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Review Article

A Review on Magnetic Nanobiochar with Their Use in Environmental Remediation and High-Value Applications

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Magnetic nanobiochar (MNBC) is a sort of nanobiochar that has been enhanced with magnetic qualities. MNBC is made from a variety of feedstocks, including wood chips, agricultural waste, municipal sludge, animal manure, and other organic waste. These feedstocks are pyrolyzed at various temperatures to produce biochar, which is then mixed with magnetic precursors to create MNBC. Crystallinity, high porosity, specific surface area, and great catalytic activity are a few of the dynamic properties of MNBC. The major purpose of this review paper is to characterize MNBC, using the various biochar synthesis methods and how bulk biochar is converted into MNBC with their high-value applications discussed here.

1. Introduction

Magnetic nanoparticles (MNPs) are materials that reciprocate to an applied magnetic field. These MNPs are highly stable and have controlled shapes and narrow sizes [1]. Due to their dynamic properties, the MNPs are used in the magnetic separation of some specific molecules in bioscience, diagnostic of different diseases, drug delivery, and nanosensor to identify the particular molecular target [2–4]. By observing the popularity of MNPs, researchers works on low-cost bulk biochar to convert it into magnetic nanobiochar (MNBC) by adding magnetic properties. Biochar already has drawn the attention of researchers due to its multifunctional properties and after adding magnetic properties to them, it becomes like icing on the cake. Increasing the consciousness toward the environment and producing organic food among the people trigger the production of biochar. According to the global biochar market, it was mentioned that 1.3 billion USD biochar is produced in 2018, and Triton Market Research analysis concludes that the compound annual growth rate of biochar will increase the revenue by 13.40% from 2022 to 2028 in the global biochar market.

When we look back at history, particularly in ancient times, biochar has been used as a fertilizer in agriculture by the Amazonians and in that period, it was known as "*terra preta de indio*" [2]. As time went on, people have discovered new things on biochar and they recognize the real values of biochar how they are helping in sustainability and recovery from the disaster of environment. After that now, people are developing the engineered biochar by modifying their properties. For example, by reducing the size of biochar, it is converted into the nanobiochar and when magnetic property is added into it, then it becomes MNBC. MNBC and nanobiochar are the best examples of modified engineered biochar. As we all know that biochar is a charcoal-like substance that is synthesized by pyrolyzing biomasses at different temperatures [2]. Pyrolysis is the process of creating biochar by thermally degrading biodegradable material without oxygen, and the temperature at which biomass is converted into biochar is known as pyrolyzing temperature [3]. Generally, three types of pyrolysis methods (slow, fast, and flash) for biochar production are existing. Slow pyrolysis involves heating biomass gradually (0.6–6.0°C/min) at about 500°C for a prolonged residence duration of 5–30 min [4]. Fast pyrolysis is quite different from slow pyrolysis in temperature and residence time. Here biomass is pyrolyzed at a high temperature (500–1,000°C) in a short time period (1–5 s) [5].

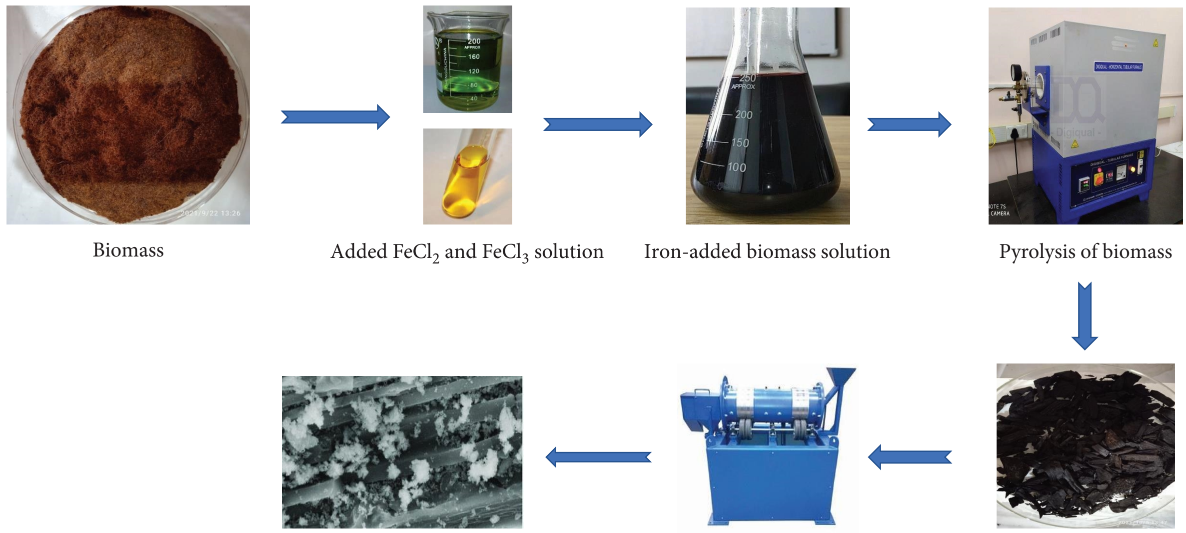

Figure 1: Diagrammatic representation of magnetic nanobiochar production.

Flash pyrolysis is a kind of fast pyrolysis that is more advanced. The requisite temperature for this pyrolysis is between 900 and 1,200°C [6]. Pyrolyzing temperature is important for the formation of biochar because if the temperature is low, the production of biochar will be high, and if the temperature is high, the production of biochar will be low [7]. Choosing feedstock in the production of biochar is also an important part and it can be anything like plant material, a waste product, animal debris, municipality sludge, etc. These feedstocks are pyrolyzed by different types of advanced technologies (ball milling, sonication, ultrasonic vibrator, double-disk milling, flash heating, hydrothermal reaction, coprecipitation, reductive codeposition, and so on) for the production of MNBC. In the current scenario, researchers give importance to the production of MNBC because it has various applications in different fields. Mainly, it is used as an amendment for remediation of environmental contaminants like heavy metals, polycyclic aromatic hydrocarbons (PAHs), pharmaceutical and personal care products (PPCPs), steroids, and different types of hormones. MNBC not only helps in the reduction of pollution but also saves the waste biomass by recycling [8]. In addition, nanobiochar helps in plant growth improvement, soil fertility enhancements, and nutrient retention [7]. Since biochar is a carbon sequester, so it is mostly used in agricultural farms as a fertilizer, which makes the soil contaminants free and holds the moisture of soil due to its water-holding capacity [9]. So, it enhances the growth and productivity of the plants.

Only a few studies in the literature have reported the synthesis of MNBC and its applications in agriculture, biomedical research, and high-value applications [10]. We are trying to detail all of the techniques utilized to create biochar, as well as how they were transformed into MNBC, along with their characterizations, qualities, and applications in the aforementioned industry in order to address this vacuum in the literature. Furthermore, the future prospects and limitations are reviewed.

2. Synthesis of Magnetic Nanobiochar

The biomass is first transformed into biochar using the pyrolyzing process, and subsequently into MNBC using the magnetic precursor impregnation method. Here, we provide a brief description of some of the methods that can be used to create biochar, such as slow pyrolysis, quick pyrolysis, gasification, flash carbonization, and torrefaction. The synthesis of MNBC is diagrammatically elaborated in Figure 1.

2.1. Slow Pyrolysis. The process where biomass is converted into biochar at mild heating temperature (<100°C) in absence of oxygen is known as slow pyrolysis [11]. A straightforward and efficient method for producing biochar on a small-scale farm is slow pyrolysis [12]. The slow pyrolysis process is completed in three stages, i.e., drying, thermal decomposition, and cooling. The biomass is dried at temperatures over 100°C during the drying process. At extremely low temperatures, cellulose, hemicellulose, and lignin are converted into charcoal after drying, and volatile substances (CO, CO_2, CH_4, H_2, and tars) are evaporated. According to a prior study, low-temperature biochar has a small surface area, but this can be enhanced by lengthening the residence duration [9].

2.2. Fast Pyrolysis. Fast pyrolysis is a little upgraded technology from slow pyrolysis. Here, biomass is converted into biochar at the highest temperature (500–1,000°C) in limited amount of oxygen. Fast pyrolysis is generally used to pyrolyze wood biomass and converts biomass into biochar so quickly that it passes the peak temperature before decomposition [13]. The specific surface area of biochar produced by fast pyrolysis is large. For example, Wang et al. investigated the properties of rice husk biochar produced through fast pyrolysis and discovered that rice husk biochar has a significant specific surface area, implying that it has more functional groups on its surface. Biochar is created through fast pyrolysis, which increases specific surface area and carboxyl groups while somehow improving soil nutrients [14].

2.3. Gasification. Gasification is a waste-to-energy method that converts biomass into synthesis gas and produces charcoal as a byproduct. Biomass is often burned inefficiently in combustion boilers during gasification. Biochar produced by gasification is primarily used for carbon sequestration in soils and soil quality enhancement [15]. In the removal of azo dyes from textile water at low pH, biochar produced from wood residue is utilized as an adsorbent. Furthermore, biochar produced by this method has the highest adsorption capability [16].

2.4. Flash Carbonization. Flash carbonization is a very fast thermolysis technique with a high combustion rate. This flash carbonization technique is primarily used to generate gases and bio-oil from biomass pyrolysis at 900 and 1,200°C. Because this process can only convert a small amount of biomass into biochar, flash carbonization is rarely used to produce biochar [17].

2.5. Torrefaction. Torrefaction, also known as dry mild pyrolysis, is a carbonization process that converts biomass into charcoal at temperatures ranging from 200 to 300°C. It is a type of anaerobic pyrolysis that is quite gentle [13]. Torrefaction's primary product is biochar, with gaseous and liquid products as byproducts [18]. Torrefaction can be used to manufacture high-quality biofuel from biomass, which can be used to replace coal in the production of electricity and heat. Microwave torrefaction of *Leucaena* produces biochar that is more thermodynamically viable and produces more fuel than bituminous coal [19].

Besides the abovementioned pyrolysis method, there are some mechanical and biochemical techniques that are used to produce MNBC that have been elaborated in the next sections.

2.6. Ball Milling. Biochar is ground into nanoparticles or nanobiochar using a mechanical technique called ball milling. A ball milling is a cylindrical hollow shell that revolves around its axis. Steel, stainless steel, ceramic, or rubber might be used for the shell's axis. The cylindrical shell's interior surface is typically coated with a surface roughness material such as manganese steel or rubber. The size of the nanopowder is governed by the speed at which the balls rotate in this process, and it can range from 2 to 20 nm. It is a cheap and eco-friendly way to make nanobiochar [20]. Ball milling can be done in a variety of ways, including double-disk milling vibration disk milling, and so on. The double-disk milling process is typically not utilized to produce nanobiochar, since it is a large-scale operation, but vibrating disk milling is a proven method for manufacturing nanobiochar of consistent size and shape [21]. For the manufacturing of nanobiochar, ball milling is an eco-friendly green technique. Because of its low cost and environment-friendly characteristics, it is commonly used in global business. In general, there are two types of ball milling processes: dry and wet. Nanobiochar made by ball milling has a greater specific surface area than the pristine biochar, allowing it to absorb more contaminants [22].

2.7. Hydrothermal Reaction. Hydrothermal synthesis refers to the fabrication of compounds in a closed and warmed environment above normal pressure and temperature. The term "hydrothermal" originates in 19th-century geoscience and refers to a temperature and water pressure regime [23]. This is another approach to generate nanobiochar that converts the biochar into nanobiochar from high-temperature aqueous solutions under high pressure [24]. Hydrothermal autoclave reactors are used to perform high-temperature and high-pressure hydrothermal synthetic operations. These reactors are often divided into two types: polytetrafluoroethylene or teflon-lined hydrothermal autoclave reactors and polyphenylene polymer-lined autoclave reactors. A hydrothermal reactor usually has two sections where the outer side is made up of a stainless steel jacket and the inner side is made up of a teflon-lined chamber [25]. The hydrothermal synthesis of MNBC from biosolids and municipal sludge is used as an adsorbent for antibiotic removal and enzyme immobilization [26]. In the hydrothermal reaction method, the samples were first mixed with ultrapure water and then stirred for 30 min at 600 rpm before hydrothermal carbonization and the samples were transferred to a teflon-sealed autoclave or a hydrothermal reactor is maintained temperature. After naturally cooling, the samples were washed several times with ethanol and distilled water, and then the synthesized magnetic biochar was dried for 24 hr in a vacuum freeze dryer at –40°C after being collected by suction filtration [27]. The MNBC derived through hydrothermal carbonization has an advanced chemical and morphological structures, for example, it has a high surface area, electrical conductivity, magnetic saturation, and coercivity [28].

2.8. Sonication. Ultrasonic sound waves are employed in this technique to agitate nanoparticles in the polymer matrix, and an ultrasonic bath/probe is used to deliver sound energy into a liquid containing particles. This procedure is called ultrasonic because ultrasonic frequencies are utilized to agitate the material [29]. The generator, transducer, and probe are the three main components of a sonicator. The generator turns incoming electrical energy into an electrical signal that drives the transducer. An electrical signal is converted into vibration via a transducer, which is amplified and employed in the probe tip to form a hollow in the sample [30].

2.9. Pretreatment of Biomass with Iron. Iron is a common metal that makes about 5% of the earth's crust. Because iron metal, its salts, and oxides are inexpensive, they are readily available [31]. Iron can be used to remove impurities or pollutants from the environment since it is magnetic. The biomass is treated with iron to reduce cellulose crystallinity, increase biomass porosity, and smoothen the lignocellulosic materials lignin cover that encircles the cellulose [32]. When iron salt solutions like ferric chloride, ferrous chloride, sulfate, or nitrate are employed in pretreatment, the hydrogen bonds in cellulose are broken, softening the ridge crystalline structure of biomass and increasing the total specific surface area of lignocellulosic material [33]. A catalyst-based iron is used to create nanostructured graphitic carbon. Fe_3C nanoparticles synthesized via the thermal breakdown of an iron

Table 1: List of feedstocks used for the preparation of magnetic biochar.

Feedstock used for synthesis of MNBC	Pyrolyzing temperature (°C)	Application	References
Oil palm empty fruit bunches	500–600	Act as an acid catalyst in a catalyzed esterification reaction	[48]
Bamboo	450	Remove sulfamethoxazole and sulfapyridine from aquatic environment	[49]
Hickory chips	600	Remove pharmaceuticals from environment	[49]
Wheat straw	700	Remove pharmaceutical and heavy metals	[50]
Sugarcane bagasse	60	Remove heavy metals from aqueous media	[51]
Cornstalk	650	Remove phosphorus from wastewater	[40]
Groundnut waste	600	Remove heavy metals from wastewater	[41]
Pine bark	950	Remove heavy metals from aqueous solution	[52]
Eucalyptus globule bark waste	750	Pb(II) remove from aqueous medium	[53]
Cynodon dactylon	700	Remove copper and lead ions	[54]
Rice residue	550	Remove As(III) and As(V) from aqueous solution	[55]
Jatropha seed	180	Use as reinforcement filler for high-strength composite	[56]
Corn straw	350	Use in soil remediation and carbon fixation	[57]
Coffee grounds	250	Remove tetracycline from the aquatic environment	[39]
Coconut shell	500	Use to remove carbamazepine from wastewater	[43]
Waste sludge	750	Remove tetracycline from wastewater	[58]
Date palm waste	600	Remove chlortetracycline from wastewater	[59]
Astragalus residue	700	Adsorb ciprofloxacin from aqueous solution	[60]
Vinasse	800	Adsorb pefloxacin and ciprofloxacin from wastewater	[61]
Grapefruit	450	Remove ciprofloxacin from water	[62]
Banana peels	600	Help in degradation of organic contaminants	[63]

precursor and carbothermal reduction were previously described in a study [34].

2.10. Coprecipitation Method. Coprecipitation is a well-known technique for generating MNPs. Two distinct salts with different solubilities are employed as reagents in this approach. Some of these reagents are water-soluble, while others are not, and the reaction takes place between two distinct solubility salts, followed by precipitation [35]. According to Wang et al., magnetic biochar made with coprecipitation, technology is more successful at eliminating heavy metals from aquatic environments than other technologies [36]. Santhosh et al. employed the coprecipitation approach to make magnetic biochar from sludge and woodchips, which were pyrolyzed at 450–700°C [37, 38]. Ferric chloride and ferrous chloride were mixed with deionized water in a 250 ml conical flask, and the mixer was stirred in magnetic stirring after the addition of the biochar sample. The NaOH solution was then poured into the mixer to maintain the pH, and the magnetic stirring was agitated for some time. Magnetic biochar was accumulated over time by an externally applied magnetic field and rinsed numerous times in ethanol and water drying overnight in a vacuum oven at 450°C [38].

Furthermore, the reductive codeposition method is mentioned in previous studies for the synthesis of MNBC. The reductive codeposition method is also a separation technique that produces iron–carbon microelectrolysis materials [39]. Iron–carbon microelectrolysis materials are created by reducing iron when it reacts with activated carbon in the existence of reducing agents such as sodium borohydride ($NaBH_4$) or potassium borohydride (KBH_4). This method produces magnetic biochar with high contaminant removal capabilities [40, 41].

2.11. Feedstock Used. Biochar is rich in carbon and very minutely grained residue is obtained through pyrolysis. A wide variety of biomass is used as raw material in the manufacture of biochar, for example, farm residue, forest wood, unwanted weeds, etc. A variety of agricultural waste, such as corn, wheat straw, rice straw [42] and husk, potato, soybean, sugarcane bagasse [43], grape, orange, peanut, and rape seeds, are used for the synthesis of biochar [44]. Some unwanted weeds, which trouble the agricultural crops, viz., *Miscanthus* spp., *Panicum virgatum*, *Arundo* spp., *Phragmites australis*, *Typha* spp., *Eichhornia crassipes*, can also be used for the synthesis of biochar [45]. The aromatic plants like *Aquilaria malaccensis*, *Acorus calamus*, and *Cymbopogon spreng* are used to extract the essential oil but after extraction of oil, the waste product can be used for the production of biochar. Apart from these animal manures [46], bamboo biomass [47] is also used for the synthesis of MNBC by the hydrothermal reactor method. Some examples of feedstocks are listed in Table 1.

3. Characterization of Magnetic Biochar

In terms of characterization, MNBC is not the same as macro-biochar. The physicochemical properties of macro- and microbiochar differ in terms of particle size, surface area, zeta potential, ion exchange capacity, and pH [64]. Various techniques are used to characterize the MNBC, including X-ray diffractometer (XRD), Brunauer–Emmett–Teller (BET), scanning electron microscopy (SEM) and transmission electron microscope (TEM) (used to determine the size and shape of the MNBC), Fourier transform infrared (FTIR) spectroscopy (investigate functional groups), NH_3-temperature programed-desorption (NH_3-TPD), and vibrating sample magnetometer (VSM) [40]. The most commonly used instruments in the identification of MNBC are discussed later.

3.1. X-Ray Diffractometer. XRD is a nondestructive technique used for the identification of crystalline materials. It offers thorough details of the crystallographic information, the crystallographic structure, chemical makeup, and physical characteristics of materials [65]. When an X-ray passes through a crystal particle, then it can be diffracted at any angle of that crystal in a three-dimensional manner. Therefore, depending on this principle when monochromatic light passes through a sample, then the refractive X-ray is detected by a detector. It is a convenient physical method through which one can determine the electron distribution of materials along with their bond length and bond angle [66].

3.2. Transmission Electron Microscope (TEM). TEM is a highly magnifying electron microscope that consists of an electron beam to focus the image of a specimen [67]. TEM can focus on a very ultrathin species (<100 nm thick) too for the formation of an image. In TEM, an electron gun emits electrons that pass through the vacuum tube of the microscope and produce a very fine beam of electrons. This tiny beam enters the sample, travels through it, and hits a fluorescent screen at the base of the microscope, creating a view of the sample with its individual components shown in various shades according to their density [68].

3.3. Scanning Electron Microscope (SEM). SEM is used to determine the crystallinity, structural composition, and morphology of a given sample [69]. SEMs use high-energy electron beams to produce a range of signals at the surface of solid specimens [70]. In order to enlarge an image in a SEM, the sample must be solid and fit into the microscope; it also cannot detect very light elements such as H, He, Li, and so on. SEM is nearly identical to TEM, but SEM creates images by detecting reflected electrons and analyzing the surface of a sample, whereas TEM creates images by detecting transmitted electrons and analyzing the internal structure of a sample [71].

3.4. Fourier-Transform Infrared Spectroscopy (FTIR). The FTIR spectroscopy is commonly used to analyze solid, liquid, or gas in absorption or transmission mode. It is used to identify unknown materials, as well as to detect quality, consistency, and mixture components [72]. In FTIR, there is a source that generates infrared radiation and it passes to an interferometer. In an interferometer, the infrared radiation is hit with the beam splitter and it splits into two separate beams with different intensities. Out of these two one goes to the stationary mirror and another goes to the moving mirror where both the beam reflects and return to the beam splitter again. Since each beam has two distinct strengths, some of the varied intensities pass through the sample and are consumed by it, while other portions pass through and are later recorded by a detector, creating a spectrum that is known as an interferogram [73].

3.5. Brunauer–Emmett–Teller (BET). BET is employed to measure the physical structure, i.e., the surfa ce area of MNBC [42]. The BET theory is a development of Langmuir's idea, which was first developed by Brunauer, Emmett, and Teller [74]. The most used technique for calculating the surface area of nanoparticles is this one. The BET method was created to directly quantify the specific surface area and pore diameters of MNBC under high vacuum. In a conventional BET analysis, the amount of N_2 gas absorbed on the MNBC is utilized to compute the MNBC surface. The assumption is that the full MNBC surface is accessible to N_2 gas. Measurements of surface area are based on the adsorption of gas molecules in infinite layers with no interlayer contact [75].

3.6. Energy Dispersive X-Ray Analysis. Energy dispersive X-ray analysis (EDX) is employed to ascertain a material's elemental composition. There are four main parts in the EDX, which are the excitation source, X-ray detector, pulse processor, and analyzer. A detector for X-rays deflects the X-ray beam and converts the energy into voltage signals. The information from the detector is then sent to a pulse processor, which measures the signals and sends them to an analyzer for further data analysis. The sample's electron content is analyzed using EDX in both qualitative and quantitative ways [52].

3.7. Vibrating-Sample Magnetometer (VSM). A VSM, which examines a sample's superparamagnetic nature, is utilized to determine the magnetic properties of the produced nanobiochar [55]. VSM measures the magnetic properties of samples depending on Faraday's law of induction. The VSM converts the dipole field of the sample into an AC electrical signal to determine the magnetization of MNBC in the presence of an external magnetic field. The magnetism of a sample is measured in VSM by sandwiching it between two electromagnetic components to create an applied field. A vibrational unit extended on a rod allows the sample to oscillate here. When the sample oscillates, a voltage is created between the search coils, which is used to detect the sample's magnetic characteristics. The fundamental benefit of VSM is that it allows the sample to be evaluated at different angles in terms of magnetization [76].

3.8. Elemental Analyzer. An elemental analyzer is another instrument for the detection of elements in the sample [51]. It determines the amount of an element in a compound, usually in weight percent. Under static conditions, the sample is placed at a high-temperature (1,000°C) furnace and combusted in pure oxygen. A dynamic burst of oxygen is injected after combustion to ensure the complete burning of all inorganic and organic components. This tool is mostly used to evaluate the samples carbon, hydrogen, nitrogen, oxygen, and mineral composition. There are different types of elemental analyzers are present like combine carbon, hydrogen, and

Table 2: List of MNBC feedstocks with their respective properties.

Feedstocks of MNBC	Carbonization temperature (°C)	pH	Specific surface area (m^2/g)	Average crystallite size (nm)	References
Oil palm MNBC	500	–	173.18	117.60	[80]
Wheat straw MNBC	700	5.0	296.3	18–32	[87]
Coconut MNBC	500	9.0	365	210	[43]
Spruce sawdust	200	–	94	23	[85]
Sewage sludge	800	5	–	–	[88]
Rice husk	600	2	1,736.81	–	[89]
Hickory chips	600	8.5	90.6	482	[90]
Douglas fir	900	10	695	–	[91]
Bagasse	400	3	166.87	245.4	[86]
Pine nut	500	6	365	–	[59]
Walnut	500	6	365	–	[59]

nitrogen, oxygen, and nitrogen, sulfur-in-oil and chlorine-in-oil, carbon and sulfur in metal, alloy, and ore, cross belt analyzer, and multipurpose analyzer [77].

4. Properties of Magnetic Nanobiochar

The only variations between MNBC's characteristics and those of macrobiochar are that MNBC is smaller and possesses magnetic properties. Some properties of MNBC are described later.

4.1. pH. A change in pH of MNBC alters the absorption and catalytic capacity of pollutants from the environment. According to a previous study, the electrostatic attraction between the adsorbent and the metal increases when the pH of MNBC increases, increasing the adsorption capacity of contaminants. A recent study showed that at pH 6.5 more than 50% of acenaphthene has been removed by the MNBC assisted with PAHs degraded bacteria from the wastewater. Another study found that as the pH grows, the adsorption capacity of Cd(II) in water increases, and when the pH lowers the adsorption capacity of Cd(II) in water reduces. pH affects the surface charge and dissociation of functional groups in MNBC [78, 79].

4.2. Elemental Composition. Essentially, each biomass has its own properties; the elemental composition of MNBC is heavily influenced by the feedstock [80]. Plant biomass-derived MNBCs have nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, zinc, and boron in almost all the biochar [81]. But biochar produced from coniferous biomass had a low concentration of N, P, K, Ca, Mg, and S levels than herbaceous and deciduous biomass feedstocks. Previous studies revealed that herbaceous biomass contained more K than the ligneous feedstocks (Biochar_Elemental_Composition_Poster_NABS_MA). Biochar derived from agricultural waste in slow pyrolysis has more C and H ratio [78].

4.3. Crystallinity. It is seen that $FeCl_3$ is added to the nanobiochar to give it magnetic characteristics and the addition of Fe increases the crystallinity [49]. Temperature differences and the carbonization procedure both influenced the crystallinity of MNBC. Aisyiyah Jenie et al. [82] observed distinct forms of MNBC at different temperatures and observed varied diffraction peaks in XRD, indicating their crystallinity fluctuation at different temperatures [80].

4.4. Surface Area and Pore Volume. The specific surface area and pore volume of MNBC increase as the carbonization temperature rises. Because the higher the carbonization temperature, the more ferric chloride dehydrates and decomposes, releasing volatile compounds (hydrochloric acid, water, carbon monoxide, carbon dioxide) resulting in an increase in surface area and pore volume [48].

4.5. Ductility. MNBC surface consists of many functional groups like —OH, C═O, and Si—O, which are negatively charged in nature, and, therefore, it can easily bind with other inorganic metals [83]. Due to the presence of these functional groups in the surface of MNBC, it can be modified to form some engineered nanobiochar [84].

4.6. Magnetic Properties. Due to the presence of magnetic properties in the nanobiochar, it has an attractive saturation-remanence value with better crystallinity [85]. It helps in the separation of contaminants from water and wastewater treatments with the help of magnetic forces so it is used in the extraction of spent gel beads which are used in the biodegradation of PAHs in marine water [58, 86].

Some more properties of MNBC are also mentioned in the previous literature like water holding capacity, mechanical stability, grindability, zeta potential, colloidal stability, agglomeration potential, fluorescence activity, etc., and the mechanical properties of MNBC are mainly evaluated by hardness and Young's modulus, for example, the toughness of MNBC is represented by its hardness properties and its ductility is measured by Young's modulus [79]. Nowadays considering these properties MNBC has many applications in different fields. Table 2 lists some examples of MNBC with their properties.

5. Mechanistic Approaches for Synthesis of MNBC

Currently, MNBC is frequently used in the cleanup of toxic metals, organic contaminants, and pharmaceuticals. The surface of biochar contains a variety of functional groups that

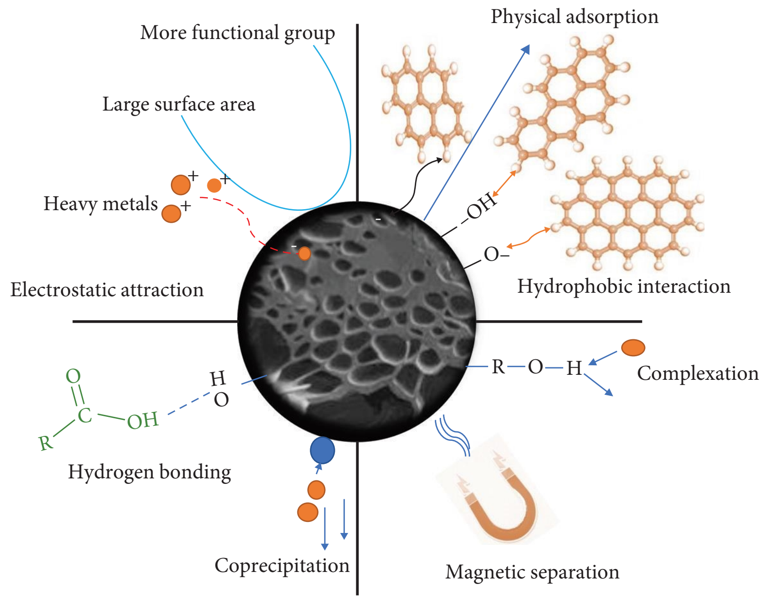

Figure 2: Mechanism of biochar in removal of contaminants from different medium.

interact with pollutants in water and soil via surface adsorption, membrane filtration, and electrostatic attraction. MNBC removes pollutants from the soil and water through these methods. Numerous studies have noted a connection between the surface functional characteristics and soil and biochar structures and the potential of biochar to fix heavy metals in soil. The functional groups of MNBC are the main factor for the remediation of contaminants. For example, biochar has negatively charged ion and heavy metals are positively charged cation so it makes a strong electrostatic bond in close proximity which help in removal of heavy metals from soil and water [91]. Organic contaminants like PAHs, phthalic acid esters, estrogen contaminants, and ionizable organic contaminants are remediated from soil and aquatic system by the hydrophobic interactions, pore filling, H-bonding, π–π electron donor–acceptor interactions, and electrostatic attraction [92]. There are two stages to the hydrophobic interaction between PAHs and MNBC. The partitioning coefficient of MNBC causes the PAH to be divided in the hydrophobic domain during the first phase, and Van der Waals forces cause the PAH to be weakly sorbed onto the MNBC surface during the second phase. Because the H/C ratio is smaller when MNBC is pyrolyzed at a high temperature, this results in greater electron donor–acceptor contacts, which have a high sorption efficiency because of intermolecular forces [89]. In Figure 2, the mechanism of MNBC application in a different field is explained very well.

6. Multifunctional Applications of MNBC

Since nanobiochar has a high specific surface area, crystalline structure, ductility, and surface chemical composition, it has various applications in different fields. Nanobiochar is mostly used to remove toxins from the environment. Heavy metals, PAHs, PPCPs, steroids, pesticides, and hazardous metals are all contaminants. Due to the presence of magnetic properties in MNBC, it can easily absorb the metals from soil and aquatic environment. Some examples of MNBC applications are explained later.

6.1. As a Nanosensor. A nanosensor is a device that is used as an active chemical species or component to generate a signal in presence of an analyte molecule. Nanosensors are used to detect chemical and mechanical information since they may support data and information about a particle's behavior [93]. Nanosensors are widely used in agriculture, food processing, food packaging, food transportation, and nutrition today. In agriculture, it is used to detect the soil conditions, a variety of pesticides, fertilizers, etc. In food packaging, it is used to identify the chemicals, pathogens, and toxins in food [94]. By observing the popularity of nanosensors in biomedical applications nowadays nanobiochar is also used in the synthesis of sensors for the detection of contaminants in the water [95]. For example, according to a recent study, a compact, affordable and sensitive paper-type electrochemical immunosensor was developed employing conductive nanobiochar paper as the conductive layer for sensitive detection of microcystin-LR (MCLR) toxin in the water [77]. The applications of nanosensors in various fields are shown in Figure 3(a).

6.2. Magnetic Nanobiochar in Heavy Metal Removal. Tetracycline and mercury(II) are removed from the aqueous solution using MNBC derived from wheat straw [86]. Moreover, As (III, V), Cd(II), Cr(VI), Cu(II), and Pb(II) are adsorbed by the MNBC. Cu(II) and Pb(II) metal ions are removed using a biochar combined with silica-coated magnetic nanocomposites made from *Cynodondactylon* [55]. It is well known that biochar can remove a good quantity of contaminants from environment by sorption, so researchers are working on the modification of biochar by enlarging the pore volume and

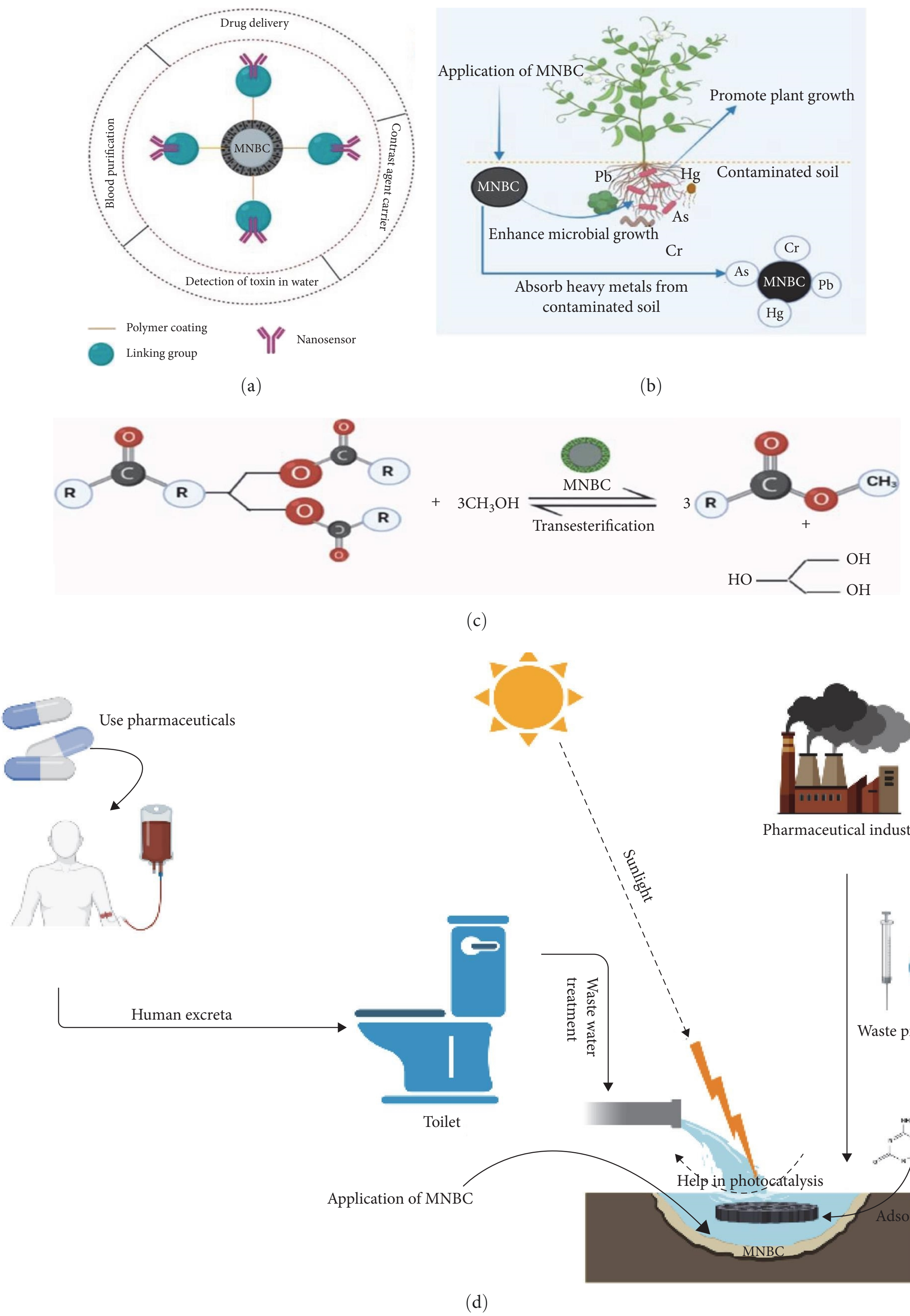

Figure 3: Applications of MNBC: (a) use of MNBC as the nanosensor; (b) use of MNBC in removal of heavy metals from soil; (c) use in esterification; (d) use in removal of pharmaceuticals from water.

surface area in order to adsorb more contaminants. Sizmur et al. [96] revealed that physicochemical activation enlarges the surface area or functionality of engineered biochar that helps in retention of inorganic contaminants like Cd^{2+}, Cu^{2+}, Hg^{2+}, Pb^{2+}, Zn^{2+}, NH_4^+, NO_3^-, PO_4^{3-}, CrO_4^{2-}, and AsO_4^{3-}. Figure 3(b) demonstrates how MNBC applied to heavy metal-contaminated soil not only adsorbs the heavy metals on its surface but also promotes the growth of rhizospheric bacteria that aid in the breakdown of the heavy metals in the soil and support phytoremediation.

6.3. Use as a Catalyst for Esterification. When a carboxylic acid reacts with alcohol, an ester is formed, and water is released [97]. To make an ester, —OH groups must be removed from the carboxylic acid and removing —OH groups demand more energy, therefore a catalyst and heat are required to generate energy and MNBC is the best example utilized for esterification [21]. Because of its larger surface area, crystallinity, and functional groups on the surface, MNBC shows strong catalytic activity in the esterification reaction. According to a recent study, sulfonation of magnetic biochar created an excellent heterogeneous acid catalyst with multiple functional groups on the surface that aids in the catalysis of oleic acid and methanol [85]. During biomass pyrolysis, the dehydration and decomposition of magnetic precursors in MNBC result in the release of volatile materials such as HCl, H_2O, CO, and CO_2, which increases the surface area and pore volume of the MNBC, Figure 3(c).

6.4. Remove Pharmaceuticals from Aquatic Environment. For the elimination of carbamazepine and tetracycline, MNBC was created from the shells of coconut, peanut, and walnuts. Biochar with Fe_3O_4 and activated carbon with Fe_3O_4 form a hybrid material to remove PPCPs by the process of adsorption and mechanochemical degradation [88]. In general, people consume so much allopathic medicine for the treatment of many diseases which results in the excretion of pharmaceutical components into the environment. So, these pharmaceutical components contaminate the soil and water which further enter into the food chain and results in some serious health issues. Consequently, it is imperative to remove pharmaceutical pollutants from water and soil [95, 96]. The adsorption of sulfamethoxazole and sulfapyridine from wastewater is achieved by ball milling biochar made from raw bamboo, bagasse, and hickory chips [50]. Biochar derived from alfalfa which is etched with phosphoric and hydrochloric shows more adsorption capacity of sulfamethoxazole than the other pristine biochar [98]. One more example of a pharmaceutical contaminant is fluconazole which can be removed from the environment by ball-milled magnetic biochar [99]. Tetracycline hydrochloride is adsorbed from aqueous solution using engineered biochar made from wheat stalks. Compared to natural biochar, engineered biochar can absorb more tetracycline hydrochloride due to its higher surface area and pore size [100]. Figure 3(d) explains how pharmaceuticals pass to the aquatic environment from human beings.

6.5. Remove Pesticides from the Agricultural Cropland. To increase the productivity of crops in agriculture, farmers used different types of pesticides to eliminate pests that damage agricultural crops. Several reports mentioned that farmers used about 30% of fungicides and 15% of herbicides to control the pest [101]. It is vital to enhance production because of the rising population in order to fully address the food problem, and productivity will grow if the plant is disease-free. Hence, farmers use different types of chemical fertilizers and pesticides to increase productivity [20]. Pesticides such as glyphosate, acephate, deet, propoxur, metaldehyde, boric acid, diazinon, dursban, dichloro-diphenyl-trichloroethane, malathion, and many others have negative impact on the environment. Diazinon use in agriculture has negative effects on other species, including humans, as it inhibits the acetylcholinesterase enzyme, which can lead to disorientation, headaches, and impairment [102]. Moreover, use of pesticides may cause soil leaching, hydrolysis, and degradation of organic nutrients. There are different types of physical and chemical technologies, which are used to eradicate pesticides from the soil but they have some negative impacts on soil. So, we have to think a way, which is beneficial for both crop productivity and environmentally friendly in nature. Application of nanoparticles for photocatalytic degradation of pesticides is the best way for the removal of pesticides from agricultural cropland. For example, application of 3D-TiO_2/BCDs MNPs shows a good result by degrading 98.5% diazinon in 30 min under sunlight irradiation [103]. Because it contains phosphorus, sulfur, manganese, and iron, biochar improves soil aeration and capillary water, which boosts plant growth and increases nutrient uptake [104].

6.6. Practice of Magnetic Nanobiochar in Renewable Energy Is a New Hope in Environmental Revolution. Nanobiochar is now used to generate electricity instead of biodiesel and microbial fuel cells [105]. According to a previous study, nanobiochar can produce 2–10 times the power of a microbial fuel cell. Biochar made from wood is used as an electrode in microbial fuel cells to reduce costs and carbon footprint [106]. When wood-based biochar is used as an electrolyte in a microbial fuel cell, it not only reduces environmental toxicity but also recycles biomass waste. As we all know, biodiesel or biofuel is created through the transesterification and esterification of plant or animal fats and oils [102]. An acid or a base catalyst is required to catalyze the transesterification reaction, and in order to produce biodiesel, transesterification uses nanobiochar as a catalyst. When biochar is used in the pre-esterification of biodiesel production, it lowers the cost and free fatty acid content [107]. Biochar is also an effective catalyst in the production of biogas. For example, when Ni-impregnated biochar is used in gasification, it produces a lot of hydrogen [108]. Biochar aids in the accumulation of ammonia and nitrogen during biogas production and can also improve the organic acid utilization efficiency in microbes [109].

7. Limitations of Magnetic Nanobiochar

Though MNBC has many benefits in agriculture, environmental remediation, and high-value applications, it also has some drawbacks in agriculture and the environment. For example, if we use an excessive amount of biochar in soil, it may reduce the activity of worms, which are known as farmers' friends [109], as well as increase the growth of undesirable weeds in agriculture. Second, while continuous use of biochar in agriculture increases productivity, it also reduces the amount of nutrients that are accessible in the soil and the impact of pesticides on the ground. If MNBC is smaller than the limited size, it can easily enter living organism cells and cause some mutational changes at the DNA level. Some genetic and cytogenic disorders may result from these mutational changes [110]. Moreover, the volatile gas produced during the pyrolysis of biochar contributes to air pollution [111].

8. Conclusion and Future Perspective

According to the research, MNBC is an effective bioremediation amendment. It has a maximum reusable capacity (15 times) and is the best performer in heavy metal removal. There are several bioremediation techniques available, but each has its own set of issues, such as being very expensive and having an adverse influence on the environment, whereas the application of MNBC as an amendment in bioremediation is both environmentally friendly and inexpensive. Because of their magnetic properties, they can be used as an electrochemical immunosensor for the screening of MCLR toxins in water. Applying nanobiochar to the soil not only remediates contaminants but also increases the abundance and distribution of microorganisms. Although MNBC serves many functions in the environment, it also has some toxic effects. The MNBC toxic effects could be physicochemical or biochemical. As we all know, nanotechnology-based products have advanced to a new level of sophistication, such as the development of controlled drug delivery, precision farming, and nanochips. As previously mentioned, a biochar-derived nanosensor can easily detect and diagnose wastewater contaminants. The MNBC is also used as an electrode in power generation. Despite the fact that MNBC has numerous applications in various fields, it is still used only in pot experiments. There have been very few studies on the application of MNBC in esterification, nanosensor, and high-value applications, so it requires more attention in the remediation of environmental contaminants to reduce pollution and make people's lives easier.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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