhao et al., 2022). Several economic challenges are created by FW, including serious resources waste and environmental pollution. Thus, the ability to sustainably use FW is desirable (Qing et al., 2022). Food waste is high in organic components and can supply a lot of energy for anaerobic microbe development. Large amounts of greenhouse gases (GHGs) can be discharged into the atmosphere if FW are not treated properly. For example, open dumping of FW leads to generation of GHGs (Xing et al., 2021). Because it has high water content and is protein-rich, FW readily rots under ambient environmental conditions. This causes odor and leachate issues, making handling difficult (Lee et al., 2019). Thus, food waste is one of society's most significant and ecologically challenging waste products. The nonhomogeneous structure of post-consumer FW limits chemical or biological conversions into useful materials, which makes it difficult to economically transform post-consumer FW into useful materials (Kane et al., 2022).

This review highlights the use of BC and NBC to remediate contaminates from soil and water. This includes a discussion of BC and NBC production, stock materials, the characteristics of various types of BC and NBC, and the mechanisms by which they function.

## 2. Biochar and its production

The terms "biochar" and "bio-charcoal" were created from the word "biomass" and "charcoal." (Kalinke et al., 2021). The existence of 50% initial carbon in BC makes it very promising not only in fixing the carbon existing in plant biomass through carbon sequestration, but also in eliminating wastes from the environment (Sajjad et al., 2020). The process factors involved in BC production from biomass are critical. Recent investigations on biomass pyrolysis have shown that the generation of BC is dependent on parameters such as the type of biomass feedstock, particle size, pyrolysis temperature (above 250 °C), carrier gas flow rate, application rate of BC, and other factors like reactor design. The process parameters of biomass pyrolysis must be tuned to get the highest BC production (Wang et al., 2018; Trinh et al., 2019; Promraksaet al., 2020). The use of sorbents such as BC and AC for on-site treatment of contaminated soil is considered to hold significant potential in terms of cost-effectiveness and enhanced remediation. Because BC has a lower density than AC, it can hold more particles per unit mass. As a result, when the same treatment rate and particle size are used, the kinetics of pollutants mass transfer from soil to BC particles may be improved as compared to AC (Shakya et al. 2020). The BC's ability to adsorb both organic and inorganic pollutants also make it an attractive soil treatment option (Shakya et al., 2020).

Just about any organic source can serve as a feedstock for BC. Corn cobs, coconut shells, coffee hulls, crushed coffee powder, and even livestock dung have been employed as biomass sources for BC production (Trinh et al., 2019), among others. Tan et al. (2021) prepared BC using peeled waste ramie stalk with the following steps: 1) cleaning the raw material with distilled (DI) water; 2) dehydrating for 72 h in a 60 °C oven; 3) grinding into a <300 µm powder; 4) drying in a ceramic crucible at 60 ℃ for 12 h; 5) placing in a vacuum tube furnace; 6) pyrolyzing in anoxic conditions at 300, 400, 500, 600, and 700 °C for 2 h; 7) treating with 1 mol/L HCl solution for 12 h; 8) washing with DI until the effluent reached a neutral pH; 9) the produced BC was handled with HCl again and dried at 60 °C for 12 hour; 10) this was kept in a desiccator until the BC was crushed with a mortar and pestle to get a powder; 11) the powder was then sieved into four size fractions.

Biochar can be modified to increase the quality of raw BC so it can remove larger volumes of pollutants (Gupta et al., 2022). It is activated and modified by regulating pyrolysis conditions or by employing various modifiers, including acid–base activators, exo-enzymes, and metal nanoparticles (NPs). When BC is exposed to air, the carboxyl groups content may rise. By combining metal ions with the surface of the BC, it is possible to modify its surface charge and adsorption performance (Zhou et al., 2020). In this case it can be chemically functionalized by elements such as maghemite ($Fe_2O_3$, $\gamma$-$Fe_2O_3$), magnetized iron oxide ($Fe_3O_4$), or nano zero valent iron (nZVI) to enhance the BCs original features (Trinh et al., 2019). The production of efficient chemically modified BC is generally more expensive than non-modified BC and may result in secondary contamination (Trinh et al., 2021).

## 2. The production of nanobiochar and its composites

The NBC is a BC material that is synthesized at nanoscale size, which improves its physiochemical and surface characteristics. It provides several advantages relative to BC, including improved bioremediation of pollutants among many others. Owing to its economic effectiveness, sustainability, and environmentally friendly nature, it may become the ideal alternative to traditional procedures for pollutants remediation (Chausali et al., 2021, Ma et al., 2023). The differences between BC and NBC are in their structural variations and physicochemical properties. NBC can show varying pH, specific surface area (SSA), pore characteristics, elemental compositions, cation exchange capacity (CEC), aromatic/polar nature, and zeta potential (Rajput et al., 2022).

Many methods can be used to produce NBC from BC such as: 1) disintegration through ball milling or sonication, 2) carbonization, or 3) centrifugation and grinding (Anupaman et al., 2021). The ball milling process is widely used to modify BC because of its environment-friendly and cost-effectiveness properties, in which materials incorporating BCs ground into nanoparticles when combined with metal oxides, is frequently utilized for this purpose (Anupaman et al., 2021, Dey and Ahmaruzzaman, 2023). Ball milling can boost the SSA, most likely via exposing pores and the O-containing functional groups (FGs) (e.g., lactone, carboxyl, and hydroxyl) (Zeghioud et al., 2022). Ball milling utilizes the impact of spherical particles to grind materials. Double-disc milling can also be used to produce NBC but has greater operational cost and is therefore less utilized. Vibration disc milling may be preferable to the ball mill approach because it gives a larger number of NBC with better size constancy and morphology (Chausali et al., 2021). Chilling oven-dried BC to -80 ˚C and disc milling in ethanol has also been used for NBC synthesis (Rajput et al., 2022).

Chemical modification of NBC can be performed to achieve given remediation goals (Rajput et al., 2022). Modifying the BC with nanosized materials can be done using traditional methods of producing nanomaterials (Chausali et al., 2021). Chemical impregnation, oxidization, and coating of functional NPs are accomplished to produce nanocomposites with capabilities that are improved relative to BC. Metal-oxide-NBC composites (based on Ca-, Mn-, Mg-, Zn-, and Al-oxide NPs) have been used to improve the adsorption of contaminants. Despite their advantages, combining NBC with metal-oxides fills the micropores, reducing the surface area (Anupaman et al., 2021). This is a disadvantage.

Graphitic nanosheets are produced through direct NBC manufacture using flash heat (Chausali et al., 2021). BC particles are physically dispersed using an ultrasonic vibrator, and subsequent sonication employed to form nanoparticles. Zhou et al. (2017) modified BC by combining it with nanosized manganese oxides ($NMnO_2$) to produce nano-metallic biochar (NMBC). The $NMnO_2$ can easily flocculate in aqueous solutions, making it hard to get a consistent mixing of BC and $NMnO_2$ in water, and maintaining disaggregation is essential to create NMBC. The properties of the NMBC produced by Zhou et al. (2017) were modified from those of BC and $NMO_2$, where C and H was noticeably reduced after modification and O, Mn, and porous structures were increased in the NMBC as compared to BC. In addition, the NMBCs pore volume was three times less than the BC and 1.5 times less than $NMnO_2$. Finally, adsorption capacity for Cu was increased in MNBC as compared to BC (Zhou et al., 2017). Zhang et al. (2021) used the following steps to obtain nano-β-$FeOOH/Fe_3O_4$/BC composites: 1) crushing and grinding of the initial material; 2) sieving with a 100-mesh sieve; 3) placing in a corundum ark and heating to 600 °C in a nitrogen atmosphere tube furnace; 4) cooling for 2 hours to bring to room temperature, resulting in BC powder; 5) dispersing one g of BC in 100 mL of DI water; 6) dissolving one g of sodium dodecyl benzene sulfonate, 1.8 g of $FeCl_3$, and 0.35 g of $FeCl_2$ in DI water (50 mL) and mixing; 7) sonicating the compound for 5 min; 8) stirring gently at 80 °C for 1 h; 9) stabilizing the mixture at pH 9 with 10 mL of aqueous ammonia solution; 10) cooling naturally for 2 h; 11) gathering the resulting powder with magnetic separation; 12) repeated washing with DI water and absolute ethanol; and 13) drying for one night 50 °C under vacuum. This procedure produced 1.5 g of nano-β-$FeOOH/Fe_3O_4$/BC composites.

## 4. Biochar from food waste

Food waste refers to any residues or waste generated during processing by the food and beverage industry and kitchen waste or swill created by residents, restaurants, canteens, and dining facilities, among others. The main components of FW (starch and complex carbohydrates, cellulose, proteins, lipids, enzymes, organic acids, and nutraceuticals), consist of many distinctive FGs, including -COOH, -OH, and C=C, and can be polymerized to form polymer materials (Li et al., 2022; O'Connor et al., 2021; Zhou et al., 2021). Food waste may prompt pathogenic microorganism reproduction that can produce toxic substance including but not limited to mycotoxins (Bian et al., 2022; Li et al., 2022). The composition of FW varies by region and is highly heterogeneous (Li et al., 2022).

Future work needs to create innovative technologies that use FW in industrial and environmental applications while mitigating any harmful effects. Thus, BC and/or NBC production from food wastes may not only greatly minimize the buildup of waste in landfills, but is also a promising ecofriendly way to enhance applications such as soil remediation, sequestration, and wastewater treatment (Xing et al., 2021; Kane et al., 2022; Zhao et al., 2022; Zhang et al., 2022) Pyrolysis of biowaste, such as FW, is becoming increasingly profitable (Maroušek et a, 2019).

Although anaerobic digestion of FW has been generally recognized as an encouraging disposal approach, this process ultimately generates a lot of FW digestate as solid residue. Due to its lignocellulosic substances, FW digestate has been regarded as a potential feedstock for BC. FW digestate often has fewer HMs and higher mineral content, for example P and Ca salts, than other biowastes. The FW digestate-derived BC generally has high adsorption capacity due to its high SSA and mineral composition (Wang et al., 2022a). Xu et al. (2021) reported that kitchen waste, which consists mainly of FW and is an important component of MSW, is useful as feedstock for BC production. BC production is a viable option to reduce FW volume and the anerobic production of products such as $H_2$, CO, and $CH_4$ gases (Xu et al., 2021).

Huang et al. (2020) and Liu et al. (2021) examined food waste digestate pyrolysis and found the derived BC was devoid of HMs with high C, CaO, and hydroxyapatite content due to the characteristics of the feedstock. The resulting BC had high As retention capacity in aqueous media. Elkhalifa et al. (2019) found that the contents of the FW, as well as the pyrolysis process conditions, influenced the yield and composition of the BCs generated and concluded additional study on converting food waste to BC, particularly mixed food blends, is required. Food waste may be an outstanding raw material for BC generation as compared to sewage sludge (Hong et al., 2020).

Modified engineering techniques can maximize BC adsorption capability when utilized for environmental remediation (Hong et al., 2020). When iron oxides (goethite, hematite and magnetite) come into contact with water, they have high sorption capacities. Iron oxy-hydroxide modified FW BC has increased Se adsorption capacity and can slow its migration into the environment. Pyrolysis increases the pH of FW BC relative to the feed stock due to degradation of the primarily acidic FGs during pyrolysis. Food waste BC surface area and pore volume were generally large, indicating that the $NH_4$ adsorption capacity was superior. Xue et al. (2019) reported that C content was also high, ranging from 63 to 75 %. This was primarily due to the higher cellulose and lignose contents of the raw FW materials that transformed into higher fixed C through pyrolysis. Ash content ranged from 28 to 53%, indicating that the raw materials contained elevated mineral concentrations.

The dairy industry, which includes milk, milk powder, cheese, butter, and yoghurt, is a global mainstay. Because of increasing milk products consumption, worldwide output is predicted to expand at a rate of 1.8 percent per year, achieving 177 million tons of product by the mid-2020s (Phares et al., 2020). Dairy processing and manufacturing techniques create a significant quantity of solid and liquid waste (Abeysinghe et al., 2022). The dairy sector is among the world's top wastewater generators and produces large amounts of sludge (Shi et al., 2021). The average waste output per liter of pasteurized milk is 2.5 - 3.0 L. Approximately 4-11 million tons of dairy waste is emitted into the environment annually, which has a significant impact on biodiversity. The quantity of sludge accumulated is predicted to be between 5% and 25% of total treated effluent (Abeysinghe et al., 2022). Treatment of dairy wastewater is projected to produce up to 20 kg sludge per $m^3$ of milk processed (Hu et al., 2021). Pyrolysis is an alternate approach to recover valuable materials from dairy sludge (DS) while also reducing the health and environmental risks related to disposal (Hu et al., 2021; Shi et al., 2021; Abeysinghe et al., 2022). Furthermore, DS pyrolysis is feasible since it may be carried out on a small scale at decentralized sites. Biomass is transformed into valuable byproducts such as syngas, bio-oil, and BC during sludge pyrolysis. Milk sludge BC is a desirable byproduct because it contains significant levels of potential inorganic components for water treatment (Abeysinghe et al., 2022).

## 5. The characteristics of biochar and nanobiochar composites

The critical factors for effective BC utilization include its physical and chemical characteristics, cost and biomass type used during pyrolysis to produce BC, various methods of producing and recovering BC (pyrolysis technology), pyrolysis conditions , and BC parameters such as SSA, bulk density, FGs, pH, and particle size (El-Ramady et al., 2020, Gupta et al., 2022). Zeghioud et al. (2022) reported that adsorption efficiency on BC is primarily determined by electrostatic interactions, partitioning, hydrophobic interactions, pore fillings, H bond formation, and $\pi$-$\pi$ interaction between BC and contaminants. Because several methods and carbon precursors are used to produce BC, no comprehensive research has been undertaken to identify the kinds of BC that have the highest effectiveness in diverse electrochemical applications (Gupta et al., 2022). In addition, Jiang et al reported that in terms of environmental parameters that affect the NBC, pH, coexisting ions, dissolved organic matter, organisms, and root exudates are the key ones that have a significant impact on NBC's effectiveness in environmental remediation. The biogeochemical behavior of NBC for environmental remediation is largely governed by the pH of the environment. The functional groups in NBC are easily protonated to create H+ at low pH levels, which causes H+ and cation pollutants to compete for cation adsorption sites and decreases NBC's adsorption capability. Additionally, electrostatic attraction on positively charged surfaces may prevent contaminants from being absorbed.

BC can have a variety of polar or nonpolar surface FGs that act in the adsorption of inorganic ions such as metals, nitrates, and phosphates as well as organic compounds. Furthermore, by varying the feedstock and pyrolysis conditions, the properties of the BC can be altered, particularly pore structure and surface area (da Silva Medeiros et al., 2021). Numerous studies on the use of BC for contaminant adsorption have been conducted (Ramanayaka et al., 2020, da Silva Medeiros et al., 2021; Yang et a, 2021).

Various plant-residue produced BCs have been shown to have high removal efficiency of soil pollutants, including HMs (Ding et al., 2019). For example, BC has been shown to decrease IHg concentrations in soil leachates and IHg bioavailability in sediment. Biochar removed MeHg from solution and decreased its bioavailability in Indian mustard and rice plants (Noreen et al., 2021).
Biochar's sorption capabilities have been investigated to remediate numerous organic and inorganic pollutants from aqueous media, including emerging contaminants (EC) such as pharmaceutical and personal care items, steroid hormones, pesticides, and HMs. Human activities such as discharge of wastewater, inappropriate disposal of wastes, and direct use of agro-chemicals in agricultural fields release these ECs into the natural surroundings (Ramanayaka et al. 2020). Mahmoud et al. (Mahmoud et al., 2021) reported BCs to treat water is gaining popularity because of BCs unique properties. Using *Cynara scolymus* (artichoke) leave wastes (CSL) as feedstock, a sustainable and renewable low-cost NBC was created with the microwave sorption method. The produced NM was evaluated for its ability to adsorb two HMs (Cd and Sm). Findings showed CSL-NBC is a sustainable, cost-effective NM that can help address water pollution concerns. Additional studies on the use of BC and NBC for soil or water remediation are summarized in Tables 1 and 2.

Surface functional carbon groups are important in the immobilization of hazardous metals. For example, aluminum adsorption on BC was mostly due to complex formation of aluminum with hydroxyl and carboxyl groups on the BC surface in a study that generated BC from rice straw and cattle dung (Pourret et al., 2028). Furthermore, the sorption of copper and lead was dependent on the quantity of O-containing carboxyl, hydroxyl, and phenolic FGs on the BC surface in a study where BC was generated at 200 to 800 °C from cotton seeds (Pourret et al., 2028). Elbehiry et al. (2020) added that complication between the O-containing FGs in BC and the metals created conditions where dissolved organic carbon might be released in the soil, possibly lowering mobility and bioavailability of the studied metals. This can transform labile Pb into the organically bound fraction (i.e., decrease mobility), decreasing plant absorption. BCs that have more pores and distinct binding sites have better ability to immobilize HMs (Zheng et al., 2015; He et al, 2019; Elbehiry et al., 2020). Although the formation of dissolved black C may improve trace metals and metalloids mobility, the changes made to BC surface and structural chemistry typically enhances trace metals and metalloids immobility (Zhong et al., 2020). When compared to unmodified BC, engineered/modified BC had greater short term trace metals and metalloids immobilization capability. However, no significant long term differences were found in the metal adsorption capacity of modified and unmodified BCs (Zhong et al., 2020). Although BC has been explored as a viable, fiscally-effective adsorbent, the adsorbed macro-molecules are simply sequestered, they are not destroyed or necessarily removed from the natural system. End-of-life disposal/regeneration of saturated adsorbents, as well as the possibility of secondary contamination, limits their use in the field. When compared to activated C or nano-C materials, BC's surface area, pore sizes, and volume, along with hydrophobicity, all influence the ability of BC to remediate contamination (Wan et al., 2020).

**Table 1. Biochar and nanobiochar applications for soil remediation from different contaminants.**

| Biochar feedstock | Concentration | Nano or bulk form | Pollutant(s) | Outcome | Reference |
|---|---|---|---|---|---|
| Poplar wood bio-carbon | BC with hydroxyapatite/ calcium silicate hydrate at different ratios | Bulk | Cd, Cu, Pb and Zn | Mixing soil and BC at a ratio of 6: 4 provided the best immobilization of contaminants and decreased their plant uptake, especially Cd | Chen et al. (2020) |
| Rice straw | BC was applied to the soil at a rate of 20g kg$^{-1}$ soil | Bulk | Cr, Cu, Fe, Mn, Ni, Pb, and Zn | Significant decrease in mobilization and bioavailability of heavy metals in landfill soils | Elbehiry et al. (2020) |
| Chicken manure-derived BC (CM) and green waste-derived biochar (GW) | 1, 5 and 15% of CM or GW. | Bulk | Cd, Cu and Pb | BC application was effective in immobilization of metals, decreased the bioavailability and phytotoxicity of heavy metals. | Park et al. (2011) |
| Hardwood-derived biochar | 20 g kg$^{-1}$ | Bulk | Heavy metals | BC decreased the amount of heavy metals that leached through soils | Sorrenti et al. (2016) |
| BC from cow manure and oak BC | 2% | Bulk | Cd, K, P, S, and Zn | BC immobilized nutrients and metals in soil water systems | Van Poucke et al. (2020) |
| BCs generated from pine sawdust at 300 and 550 °C | 5% = 70 t ha$^{-1}$ | Bulk | As and Pb | BC 300 slightly reduced the mobility and phytoavailability of As and Pb, BC 550 increased the mobility of As but reduced the phytoavailability of Pb | Beiyuan et al. (2017) |
| Wheat straw BC | 5% | Bulk | Co | Biochar is an efficient sorbent of Co$^{2+}$, decreasing mobility and availability | Medyńska-Juraszek et al. (2020) |
| Rice straw BC | 1% and 2% | Bulk | Ni | Biochar showed a maximum Ni sorption capacity of 13348 mg kg$^{-1}$ and biochar's capacity to remove Ni was demonstrated | Ali et al. (2020) |
| Rice straw derived biochar | 6% w/w | Bulk | Pb and Cu | Reduced the uptake of Pb and Cu in shoot and root by 46 and 36% and 77 and 58%, respectively | Rizwan et al. (2021) |
| Tea waste derived BC | 500 mg kg$^{-1}$ | Bulk and nano | Cd | Addition of tea waste BC increased the phytoremediation of Cd | Gong et al. (2021) |
| Rice straw BC | 1.0% | Bulk and nano | Cd | BC and NBC increased rice growth and photosynthesis, decreased soil bioavailable Cd extracted by AB-DTPA and its accumulation in rice. | Rizwan et al. (2019) |
| Wood-derived BC | 2% | Bulk and nano | Cd | Maximum sorption of Cd reached 328.9 and 1062.4 mg kg$^{-1}$, 58.6% and 412.2% more than control soil. | Ramezanzadeh et al. (2021) |
| BC produced from woodchips Japanese cedar, Japanese cypress, moso bamboo, rice husk, poultry manure, and wastewater sludge | 3% | Bulk | Cd | Cd concentrations in the above-ground portion of plants were significantly reduced by all BCs compared to unamended soil | Kameyama et al. 2021 |
| BC derived from cattle manures and rice husks | 2 - 8 mg | Bulk | Al, Cd & Pb | - BC derived from cattle manures and rice straws pyrolyzed at 400 °C were the most effective Al adsorbents<br>- Pb adsorption by commercial BC ranged from 3.1 to 32.8 mg g$^{-1}$. Pb adsorption by BC produced at 400 °C was significantly higher than those pyrolyzed at 100 °C | Han et al. (2017) |

**Table 2. Biochar and nano-biochar applications for water remediation of different contaminants.**

| Biochar feedstock | Concentration | Nano/or bulk form | Contaminant(s) | Outcome | Reference |
|---|---|---|---|---|---|
| Food waste | 0.1 g $L^{-1}$ | Bulk (bio-modified with bacterial film) | Cd and Pb | Increased adsorption of Cd and Pb | Xing et al. (2021) |
| Dairy waste sludge | 10-50 g $L^{-1}$ | | P | P removal of 85-98% | Ashekuzzaman et al. (2017) |
| Agro-food waste (12 kinds of biochar) | 0.25 g 25 $ml^{-1}$ | Bulk | Fluoxetine | Maximum adsorption capacity was 6.41 mg $g^{-1}$ for the Eucalyptus biochar | Fernandes et al. (2019) |
| Food waste digestate | 50 mg $L^{-1}$ and 0.1 g $L^{-1}$ | Bulk | As(III) | Maximum adsorption capacity was 69.03 mg $g^{-1}$ As | Liu et al. (2022) |
| Food waste | 5 g $L^{-1}$ | Bulk | Phenol | Adsorption capacity increased especially with increasing pyrolysis temperature of BC | Lee et al. (2019) |
| Food waste | 2 g $L^{-1}$ of BC in 10 mg $L^{-1}$ metformin solution. | Bulk | Metformin | BC improved the adsorption capacity | Neha et al. (2022) |
| Woody | 0.5 g $L^{-1}$ | Nano | CdII, CrVI, glyphosate, and oxytetracycline | The BC showed a high removal capacity for these contaminants | Ramanayaka et al. (2020) |
| Food waste | 0.2, 0.4, 0.6, 0.8, and 1.0 g $L^{-1}$. | Bulk | Cu | Significant enhancement of Cu coagulation as BC dose increased | Yang et al. (2021) |
| Anaerobically digested sludge | 0.5 g $L^{-1}$ in batch adsorption experiment in aqueous solution | Bulk | Pb(II) and Cd(II). | Cd(II) adsorption on BC was severely constrained, uptake of Pb(II) was insignificantly affected. | Ni et al. (2019) |
| Sesame straw | 0.1 g | Bulk | Pb, Cd, Cr, Cu and Zn | The BC is an inexpensive and abundant C source, reduces the cost associated with heavy metals adsorption. | Park et al. (2016) |
| Food waste | 0.1 g $L^{-1}$ | Bulk | Ammonia | BC removed up to 92.67% ammonia | Xue et al. (2019) |
| Dairy manure | 0.25 g | Bulk | Pb and atrazine | BC showed appreciable adsorption capability for Pb and atrazine | Cao et al. (2010) |
| Glucose-derived spherical biochar at different temperature from 300 to 1200 | 0.2 g added to 50 mL of aqueous adsorbate solution | Spherical BC | Pb and Cu | The maximum Langmuir adsorption capacities (Q max) of biochar at 900 °C: $Pb^{2+}$ (1.052 mmol $g^{-1}$) > $Cu^{2+}$ (0.825 mmol $g^{-1}$) | Tran et al. (2018) |
| Woody biochar | 0.5 g $L^{-1}$ Adsorption and isotherm experiments | Nano | Cr(VI) and Cd(II) | High removal capacities for Cr(VI) and Cd(II) from aqueous media. | Ramanayaka et al. (2020) |
| Sugarcane bagasse | 0.1 g to 50 mL Cr(VI) solution | Nano | Cr | Cr removal efficiency of BC ranged from 55.7 to 95.4% | Gan et al. (2015) |
| Corn stalk + Nano-$MnO_2$ | 0.5 g added to 500 mL of a 127.1 mg $L^{-1}$ Cu(II) solution | Nano | Cu | The maximum adsorption capacity of NMBCs for Cu(II) was 142.02 mg $g^{-1}$, while BC only was 26.88 mg $g^{-1}$ and nano-$MnO_2$ only was 93.91 mg $g^{-1}$. | Zhou et al. (2017) |
| Rape straw | 0.05 g of BC added to 40 mL of sorbate solution (20 mg L1 Cd(II)) | Modified BC (Alkaline treated BC (BC-NaOH), $KMnO_4$ impregnation of BC (BC-MnOx) and $FeCl_3$ magnetic treated BC (BC-FeOx)) | Cd | BC-MnOx provided the highest Langmuir sorption capacity of Cd (81.10 mg $g^{-1}$) | Li et al. (2017) |
| Wetland reed | 0.05 g BC was added to 25 mL of sorbate solution (50 mg $L^{-1}$ $Cr^{6+}$) | Nano | $Cr^{6+}$ | Removal efficiency 82.2% of $Cr^{+6}$ | Zhu et al. (2018) |
| Rice straw and palm trees | 1 g of BC added to 100 ml of ammonium phosphate ($NH_4H_2PO$) | Nano | $NH_4$ $H_2PO_4^-$ | 20 to 30% of $NH_4^+$ and about 10% of $H_2PO_4$ - were desorbed | Helal et al. (2019) |

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|---|---|---|---|---|---|
| Pine wood | 5ng $mL^{-1}$ | Nano | Carbamazepine (CBZ) | The BC removed up to 95% of CBZ | Naghdi et al. (2019) |
| Bagasse, bamboo, and hickory chips | 10 mg/L | BC | Culfamethoxazole (SMX) and sulfapyridine (SPY) | Best removal efficiency was 83.3% for SMX and 89.6% for SPY. Maximum adsorption capacities of SMX and SPY were 100.3 mg/g and 57.9 mg/g. | Huang et al. (2020) |
| Agroforestry waste | 1.0 g | Micro and nano | $Pb^{2+}$ | Micro/nano-structured BC was promising for Pb remediation. Used as electrode materials for $Pb^{2+}$ | Li et al. (2017a) |
| Orange peel | 6.25 g in 1 L solution | Magnetic and nano magnetic BC | Naphthalene, p-nitrotoluene and phosphate | The highest sorption capability for phosphate was 7.5 to 99.4% and organic pollutants was 6.33 to 100% | Chen et al. (2011) |

Nano-sized metal oxide particles incorporated into the BC matrix create biochar nanocomposites. The porous BC offers a stable platform for a fine distribution of nanomaterials. NMs inclusion improves sorption characteristics, thermal stability, and ion exchange capacity. Some nanocomposites have a magnetic characteristic that allows the applied BC to be separated from the effluent. Multiple variables influence the characteristics of these composites, including biomass type, pyrolysis temperatures, and the nanomaterial embedded into the BC (Pandey et al., 2021).

Classification of BC nanocomposites, based on nanomaterial added to the BC, provides three sub-categories: 1) magnetic BC composites; 2) nano-metal oxide/hydroxides BC composites; and 3) functional nanoparticles (NPs) coated BC composites. Three distinct techniques are used to create BC nanocomposites: biomass pre-pyrolysis treatment, post-pyrolysis treatment, and targeted element enrichment (Pandey et al., 2021).

## 6. Sorption mechanisms of biochar and nano-biochar

The BC's physical structure and chemical composition play a key role in immobilizing foreign objects. Favorable functional groups such as (C = O, C–C, C = C, C–O–C, –C–O– , R-COOH, –C–O–H, C–H, and –$C_6H_5$ ) on BC's surface improve the immobilization of foreign substances, resulting in a reduction in the amount of foreign substances that are leached during the reaction process. Higher support material stability is essential for immobilization since it preserves the foreign substances for subsequent usage without losing activity. The increased load of foreign elements on the support matrix is caused by the bigger SSA of BC (Wang et al., 2022b, Lin et al., 2023, Mahmoud et al., 2023). Additionally, BC's bigger pores make it possible for foreign substances to access the support's interior structure, boosting its mass transfer and diffusion process and raising the immobilization yield. It is significant that different BCs have specific mechanisms for supporting different components. For instance, some chemicals can be produced and added to the BC matrix. By altering the amounts of signal molecules, BC may also control microbial cell communication. The possibility of using BC as a support material for the immobilization of enzymes can also be examined because of its substantial SSA, developed pore structure, and abundance. The BC's physical makeup, chemical composition, and biocompatibility all have a significant impact on how it interacts with enzymes throughout the immobilization process (Lin et al., 2023). Ball milling enhances surface functional groups through the increase of SSA, which in turn improves adsorption capacity. The ability of the soil to absorb cations or anion has also increased as a result of the application of BC to the soil. The sorption and transit of coupled ions get more complicated as BC particles get smaller because of known and unknown interactions between the ions, the BC particles, and the medium's surface. The extensive use of modified BC for soil and water decontamination has shown good results. Compared to bigger particles, NBC has a considerable potential to sorb pollutants from solutions (Ramezanzadeh et al., 2023). Once BC has been applied to the soil, short- and long-term physical and biochemical characteristics, such as normal aging and synthetic oxidation, and interactions with soil properties, such as dissolved organic matter and elemental ions, all influence the adsorption mechanism of pollutants and their final transmission, fate, and bioavailability in soil (Zhao et al., 2019) (Figure 1).

The existence of large quantities of O-containing FGs is reported to increase the CEC of BC at low pyrolysis temperature. This is probably because surface area becomes greater as the temperature at which the BC was created increases, resulting in additional BC surface sorption sites (Joshi et al. 2019). BC has the ability to adsorb a wide range of organic pollutants due to its aromatic rings, micro-pores, CEC, and exterior heterogeneity. BC has great potential to improve sorption and lower the bioavailability of a range of organic contaminants in soil including phenol, phenanthrene, and polycyclic aromatic hydrocarbons. Aromatic sorption to BC, for instance, was most probably triggered by p-electron interaction and the pore-filling process, multilayer adsorption, surface coverage, condensing in capillary pores, and absorption into the polymeric matrix (Xu et al., 2015). Studies about using BC to sequester organic molecules in soil have received a lot of attention. Because BC has a 10–1000 times greater affinity to organic substances than natural organic matter, a tiny quantity of BC added to soil can effectively dominate net organic compound adsorption. For example, adding just 0.05–0.1 percent pine needle BC to the soil significantly increased the adsorption of polycyclic aromatic hydrocarbons (Zhao et al., 2019).

Aromatics adsorption to wood-based BC is additionally aided by π electron interactions and the pore-filling process, multilayer adsorption, surface coverage, condensing in capillary pores, and adsorbing into the polymeric matrix (Ogbonnaya et al., 2014). Although certain aromatics could be adsorbed into the outside surface of BC, others might be caught in interior nano-pores, restricting transfer to microorganisms. This suggests the sorption capacity of BC minimizes the fast bioaccessible proportion of pollutants, hence offsetting possible risk of accumulation in biota (Ogbonnaya et al., 2014). Kalinke et al. (2021) reported BC has negative or positive charge sites, allowing charged substances to be easily electrostatically attracted. The ion exchanges between metallic ions and FGs or mineral oxides connected to BC is another process. This can facilitate anion or cation co-precipitating or complexing with the BC FGs, resulting in metal complexes. The interaction process can be influenced by the polarity of BC. For example, BC generated at low temperature (300 to 400 °C) is low aromatic and high polarity. In this manner, polar species of BC can interact with polar pollutant molecules via H bonding with BC oxygenated groups (i.e. carboxyl and hydroxyl). Nonpolar species of BCs, however, engage more effectively with BC hydrophobic surfaces because of π–π type interactions with aromatic rings. Moreover, as with inorganic species interaction, physical adsorptions can happen between the BC surface and organic molecules (Kalinke et al., 2021). Figure 2 shows BC and NBC properties that determine the remediation mechanisms that take place in the presence of contaminants.

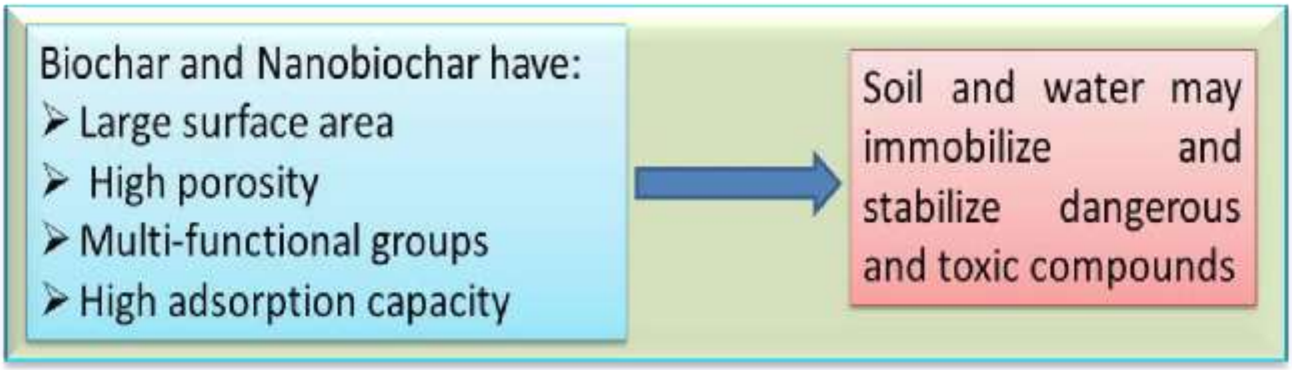

**Fig. 1. Biochar and nanobiochar properties facilitate immobilizing and stabilizing pollutants in soil and water.**

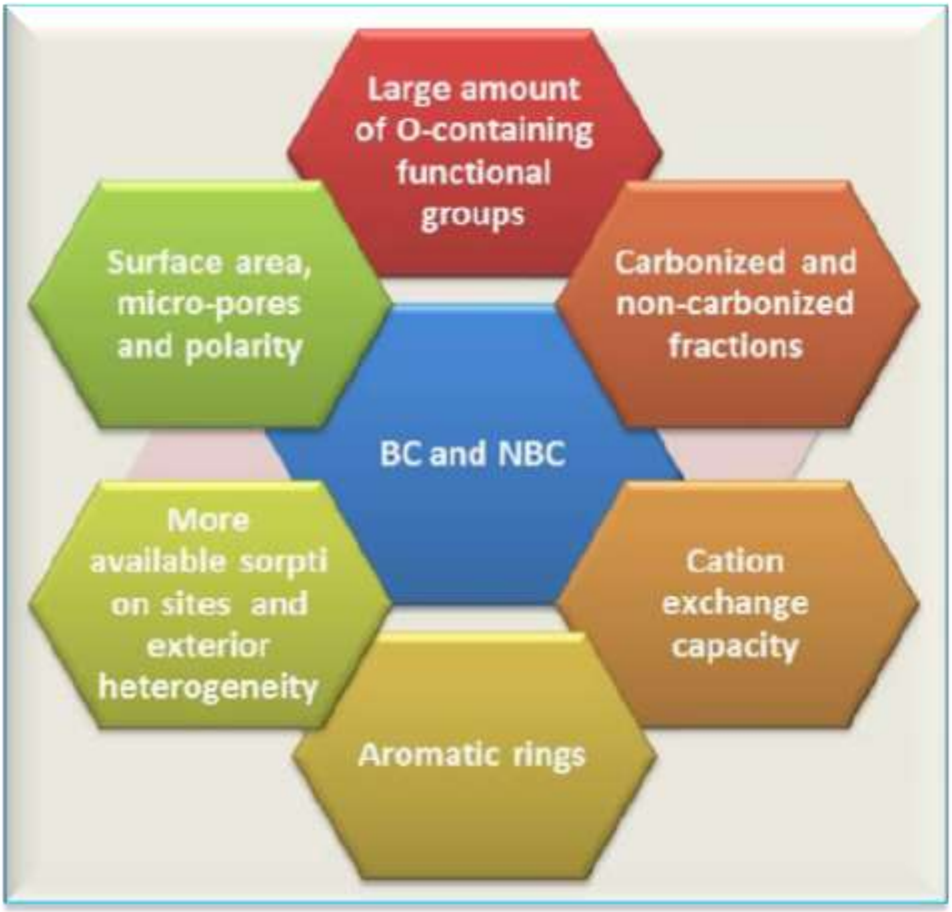

**Fig. 2. Biochar and nanobiochar properties that determine the remediation mechanisms that take place when biochar or nanobiochar are in the presence of contaminants.**

### 7. Insights from this Review

While the existing literature has highlighted many potential applications of food waste generated biochar and nanobiochar, there are also many outstanding questions in this area that need to be addressed. Discovering answers to these questions will be critical to our ability to use FW-based BC and nanobiochar to solve environmental and agronomic challenges.

First, there is a need for studies on the properties of biochar and nanobiochar produced from a variety of food waste sources and under a variety of production methods (pyrolysis temperatures, milling techniques to transform biochar to nanobiochar, creation of composites, etc.). One of the current challenges regarding the use of biochar and nanobiochar is the wide range of properties it can have depending on feed stock and production. Being able to accurately predict biochar and nanobiochar properties that will result from given feed stock properties and production methods will improve the overall economics of biochar and nanobiochar use.

There is also need for additional work on the environmental and agronomic applications of biochar and nanobiochar generated from food waste. Many potential uses have been documented, largely in laboratory or green-house scale studies. Work in these areas needs to be expanded to the field scale, which is where actual use in environmental and agronomic applications will occur. This is important as the results of work done in controlled laboratory environments does not always translate well to the field, where the number of variables increase tremendously.

Most of the work on biochar and nanobiochar has focused on their potential positive contributions to addressing environmental and agronomic issues. However, there is a need to completely evaluate the environmental implications of converting food waste to biochar and nanobiochar from a holistic perspective. Producing biochar requires high temperatures (often 300-800 °C), which requires a high input of energy. We need to consider the environmental impacts of aspects such as required energy production and waste products generated by the pyrolysis process and compare that to the benefits of items such as decreased disposal needs for food waste, environmental remediation benefits, and the value of agronomic applications. Life cycle analysis can be used to determine if the generation of biochar and nanobiochar from food waste is a net positive or negative for the environment.

The economics of converting food waste to biochar and nanobiochar also need to be holistically investigated, from the direct costs to the possibility of building markets for biochar and nanobiochar products. The cost of biochar and nanobiochar utilization also needs to be evaluated relative to the cost of other options that might be used for the same applications. Following up on earlier points in this section, if food waste-based biochar and nanobiochar are in fact scientifically better than other products at addressing various environmental and/or agronomic issues, research needs to focus on what is needed to make these biochar and nanobiochar products economically competitive with other available options.

The handling of food waste is a major challenge, and from the perspective of creating biochar and nanobiochar, the heterogeneity of food waste can be a problem. We need investigations into the point in the chain where biochar or nanobiochar should be generated. Should this happen at the food processing plant, where food waste is or could be more homogeneous than what comes out of a commercial kitchen, for example? Or is there another point in the food-processing system where location or volume of FW would make biochar and nanobiochar production more viable for some reason? In many respects this gets back to the economic issues that need to be addressed, but it is worthy of being expressly mentioned.

## 8. Conclusions

Biochar and nanobiochar have great potential for use to remove a range of pollutants from soil and water. This is because of their high surface area, cation exchange capacity, presence of aromatic groups, carbon content, low H/C ratio, and high ash content. Using different types of biochar and NBC, including that generated from FW, for remediation of contaminated soil and water offers potential opportunities that may be able to replace many less effective, more expensive, and non-sustainable materials that have been used in the past. However, there is still much we need to understand about the stability and mechanism of sorbed contaminates in soil and water on biochar and nanobiochar over increasing periods of time and in a range of environmental conditions and to address a number of economic and production issues regarding biochar and nanobiochar.

## Conflict of interest

The authors declare there is no conflict of interest.

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