

# A Review of Biochar and Its Nanocomposites for the Removal of Toxics from Wastewater

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## Abstract

*Biochar is a carbon-rich material formed by the thermochemical conversion of biomass under oxygen-limited circumstances, providing a long-term solution for waste valorization and environmental management. Because of its high stability, surface functional groups, and porous structure, biochar has been used extensively in pollutant adsorption, carbon sequestration, and soil amendment. Recent developments have produced biochar nanocomposites, in which the physicochemical properties of biochar are improved by engineering or combining it with nanomaterials like metal oxides, carbon nanotubes, or magnetic nanoparticles. The enhanced surface area, reactivity, conductivity, and catalytic performance of these nanocomposites extend their uses in environmental remediation, energy storage systems, wastewater treatment, and heavy metal removal. By turning biomass waste into high-value products, biochar, and its nanocomposites promote sustainable development and circular economy initiatives. They are generally affordable, eco-friendly, and multifunctional materials.*

**Keywords:** Biochar, biochar nanocomposites, pesticides, adsorption, wastewater

## INTRODUCTION

Persistent organic chemicals (POPs) are highly hazardous to the ecosystem and living organisms. Pesticides are one class of POPs with half-lives that can extend to years [1]. Global consumption of agricultural pesticides increases every year. The overall amount of pesticides used in agriculture in 2022 was 3.70 million tons of active ingredients (Mt), according to FAO statistics from the United Nations in 2024. This represents a 4% rise compared to 2021, a 13% increase in a decade, and a doubling since 1990. The global use of pesticides rose by 121% for herbicides, 54% for fungicides and bactericides, and 48% for insecticides when comparing the most recent decade to the 1990s. Herbicides' percentage of all pesticides used increased from 40% to 50% over that time, while insecticides' percentage decreased from 26% to 22%, and fungicides and bactericides' percentage decreased from 25% to 22% [2]. According to reports, the United States, China, Argentina, India, Canada, Japan, France, Brazil,

Thailand, and Italy are the countries that use pesticides the most [3]. Water resource pollution by hazardous pesticides is a serious global environmental and public health concern, despite the fact that pesticides have been widely utilized to regulate crop growth by eliminating pests, such as insects, fungi, and microorganisms in agricultural farms [4, 5].

In recent years, persistent pollutants have been released into surface water and groundwater as a result of the increased production and usage of pesticides for agriculture. They also have some undesirable side effects, such as toxicity, carcinogenicity, and mutagenicity [6, 7]. Their non-biodegradability allows them to accumulate easily

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in the food chain, affecting both humans and wildlife. Even at trace concentrations (ng/L– $\mu$ g/L), many of these compounds pose risks due to their persistence, bioaccumulation, and potential toxicity or endocrine-disrupting effects. For instance, commonly used rice paddy pesticides like tricyclazole, propiconazole, and imidacloprid are frequently detected in water bodies due to agricultural runoff [8, 9]. Since these materials may easily pollute land, air, and water through sewage water and household and industrial wastes, their extremely hazardous nature has become a major threat for both humans and the environment [10].

Biochar (BC) has become a viable solution for a variety of environmental problems in recent years, such as climate change, land degradation, water pollution, and accumulated waste [11]. BC is a carbonaceous product of lignocellulosic biomass produced by a variety of thermochemical processes under a limited oxygen supply [7]. Applications for BC have been identified in a variety of fields, including bioengineering, environmental remediation, agro-sectors, agro-industries, sensors, adsorbents, capacitors, photocatalytic materials, etc. [12–16].

Researchers have prepared BC from a variety of biomass/feedstock sources, including plant, fruit, and food waste materials, through the process of pyrolysis and have reported good removal efficiency and adsorption capacity. BC, with its unique properties and low production cost, offers a promising solution for water decontamination, especially in underserved regions. By addressing the high costs and complexity of conventional treatments, biochar technologies present a sustainable and scalable alternative for real-world applications [9, 17]. However, the sorption capacity of the original BC is not satisfactory due to heterogeneous properties. Therefore, the modification of BC with chemical treatments, UV radiation modification, acid-base modification, functional group loading, addition of metals or metal oxides to BC, and other modification methods have gained much attention to enhance the adsorption performance and improve selectivity, separability, and structural stability [11, 18]. One such approach is developing biochar nanocomposites (BNCs).

Nanocomposites are a family of nanomaterials in which ceramic, metal, or polymer materials comprise one or more phases of nanoscale dimensions (zero, one, or two dimensions) [19, 20]. BNCs are formed by incorporating nanomaterials into a biochar matrix, enhancing their adsorption and catalytic properties and providing promising performance in removing organic and inorganic pollutants, heavy metals, and pathogens from wastewater [21]. Biochar-based solutions offer a sustainable and scalable way to overcome the drawbacks of traditional water treatment techniques, such as their high prices and intricate operational requirements. This could help close the gap between laboratory results and field implementations [17, 22].

The potential of BC and BNCs as long-term remedies for organic pollutants, especially pesticides, was the main emphasis of this review, which highlights several important areas that require more investigation. The primary issues and deficiencies were also noted. Although the use of BC and BNCs has been thoroughly covered in the literature, their application specifically for water treatment from harmful pesticides has been insufficiently explored. The sustainability of raw BC and BNCs is addressed as well in this review.

Moreover, a wide range of experimental studies and reviews have been conducted on the adsorption of organic and inorganic waste from water. However, few studies focusing on the adsorption technique of pesticides using BC and BNCs have been conducted. Furthermore, the extensive use of BNC-based adsorbents for the removal of several pesticide classes was not covered in earlier literature. Additionally, this review was limited to the adsorptive removal of pesticides utilizing BC or BNCs. Unlike the previous literature, a comprehensive review was done on the remediation of water from different classes of toxic pesticides. This offers an opportunity for assessing their performance and comprehending recent scientific discoveries, thus figuring out the related benefits and drawbacks as well as experimental insights. Finally, this review identifies important knowledge gaps and barriers for guiding targeted research for large-scale, commercial applications.

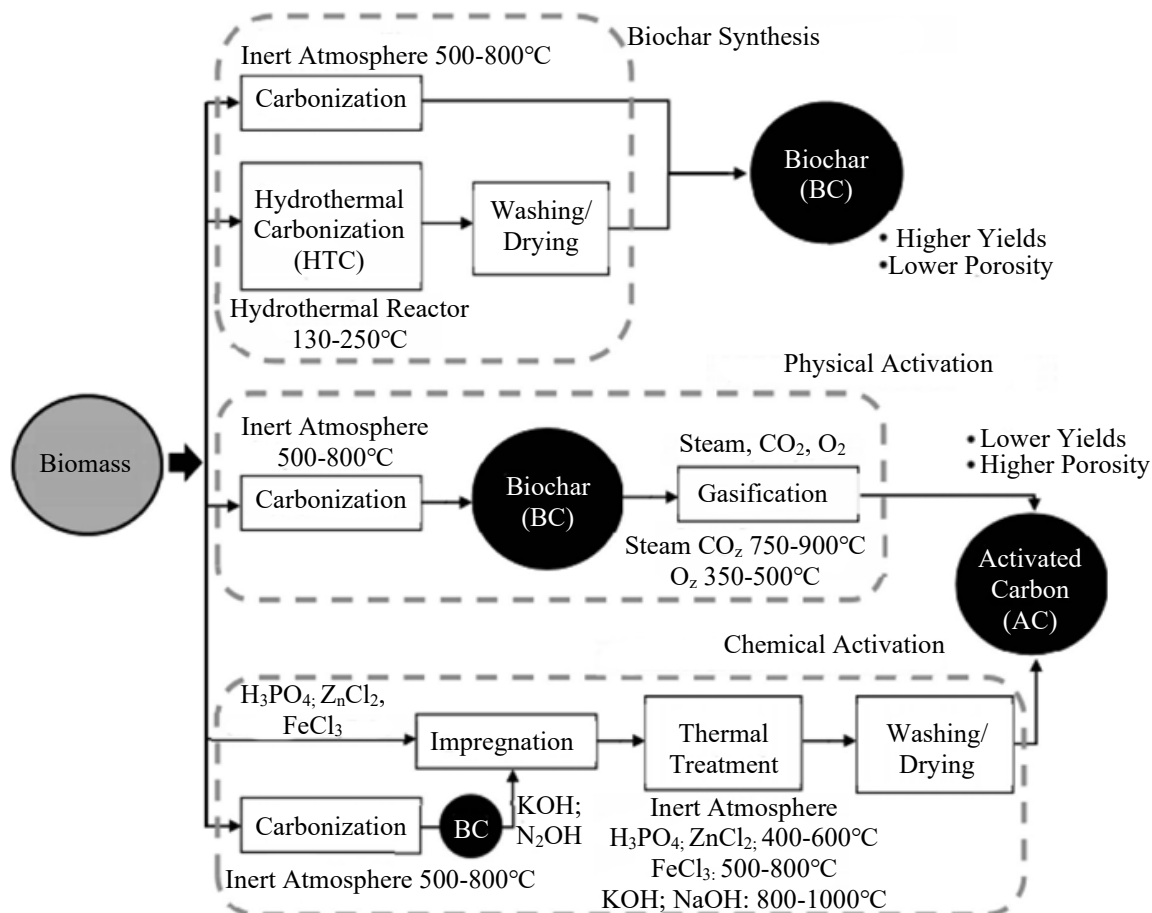
## SOURCE, PREPARATION, AND MODIFICATION TECHNIQUES

### Source and Characteristics

A variety of carbon-rich biomass feedstocks, such as industrial and organic wastes, forestry byproducts, and agricultural crop residues, can be converted into biochar. Common sources of biochar include forestry waste (wood chips, sawdust, bark), industrial or municipal biomass (sewage sludge, food processing waste, manure), and agricultural residues (rice husks, corn stover, straw, coconut shells). The characteristics of the final biochar are significantly affected by the feedstock type. Different biomass types yield charcoal with different carbon content, ash/mineral content, pore structures, and surface functional groups. For instance, woody and husk-derived biochar tend to have higher fixed carbon and aromaticity, whereas biosolids-derived biochar may contain more ash and embedded metal oxides from the waste stream [9].

### Methods of Biochar Preparation

Several methods are available to convert biomass into biochar. Pyrolysis is by far the most widely used technique for converting the wide range of biomass that are accessible and suitable as feedstock. Torrefaction, gasification, hydrothermal carbonization, and flash carbonization are other important methods to be considered (Figure 1).



**Figure 1.** Synthetic route for preparing biochar and activating carbon from biomass [23].

### Pyrolysis and Torrefaction

Pyrolysis is the thermochemical breakdown of organic (carbon-based) materials by applying heat without oxygen in an inert atmosphere at temperatures between 250 and 900°C. To recycle the waste biomass [24]. The biomass feedstock is loaded into a pyrolysis reactor for biochar production and then heated; volatile compounds are driven off, leaving behind a carbon-rich solid material that is the biochar product [25].

In addition to feedstock type, pyrolysis conditions (especially temperature and atmosphere) critically determine biochar's physicochemical characteristics. Temperature is the key factor in controlling the efficiency of the pyrolysis process [9, 26]. Higher pyrolysis temperatures (e.g., 600–800°C) compared to lower pyrolysis temperatures (300–400°C) generally produce biochar with greater aromatic carbon content, higher surface area, and more hydrophobic surfaces, but fewer native oxygen-containing functional groups. Low-temperature chars tend to retain more polar functional groups (hydroxyl, carboxyl, etc.) and have a lower surface area. As a result, the adsorption capacity of biochar for pesticides can vary widely – it “depends on the feedstock type and pyrolysis temperature,” which together affect surface area, pore structure, and surface chemistry. Optimizing these properties is key to maximizing pesticide removal. For example, producing biochar at a high enough temperature to create a largely nonpolar, aromatic surface can enhance the adsorption of hydrophobic pesticides via  $\pi$ – $\pi$  interactions and van der Waals forces. Conversely, preserving polar functional groups can benefit the uptake of more polar or ionic pesticides through hydrogen bonding and electrostatic interactions [9].

Lower process temperatures around 300–500°C favor a higher biochar yield, whereas temperatures above 700°C increase biochar carbon content. For slow pyrolysis, the feedstock is added to the reactor at the beginning of the process, and it is characterized by a residence time that ranges from half an hour to several hours. Slow pyrolysis with longer solid and vapor residence times yields higher biochar yields. In contrast, fast pyrolysis with short vapor residence times favors bio-oil production over biochar formation. In the case of fast pyrolysis, the feedstock is added to the reactor after raising its temperature to the desired value, implying a residence time for the reaction in the order of several seconds only. In general, biochar production decreases with the increase in the reactor temperature, which leads to an increase in syngas production [27–29].

Torrefaction is a mild pyrolysis process that uses a low heating rate (ranging from 200–300°C) for feedstock conversion into biochar products. The process will be conducted under ambient pressure and in an inert atmosphere. Torrefaction has comparatively long residence times of up to one hour and involves a relatively moderate heating rate below 50°C/min. Biochar and biocarbon are the end products of the process, which partially breaks down the biomass into condensing and non-condensing gases. However, the resulting biochar has a poor adsorption capacity [30–32].

### ***Gasification***

The feedstock undergoes partial oxidation during the gasification process, which takes place at high temperatures (>700°C) with gasification agents (air, oxygen, steam, etc.). It is the final stage of the biomass pyrolysis process. The gasification process produces gaseous products (e.g., CO, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub>) and solid and liquid products. It leads to low biochar yields because, in this process, the gaseous products are targeted. As the temperature rises, more hydrogen and carbon monoxide are produced, but less carbon dioxide, methane, and hydrocarbons are produced. Before the main process, a drying process is usually needed [31]. However, it is necessary to note that the biochar yields tend to drop substantially during this activation and gasification stage, as a significant portion of the remaining mass is lost due to the oxidative etching process [33]. The remaining solid residue at the end of this high-temperature gasification process is a highly activated and porous biochar material, representing only a fraction of the initial biomass feedstock [21].

Despite the lower yields, the biochar produced during this final stage has a highly developed porous structure, large surface area, and abundant active adsorption sites, making it well-suited for various environmental and filtration applications [34–37].

### ***Hydrothermal Carbonization***

A mixture of feedstock and water will be gradually heated inside the reactor with an eventual rise in temperature and pressure for the hydrothermal carbonization process [31]. The most significant factor affecting the reaction products is the reactor's temperature. It was found that biochar is produced at

temperatures below 250°C (hydrothermal carbonization), bio-oil is produced at temperatures between 250 and 400°C (hydrothermal liquefaction), and various gaseous products (such as CO, CO<sub>2</sub>, H<sub>2</sub>, and CH<sub>4</sub>) are produced at temperatures above 400°C (hydrothermal gasification) [26, 38]. It can be concluded that biochar produced by hydrothermal carbonization has a larger carbon content than that produced by pyrolysis or gasification.

### Flash Carbonization

The feedstock is transformed into solid and gas products by flash carbonization at temperatures between 300 and 600°C and pressures ranging from one to two MPa. The residence period is around 30 minutes [31]. Biomass can be turned into a hydrophobic solid by burning it in an inert environment to eliminate its oxygen and water. High pressure and a flash fire were present during the process [39, 40].

### Factors Affecting Biochar Production

Biochar production is influenced by various factors that affect process quality, yield, and efficiency. These factors are crucial for optimizing biochar production and effectively harnessing its benefits. Feedstock selection, pyrolysis process parameters, feedstock particle size, feedstock moisture content, pyrolysis atmosphere, reactor design, and quenching and postprocessing treatments are vital factors influencing biochar production, as given in Table 1.

**Table 1.** Pyrolysis and gasification processes and product distribution.

Process	Heating rate (°C·min <sup>-1</sup> )	Temperature (°C)	Residence time	Products			Reference
				Liquid (bio-oil) (%)	Gas (syngas) (%)	Solid (biochar) (%)	
Low pyrolysis	1–20	100–1000	Long residence time (mins–days)	30	35	35	[29]
Intermediate pyrolysis	100–500	500	Moderate (10–20 s)	50	25	25	[41]
Fast pyrolysis	>300	300–1000	Short (<2 s)	75	13	12	[29]
Gasification	2–100	>800	Moderate (10–20 s)	5	85	10	[41]

Feedstock selection is vital, as different biomass sources have varying chemical compositions and structural properties that impact the biochar yield and characteristics [42, 43]. The pyrolysis process parameters, including heating rate, temperature, and residence time, significantly affect the biochar yield and quality [44, 45]. Feedstock particle size affects heat transfer and reaction kinetics, with smaller particles yielding faster pyrolysis rates [46, 47].

Feedstock moisture content is another critical factor, as higher moisture content requires more energy for drying and can lead to lower biochar yields [45, 48, 49]. The pyrolysis atmosphere, whether inert, oxidative, or reduce, can significantly impact the chemical composition and surface area of the resulting biochar [50, 51]. Reactor design, including size, shape, and heating method, affects the efficiency of the process, and different designs are suitable for various scales and feedstock types [44]. Quenching and postprocessing treatments can influence the surface area, porosity, and nutrient retention of biochar and modify its properties for specific applications [52, 53].

## BIOMASS AND BIOCHAR MODIFICATION TECHNIQUES

### Biomass Modification

Before raw feedstock is transformed into biochar using procedures like pyrolysis and calcination, it must undergo biomass pretreatment. Because it enables the simultaneous processing of the biomass and metal-containing precursors, this method is thought to be energy-efficient. A variety of metal-containing substances, including metal oxides, metal chlorides, metal sulphides, metal sulphates, and metal nitrates, as well as nanoparticles and organic–inorganic polymers, may be used to modify the original biomass’s surface during these alteration processes. These changes make it easier to create nanomaterials supported by biochar [54].

Using metal salts to pretreat biomass prior to pyrolysis is a technique for generating biochar–metal nanoparticles. Biomass can be impregnated with various metal salts like  $\text{FeCl}_3$ ,  $\text{Fe}(\text{NO}_3)_3$ ,  $\text{AlCl}_3$ ,  $\text{MgCl}_2$ ,  $\text{MnCl}_2$ ,  $\text{CaCl}_2$ , and  $\text{ZnCl}_2$ , as well as sulfur-based and organic-based metal salt solutions [55–57]. This allows metal ions in the solutions to deposit onto the surface or interior of the feedstocks. Following this, the pretreated biomass undergoes pyrolysis at temperatures ranging from 400 to 800°C in an environment with limited or no oxygen. During the pyrolysis process, these metal ions transform into metal oxide nanoparticles (MNPs) like  $\text{Fe}_2\text{O}_3$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{MnO}_2$ ,  $\text{CaO}$ , and  $\text{ZnO}$ , or into zero-valent metals that stick to the biochar surface. For illustration, in a study reported by Chaukura et al. [58], 750 °C was used to pyrolyze  $\text{FeCl}_3$ -impregnated paper and paper sludge (PPS) to create the  $\text{Fe}_2\text{O}_3$ –biochar nanocomposite. After two hours of immersion in a  $\text{FeCl}_3$  solution, the PPS biomass was allowed to air dry for a further two hours at 80°C.  $\text{FeCl}_3$ -impregnated PPS with a mass-to-volume ratio of 1:3 was pyrolyzed for two hours at 750°C in a  $\text{N}_2$  environment to produce  $\text{Fe}_2\text{O}_3$ –biochar. Methyl orange (MO) was effectively removed from contaminated wastewater using this nanocomposite, and the results demonstrated that its MO adsorption capacity was 52.79% greater than that of virgin biochar.

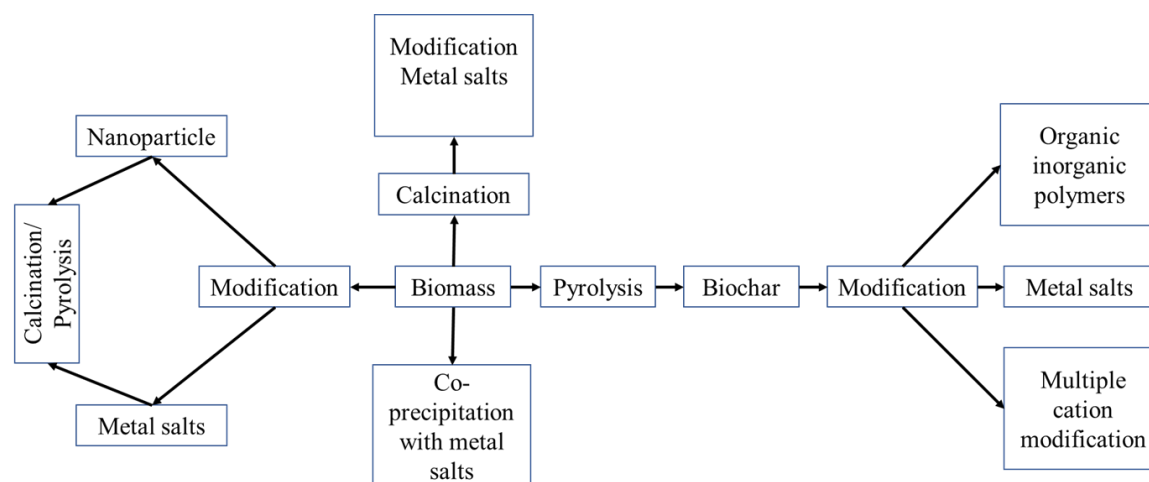
In contrast to the pure biochar, the  $\text{Fe}_2\text{O}_3$ –biochar composite had a lower surface area and porosity as determined by the BET technique.  $\text{Fe}_2\text{O}_3$  and other naturally occurring metallic compounds in the absorbent material may be responsible for this decrease by obstructing the pores of the biochar. Similarly,  $\text{FeCl}_3$ -treated maize straw was pyrolyzed for one hour at 600°C in an electric field to create  $\text{Fe}_3\text{O}_4$ -based magnetic biochar. On the surface of the biochar, this procedure produced uniformly distributed, rod-like  $\text{Fe}_3\text{O}_4$  nanoparticles. Interestingly, the  $\text{Fe}_3\text{O}_4$ -based magnetic biochar showed a remarkable capability to adsorb lead (113 mg/g) [59].

Orange peel powder (OPP) can be coprecipitated with ferric chloride hexahydrate and ferrous sulphate heptahydrate to change its surface, according to a study by Gupta et al. This resulted in the development of a unique magnetic nanoadsorbent  $\text{Fe}_3\text{O}_4$ –OPP (MNP–OPP), which demonstrated the covalent bonding between the carboxyl groups in OPP and the hydroxyl groups in MNP. The elimination of cadmium ions from aqueous solutions was another use for the nanocomposite [60]. According to the Langmuir Model, it was shown that under ideal circumstances, MNP–OPP removed the most  $\text{Cd}^{2+}$  at 76.92 mg/g, and the adsorption was thermodynamically favorable. Table 2 summarizes the various biomass modifications including feedstocks used, types of metal precursors, conditions under which pyrolysis was carried out, specific nanocomposites formed, and their respective applications (Figure 2).

**Table 2.** Studies on biomass modifications for metal nanocomposite synthesis and applications.

Feedstock	Metal/organic or inorganic precursor	Pyrolysis temperature	Formed nanocomposite	Application	Adsorption efficiency	Adsorption capacity mg/g	Ref.
Corn stalk	$\text{FeCl}_3$ pre-treatment	600°C	$\text{Fe}_3\text{O}_4$ –biochar	Adsorption of $\text{Pb}^{2+}$ from wastewater	/	113	[59]
Wheat straw	$\text{Bi}_2\text{O}_3$ and hydrochloric acid	400–600°C	Bismuth impregnated biochar	Adsorption of P, As (III), and Cr (VI)	/	125.40	[61]
Paper and paper sludge (PPS)	$\text{FeCl}_3$	750°C	$\text{Fe}_2\text{O}_3$ –biochar	Removal of MO from contaminated wastewater	52.79%	20.53	[58]
Acacia Nilotica seed shell ash	Nickel and zinc salts	550°C	$\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$	Adsorption of $\text{Pb}^{2+}$ from wastewater	94.8%	37.6	[62]

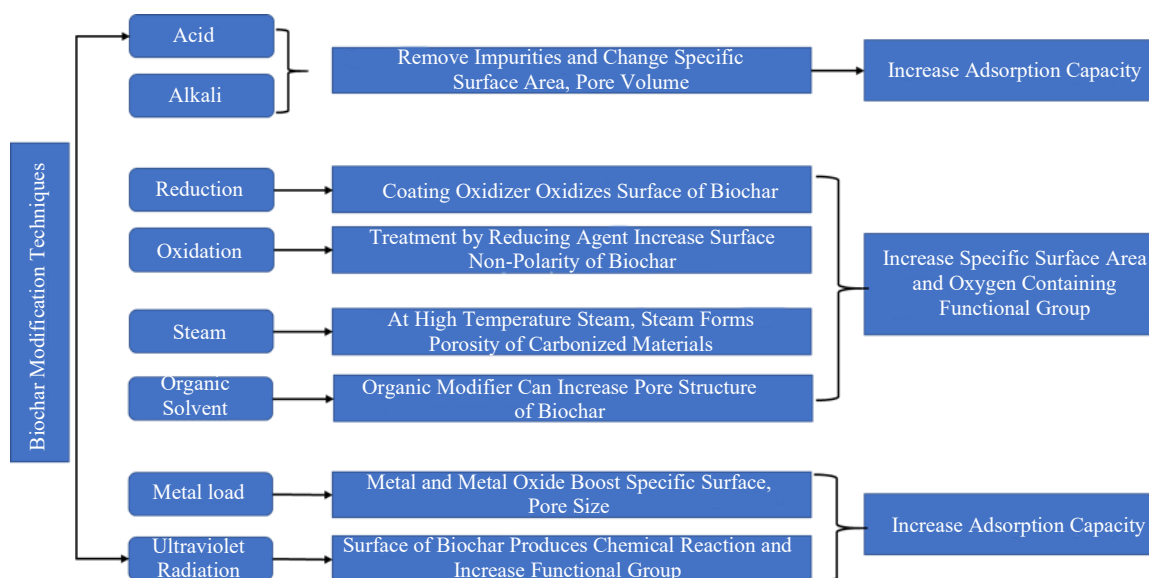
Corn Stover biomass	Zinc compounds	500, 600, 700, 800°C	ZnO/ZnS modified biochar	Adsorption of Pb <sup>2+</sup> , Cu <sup>2+</sup> , and Cr <sup>6+</sup>	~99%	Pb <sup>2+</sup> = 135.8 Cu <sup>2+</sup> = 91.2 Cr <sup>6+</sup> = 24.5	[63]
Crab shells	Naturally present calcium in crab shells	300-900°C	Calcite-based and lime-based CRB	Phosphorus removal	26%–100%	/	[64]
Orange peel powder (OPP)	FeCl <sub>3</sub> .6H <sub>2</sub> O FeSO <sub>4</sub> .7H <sub>2</sub> O	Low temperature	Fe <sub>3</sub> O <sub>4</sub> - OPP (MNP- OPP)	Cadmium ions	82%	76.92	[60]
Cow dung	Magnesium	600 °C	MgO-biochar Composite	Phosphorus removal	89.25%	30	[65]



**Figure 2.** Schematic diagram of different biomass modification techniques.

### Biochar Modification

Biochar can be modified by gas activation, ball milling, radiation, acid, alkali, oxidant, metal ion, and other treatment methods in (Figure 3). For instance, modifying biochar to increase its surface area, porosity, and/or functional groups to increase its sorption capacity has gained more attention in recent years [66]. The choice of method depends on its application field [67].



**Figure 3.** Schematic diagram of biochar modification techniques.

The modification of biochar can significantly improve its activity and increase its application potential in pesticide-polluted environmental remediation [68]. Chemical reagent modification of biochar may alter its physicochemical properties and increase its sorption capacity.

The surface properties of biochar are among the most crucial factors influencing how it interacts with pesticides. These include the presence of functional groups, surface area, and porosity, all of which have an impact on the adsorption process.

A higher surface area for the adsorption of hydrophobic contaminants and certain pesticides is provided by biochar that has a high percentage of micropores (<2 nm) and mesopores (2–50 nm) [69, 70]. Physical locations for the contaminants to be trapped are provided by these pores. Through hydrogen bonds and electrostatic interactions, oxygen-containing functional groups like hydroxyl, carboxyl, and carbonyl can improve the adsorption of polar pesticides [71].

To maximize the effectiveness of biochar, these qualities must be optimized through controlled pyrolysis and post-treatment changes (such as chemical activation or functionalization) [72, 73]. Several approaches can be used to maximize biochar's ability to remove pesticides.

#### *Physical Activation*

The most popular oxidizing agents for physically activating biochar are carbon dioxide (CO<sub>2</sub>) and water vapor (Sajjadi et al., 2018). Extremely high temperatures (800 °C to 1100 °C) and active atmospheric pressure with CO<sub>2</sub>, vapor, or a combination of both are applied to biochar. The procedure raises the biochar's specific surface area and porosity. Following physical activation, notable alterations in surface chemical properties (such as functional groups, polarity, and hydrophobicity), specific surface area, and micropores were noted in the work by Kołtowski et al. [74, 75].

#### *Chemical Activation*

Biochar can be impregnated with acids, bases, or metals to increase its porosity and provide functional groups that increase its affinity for particular contaminants [72, 73]. Highly reactive species, including hydroxyl radicals, are used in chemical processes, especially advanced oxidation processes (AOPs) like ozonation and UV/H<sub>2</sub>O<sub>2</sub> treatment, to convert complicated compounds into less hazardous or more biodegradable forms [76]. The best method for creating adsorbents with a high (>1800 m<sup>2</sup>/g) surface area is chemical activation employing metal hydroxide reagents, such as KOH [77].

#### *Magnetic Modification*

Biochar is more feasible for large-scale applications when magnetic nanoparticles, such as Fe<sub>2</sub>O<sub>3</sub> or Fe<sub>3</sub>O<sub>4</sub> nanoparticles, are added since they make recovery easier after usage [78, 79].

#### *Multi-Functionality*

Treatment outcomes can be enhanced by creating biochar that can simultaneously adsorb and degrade contaminants, for example by adding photocatalytic materials like ZnO and TiO<sub>2</sub> nanoparticles [80, 81]. The intricate interactions between biochar and pesticides are frequently affected by the synergy between adsorption mechanisms. For instance, large removal efficiencies might result from the simultaneous action of hydrophobic and electrostatic interactions.

The modification methods of biochar are mainly chemical methods, and pH before and after modification is related to the added modified substances, as seen in Table 3. By modification, biochar's maximum pesticide adsorption capacity (mg·g<sup>-1</sup>) and removal rate (%) are increased. The specific surface area (m<sup>2</sup>·g<sup>-1</sup>) and total pore volume (cm<sup>3</sup>·g<sup>-1</sup>) of the modified biochar were also increased. The removal rate of pesticide pollutants from corn straw biochar modified with acid substances increases from 38% to 96% [82].

**Table 3.** Study of pesticides removed by modified biochar under different modification methods.

Raw material	Pyrolysis temp. (°C)	pH	Modification method	S. surface area (m <sup>2</sup> ·g <sup>-1</sup> )	Max. adsorption Capacity (mg·g <sup>-1</sup> )	Max. removal rate%	Contaminant	Adsorption mechanism	Ref.
Moringa Oleifera Lam. Seed Husk	300	–	Nitric acid	5.77	10.321	33.03%	Atrazine	Electrostatic Interactions and Hydrogen bonds	[83]
Rice husk	700	10.12	Steam Activated	251.47	160.77	16.08%	Carbofuran	Electrostatic Action, Physisorption And Chemisorption	[84]
Corn Straw	300	–	H <sub>3</sub> PO <sub>4</sub>	638.1	79.6	96%	Atrazine	Van der Waals' Forces, H-bond, Electrostatic Interaction and Pore filling	[82]
Tangerine Seed	600	7	H <sub>3</sub> PO <sub>4</sub>	659.62	93.46	87.52%	Carbamate pesticides	Van der Waals', H-bond	[85]
Corn straw	500	7	KOH	59.23	2.84	88%	Atrazine	Electrostatic interaction	[86]
Rice straw	600	6.93	H <sub>3</sub> PO <sub>4</sub>	192.3	0.05	89.5%	Imidacloprid	–	[87]
Corn stalk	600	2.38	K <sub>2</sub> CO <sub>3</sub> H <sub>2</sub> SO <sub>4</sub> HNO <sub>3</sub>	691.28	22.84	38.07%	2,4 Dichlorophenoxyacetic Acid (2,4-D)	-π-π interaction, Chemical Adsorption and H-bond	[88]
Tea waste	500	7	Chitosan AgNO <sub>3</sub>	–	5.643	93%	Imidacloprid	Chemical adsorption	[89]
Corn stalk	800	–	2Methylimidazole Co(NO <sub>3</sub> ) <sub>2</sub> ·6H <sub>2</sub> O	280	189	97%	Imidacloprid	The pore filling, H-bond and π-π Interaction	[90]
Phragmite Powders	500	–	Nano CuFe <sub>2</sub> O <sub>4</sub>	189.6	269.4	98.9%	Glyphosate	Physisorption, Chemisorption, Electrostatic Interactions and Coordination Bonding	[91]
Corn stalk	600	10	Ni (NO <sub>3</sub> ) <sub>2</sub> , FeCl <sub>3</sub> ZnCl <sub>2</sub>	14.26	143.15	71.58%	Atrazine	Chemisorption, Π-π bond interaction	[92]

Pyrolysis temperature, duration time, composition, and concentration of input organic matter, as well as the inclusion of exogenous modifiers, all have a significant effect on the resulting biochar's characteristics [93]. The effect of biochar's pore geometry on adsorption is not clear [94]. Furthermore, to maximize the overall effectiveness of biochar amendments, the pertinent mechanisms should be sufficiently taken into account [95].

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## KNOWLEDGE GAPS AND RESEARCH NEEDS

### Molecular-Level Mechanistic Understanding

Despite numerous studies, the precise interactions between biochar (especially modified biochar) and pesticide molecules at the molecular scale are not fully understood. A better grasp of these mechanisms would help in rationally designing biochar surfaces tailored for particular contaminants, rather than the current trial-and-error approach.

### Long-Term Performance in Real Conditions

A critical unknown is how biochar-based systems perform over extended periods in real-world conditions. Most studies are short-term; the longest field pilots might run for months, whereas a full-scale application would need to function for years. Questions remain about biochar's long-term stability: Does its adsorption capacity fade due to gradual pore blockage, biofouling, or structural breakdown? Does aging (oxidation of the carbon surface, or slow nutrient/pollutant accumulation) change its affinity for target pesticides? There is also limited information on reusability in the long run – how many cycles of adsorption/desorption can a biochar/biochar nanocomposite undergo before it is spent? Addressing these uncertainties will likely require long-duration field trials and monitoring. Researchers have noted the limited data on long-term effectiveness and called for standardized protocols to test biochar and its composites in conditions simulating prolonged use [9].

### Complex Matrix Effects and Synergistic/Antagonistic Interactions

Real wastewater contains mixtures of pesticides (multiple compounds) as well as other organic chemicals, nutrients, and particulates. The combined effects of these complex matrices on biochar performance are not well characterized. For example, does the presence of one pesticide hinder the adsorption of another (competitive adsorption), or could there be synergistic effects (e.g., one pollutant's adsorption creating sites or conditions favorable for another's removal)? Some studies have observed competitive sorption between co-existing pesticides on biochar [96], but systematic understanding is lacking. Additionally, how do biochar-based systems handle mixed pollution scenarios – for instance, a pesticide plus heavy metals combination? Most research isolates one pollutant class at a time. This represents a gap, as environmental waters rarely present contaminants in isolation. Developing predictive models (possibly via machine learning) for biochar performance in multi-contaminant systems is an emerging need [97].

### Biochar Aging and Environmental Interactions

Once deployed, biochar will interact with its environment in ways that may alter its properties. "Aging" of biochar – through processes like slow oxidation, microbial colonization, or coating by mineral deposits – can change surface functional groups and pore accessibility. Detailed knowledge is lacking on how such aging effects adsorption capacity for pesticides over time. Does an aged biochar become less effective, or could it sometimes become more effective (e.g., by acquiring additional oxygen-containing groups that enhance polar pollutant uptake)? Similarly, biochar's tendency to fragment or produce colloidal charcoal particles over time is not well quantified; such fragments could both reduce the available adsorbent and potentially carry sorbed pollutants into the environment. Research is needed to simulate accelerated aging of biochar and measure consequent changes in performance and risks.

### Standardization and Protocol Development

As the field progresses, there is a need for standardized testing protocols and reporting metrics for biochar adsorbents. Right now, results from different studies are hard to compare due to varying units (mg/g vs. % removal), different contact times, pollutant concentrations, etc. Standard methods (like how activated carbon is evaluated by, e.g., iodine number or BET surface area) could help in assessing biochar performance uniformly [9]. Additionally, guidelines for producing and using biochar for water treatment (covering everything from recommended pyrolysis conditions to safe application rates and post-use handling) are largely absent. Developing such best-practice guidelines and possibly certification standards for water-treatment-grade biochar will be important for translating research into practice.

## CONCLUSION

Advanced material engineering and sustainable waste management come together powerfully in biochar and biochar nanocomposites. Biochar, which is produced by thermochemically converting biomass, is an inexpensive, carbon-rich, and eco-friendly substance that can be used for pollution removal, soil enhancement, and carbon sequestration. Biochar nanocomposites show better mechanical strength, adjustable porosity, increased surface area, and greater adsorption, catalytic, and electrochemical performance when combined with nanoparticles. These developments increase their potential for high-value uses like energy storage, environmental sensing, wastewater treatment, and greenhouse gas mitigation. All things considered, biochar-based materials offer a viable route toward circular economy principles by converting organic and agricultural waste into multipurpose, high-performance materials that address critical energy and environmental issues.

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