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Biochar-based technologies for pesticide removal from water: A comprehensive review

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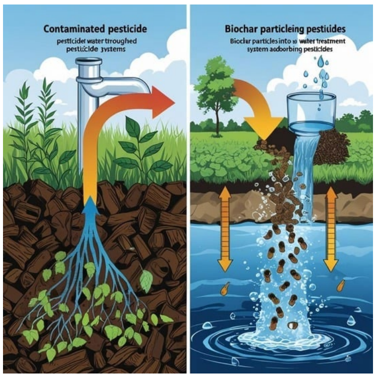
ABSTRACT

Pesticide contamination in water sources poses a significant threat to environmental and human health, demanding effective and sustainable remediation strategies. Biochar, a carbonaceous material produced through the pyrolysis of biomass, has emerged as a promising adsorbent due to its high surface area, porosity, and functional surface groups. This comprehensive review examines recent advances in biochar-based technologies for the removal of pesticides from water systems. It discusses the mechanisms of adsorption, influences of feedstock type and pyrolysis conditions, and various modification techniques to enhance adsorption capacity. The review also evaluates the practical application of biochar in water treatment, highlighting environmental benefits such as resource recycling and carbon sequestration. Challenges and future perspectives including scalability, regeneration, and integration into existing treatment frameworks are addressed. Overall, biochar-based approaches offer a sustainable, cost-effective solution for mitigating pesticide pollution and improving water quality.



Graphical Abstract

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1. Introduction

Biochar is a stable, carbon-rich material that is produced through the process of pyrolysis, which involves the thermal decomposition of organic biomass in the absence or near-absence of oxygen. This biomass can include a wide variety of feedstocks such as agricultural residues like crop stalks and husks, forestry waste such as sawdust and bark, manure from livestock, and other organic waste materials.[1-4] The pyrolysis process typically occurs under controlled conditions of low or no oxygen, which prevents combustion and instead converts the biomass into a form of charcoal known as biochar. This transformation not only stabilizes the carbon content but also generates useful byproducts like bio-oil and syngas, which can be utilized for energy production. Biochar's production and application have gained increasing attention due to its potential environmental and agricultural benefits. It is recognized as a sustainable way to improve soil quality by increasing fertility, enhancing water retention capacity, and promoting beneficial microbial activity, all of which contribute to higher crop yields. The porous structure of biochar, characterized by a large surface area, plays a critical role in its ability to retain water and nutrients efficiently, thereby reducing the need for frequent irrigation and fertilizer application. Additionally, biochar's alkaline nature helps to neutralize acidic soils, making them more suitable for a wider range of crops.[5-7] One of the most significant advantages of biochar is its capacity to sequester carbon in the soil for extended periods (ranging from hundreds to thousands of years) making it an effective strategy for mitigating climate change by reducing the amount of greenhouse gases in the atmosphere. Furthermore, biochar contributes to sustainable waste management practices by converting agricultural and forestry waste into valuable soil amendments, thus reducing pollution, waste accumulation, and the environmental impact of open burning or decomposition of organic waste. The surface chemistry of biochar includes various functional groups such as hydroxyl, carboxyl, and phenolic groups, which influence its interactions with nutrients, metals, and pollutants in the soil, thereby improving soil chemistry and pollutant retention. Properly produced biochar generally contains minimal levels of toxins or contaminants, especially when produced under controlled conditions, although its specific characteristics (such as pH, porosity, and water affinity) can vary depending on the feedstock used and the pyrolysis process parameters. Due to its high resistance to microbial degradation, biochar tends to remain stable in soils over long periods, ensuring long-term carbon storage and contributing to climate change mitigation efforts. Its versatility as a soil amendment supports sustainable agricultural practices by improving soil health, reducing dependency on chemical fertilizers, and increasing resilience against drought and erosion.[8-13] Overall, biochar's multifaceted benefits make it a promising tool for ecological restoration, climate mitigation, and sustainable land management worldwide. To provide a broader perspective, the following simplified **Table 1** highlights biochar production around the world, including key regions, typical production methods, estimated scales of production, and relevant references, illustrating the global interest and ongoing developments in biochar technology and application.

Table 1. Biochar production around the world

Region/Country	Production method	Estimated scale / Notes	References
United States	Pyrolysis (laboratory and commercial scale)	Several commercial facilities; production in the thousands of tons annually	12
European Union	Slow pyrolysis, gasification	Commercial and pilot plants; over 10,000 tons/year in some countries	https://biochar-europe.org/
China	Large-scale biomass pyrolysis; traditional and modern methods	Rapidly expanding biochar market	13-14
India	Traditional methods, pyrolysis	Small to medium-scale; growing interest in sustainable agriculture	https://www.indianjournals.com/article/ijf-13-8-009
Africa (Kenya, South Africa)	Charcoal kiln pyrolysis, improved cookstoves	Small-scale production; used for soil amendment	14
Australia	Pyrolysis, gasification	Commercial operations; biochar for agriculture and remediation	https://bioenergyaustralia.org.au/publications/
Brazil	Pyrolysis, forest residue management	Biochar for reforestation and soil health	14 https://biochar-international.org/biochar-in-brazil/

2. Mechanisms of biochar as an adsorbent for pesticide removal

Biochar has gained significant attention as an effective adsorbent for removing pesticides from contaminated environments. Its efficacy stems from a combination of physical and chemical mechanisms that facilitate pesticide retention.[14-15] The key mechanisms include; physical adsorption, electrostatic interactions, chemical interactions, and surface functional groups. Physical adsorption (physisorption) refers to the process where molecules or particles adhere to the surface of biochar through weak intermolecular forces such as Van der Waals forces, electrostatic interactions, or hydrogen bonding.[16-18] Unlike chemical adsorption, it does not involve the formation of chemical bonds. The key features of physical adsorption are its reversibility, allowing adsorbed materials to be easily desorbed by changing conditions such as temperature or pressure; its dependence on surface area, with greater surface areas providing more active sites for adsorption; the influence of pore structure, where porosity and pore size distribution affect the capacity and accessibility for adsorbates; and its temperature sensitivity, as the adsorption process typically decreases with increasing temperature due to its exothermic nature.[19-25] Biochar's porous structure provides a large surface area and numerous active sites where molecules such as pollutants, nutrients, or gases can physically adhere.[26] The process is driven by physical forces rather than chemical bonds. Electrostatic interactions of biochar are characterized by the presence of surface charges that influence its behavior and interactions within biological and environmental systems. These interactions are primarily governed by the surface functional groups (such as carboxyl, hydroxyl, and carbonyl groups) that impart negative or positive charges depending on the pH and chemical environment. The electrostatic attraction or repulsion between biochar surfaces and charged molecules, ions, or microbial cells significantly affects adsorption capacity, contaminant immobilization, and microbial adhesion.[27-28] Additionally, the zeta potential of biochar provides insights into its stability and dispersibility in aqueous solutions. Overall, electrostatic interactions play a crucial role in determining biochar's efficacy in pollutant removal, soil amendment, and environmental remediation applications. Biochar interacts chemically with soil environments primarily through its surface functional groups, such as carboxyl, hydroxyl, and phenolic groups, which facilitate the adsorption of nutrients like ammonium, phosphate, and potassium, thereby enhancing soil fertility.[29-32] It can also adsorb organic contaminants and heavy metals via cation exchange and complexation, reducing their bioavailability and toxicity. Additionally, biochar's alkaline nature can neutralize acidic soils, influencing pH and indirectly affecting microbial activity and nutrient cycling. Over time, biochar may undergo oxidation and other chemical transformations, further modifying its interaction with soil constituents and contributing to long-term carbon sequestration and soil health improvements. Biochar surface functional groups primarily consist of oxygen-containing functionalities such as hydroxyl (-OH), carboxyl (-COOH), carbonyl (C=O), and phenolic groups, which collectively contribute to its hydrophilicity and reactivity. These groups originate from the biomass feedstock and the pyrolysis process, influencing biochar's ability to adsorb nutrients, pollutants, and metal ions. Additionally, other functional groups like ether (C–O–C) and ester linkages may be present depending on the pyrolysis conditions and feedstock type. The abundance and types of surface functional groups are crucial in determining biochar's chemical interactions, stability, and overall effectiveness in environmental applications such as soil amendment and pollutant remediation. **Table 2**, summarizing the mechanisms by which biochar acts as an adsorbent for pesticide removal.

Table 2. Mechanisms of biochar acts as an adsorbent

Mechanism	Description	Key Features
Physical adsorption	Pesticides are held via van der Waals forces on biochar's surface pores.	Pore structure and surface area are critical.
Chemical adsorption	Formation of chemical bonds between pesticide molecules and functional groups on biochar.	Involves surface functional groups like hydroxyl, carboxyl.
Electrostatic attraction	Attraction between charged pesticide molecules and charged sites on biochar.	Influenced by pH and surface charge of biochar.
Hydrogen bonding	Hydrogen bonds form between pesticide molecules and biochar’s functional groups.	Contributes to specificity and strength of adsorption.
π-π Interactions	Stacking interactions between aromatic rings of pesticides and biochar’s graphitic domains.	Relevant for aromatic pesticides.
Surface complexation	Formation of stable complexes between pesticide molecules and metal/functional groups on biochar surface.	Enhances removal efficiency for certain pesticides.

3. Factors affecting biochar efficacy

The effectiveness of biochar is influenced by several factors, including feedstock type, pyrolysis conditions, particle size, application rate, and soil properties. The choice of feedstock determines the nutrient content and structural characteristics of the biochar, while pyrolysis temperature and duration affect its porosity, surface area, and stability (higher temperatures generally produce more stable and carbon-rich biochar). Particle size impacts soil integration and microbial interactions, with smaller particles offering greater surface area but potentially increasing runoff risks. The application rate must be optimized to enhance soil fertility without causing nutrient imbalances or other adverse effects. Additionally, soil pH, texture, moisture content, and existing microbial communities can modulate how biochar influences nutrient retention, microbial activity, and plant growth, making site-specific conditions critical to maximizing its benefits.[33-34]

4. Technological approaches

Biochar production and application involve various technological approaches aimed at optimizing yield, quality, and environmental benefits.[35-36] Here are some of the main technological approaches of biochar; slow pyrolysis, fast pyrolysis, intermediate pyrolysis, gasification, hydrothermal carbonization, microwave-assisted pyrolysis, catalytic pyrolysis, and plasma arc technology. Slow pyrolysis of biochar is a thermal decomposition process carried out at relatively low temperatures, typically between 350°C and 700°C, over extended periods that can range from several hours to days. During this process, biomass is heated in the absence or limited presence of oxygen, which allows it to decompose gradually, resulting in the formation of a stable, carbon-rich solid known as biochar. This method promotes the development of biochar with high porosity, stability, and nutrient retention, making it particularly suitable for soil amendment and carbon sequestration applications. Because of its slow heating rate and longer residence time, slow pyrolysis tends to maximize biochar yield and quality, though it is generally more energy-intensive and time-consuming compared to faster pyrolysis methods.[37-38] Fast pyrolysis of biochar involves rapidly heating biomass at high temperatures, typically between 500 to 700°C, in the absence of oxygen over a short residence time, often just seconds to minutes. This process primarily aims to convert biomass into bio-oil, syngas, and a smaller proportion of biochar, with the rapid heating preventing extensive carbonization and preserving some of the biomass's volatile compounds. The resulting biochar from fast pyrolysis tends to have a higher porosity and surface area compared to slow pyrolysis, making it suitable for applications such as soil amendment, carbon sequestration, and adsorption. The process is energy-efficient and allows for the simultaneous production of valuable bio-oil and syngas, which can be used for energy generation, while the residual biochar can be tailored for environmental or agricultural uses.[39-40] Intermediate pyrolysis of biochar is a thermal conversion process conducted at moderate temperatures, typically between 450°C and 600°C, with residence times that balance between slow and fast pyrolysis. This method aims to optimize the yields of both biochar and bio-oil, producing a versatile product suitable for various applications such as soil amendment, carbon sequestration, or energy production. The process involves controlled heating of biomass in an oxygen-limited environment, which facilitates the breakdown of organic materials into solid carbon-rich biochar, liquid bio-oil, and syngas. By adjusting parameters like temperature, heating rate, and residence time, intermediate pyrolysis can tailor the properties of biochar (such as porosity, surface area, and nutrient content) to meet specific functional requirements, making it a flexible and efficient technique in biochar production systems.[41-42] Gasification of biochar is a high-temperature thermochemical process typically conducted at temperatures above 700°C in a limited oxygen environment, where biomass or biochar is converted into syngas (mainly composed of carbon monoxide, hydrogen, and methane) while leaving behind a residual solid called biochar or char. This process effectively transforms organic materials into valuable gaseous fuels that can be used for energy generation or chemical synthesis, offering advantages such as energy recovery, reduced emissions, and efficient utilization of biomass residues. The residual biochar produced through gasification can also be used as a soil amendment or activated carbon, depending on its properties and processing conditions. Gasification is considered an advanced, clean technology that supports renewable energy systems and waste-to-energy applications, providing a sustainable pathway for biomass valorization.[43-44] Hydrothermal carbonization of biochar is a thermochemical process that involves treating biomass or organic waste materials with water at elevated temperatures (typically between 180°C and 250°C) and pressures under subcritical conditions. This process occurs in a sealed reactor, where the water acts as a reaction medium, facilitating the breakdown of complex organic molecules into a carbon-rich, stable, and porous solid known as hydrochar. Hydrothermal carbonization is particularly effective for processing wet biomass without the need for prior drying, making it energy-efficient and environmentally friendly. The resulting hydrochar has enhanced properties such as higher carbon content, improved porosity, and increased stability, which makes it suitable for applications in soil amendment, carbon sequestration, and energy storage. Additionally, hydrothermal carbonization reduces the moisture content and organic volatiles of the feedstock, producing a clean, solid product with a lower environmental footprint compared to traditional pyrolysis methods.[45-46] Microwave-assisted pyrolysis of biochar is an advanced thermal processing technique that utilizes microwave energy to rapidly and selectively heat biomass, leading to efficient conversion into biochar, bio-oil, and syngas. This method offers several advantages over conventional pyrolysis, including faster processing times, more uniform heating, and the ability to precisely control temperature and energy input. The microwave energy interacts directly with the biomass's polar molecules, resulting in internal heating that reduces processing duration and improves the quality and properties of the resulting biochar, such as increased porosity and surface area. Additionally, microwave-assisted pyrolysis is energy-efficient and environmentally friendly, making it a promising approach for sustainable biochar production with tailored characteristics for specific applications like soil amendment, carbon sequestration, or material development.[47-48] Catalytic pyrolysis of biochar involves the use of specific catalysts during the thermal decomposition of biomass to influence the formation and properties of the resulting biochar. By introducing catalysts such as metals, metal oxides, or mineral-based substances, this method can enhance the biochar’s surface functionality, porosity, and adsorption capacity, tailoring it for specific applications like soil amendment, pollutant removal, or energy storage. The catalytic process often occurs at controlled temperatures, enabling more efficient conversion and improved quality of the biochar compared to non-catalytic pyrolysis. Additionally, catalytic pyrolysis can facilitate the production of valuable secondary products such as bio-oil or syngas, making the overall process more economically viable and environmentally friendly.[49-50] Plasma arc technology for biochar involves using ultra-high temperature plasma torches to convert biomass into highly porous and functionalized biochar. This advanced process operates at temperatures exceeding several thousand degrees Celsius, enabling rapid and complete carbonization of feedstock with minimal emissions.

Table 3. Technological methods for biochar

Method	Description	Key Features
Slow pyrolysis	Low temperature (350–700°C), long residence time, yields high-quality biochar	Suitable for soil amendment, energy-intensive
Fast pyrolysis	Rapid heating (~500–700°C), short residence time, produces bio-oil, biochar, syngas	Balanced biochar and bio-oil production
Intermediate pyrolysis	Moderate temperature and residence time, optimized yields	Versatile, balances biochar and bio-oil yields
Gasification	High temperature (>700°C), limited oxygen, produces syngas and residual biochar	Energy recovery, clean conversion process
Hydrothermal carbonization	Uses water at 180–250°C under pressure, suitable for wet biomass	Produces hydrochar, reduces feedstock moisture
Microwave-assisted pyrolysis	Microwave energy rapidly heats biomass, energy-efficient processing	Faster, selective heating, enhanced biochar properties
Catalytic pyrolysis	Uses catalysts to influence biochar properties	Tailored biochar characteristics for specific uses
Plasma arc technology	Ultra-high temperature plasma torches, produces porous, functionalized biochar	Advanced, high-energy process, high-value biochar

The intense heat facilitates the formation of biochar with a highly developed porous structure, enhanced surface area, and tailored functional groups, making it suitable for applications such as soil enhancement, contaminant adsorption, and material reinforcement. Additionally, plasma arc processes can simultaneously generate syngas and other valuable byproducts, contributing to energy recovery and process efficiency. Due to its high energy input and technological complexity, plasma arc biochar production is considered a high-value, specialized method primarily used for producing customized biochar with specific properties for advanced environmental or industrial applications.[51] The technological methods for biochar production are summarized in **Table 3.** Technological approaches to biochar production are diverse, ranging from traditional slow pyrolysis to advanced plasma technologies. The choice depends on feedstock type, desired biochar properties, environmental considerations, and economic feasibility.

5. Advantages and limitations

Biochar provides numerous advantages, including improving soil fertility by enhancing nutrient retention and pH balance, increasing water retention and soil aeration, and promoting healthy microbial activity. It also plays a significant role in carbon sequestration, helping to mitigate climate change by locking carbon in the soil for long periods. Additionally, biochar can reduce the need for chemical fertilizers and pesticides, contribute to waste management by recycling biomass, and enhance crop productivity sustainably, making it a valuable tool in agriculture and environmental management.[52-53] The limitations of biochar include variability in its quality and effectiveness due to differences in feedstock types and pyrolysis conditions, which can lead to inconsistent results in soil application. Additionally, the production process can be energy-intensive and may generate greenhouse gases if not managed properly, potentially offsetting environmental benefits. There is also a risk of contamination if feedstocks contain toxic substances or pollutants, and large-scale deployment requires sustainable sourcing of biomass, which could compete with other land uses or food production. Furthermore, long-term impacts on soil health and ecosystems are not fully understood, necessitating further research to optimize its use.[54-56]

6. Pesticide pollution in water

Pesticide pollution in water bodies poses a significant threat to aquatic ecosystems and human health.[57-59] When pesticides are applied in agriculture or urban areas, they can runoff into rivers, lakes, and groundwater, contaminating these vital water sources. These chemicals are often persistent and can accumulate in aquatic organisms, disrupting ecosystems and causing harm to fish, amphibians, and other wildlife. Additionally, pesticide residues in drinking water sources may pose health risks to humans, including neurological, reproductive, and carcinogenic effects.[60-61] Effective management practices, such as proper pesticide application, establishing buffer zones, and promoting organic farming, are essential to reduce water contamination and protect environmental and public health.[62] Pesticide pollution in water primarily results from agricultural runoff, where rain or irrigation wash pesticides from treated fields into nearby water bodies, and from leaching, where chemicals seep through the soil into groundwater.[63-67] Additionally, atmospheric deposition can carry pesticides through the air into water sources, while improper disposal of unused chemicals and wash-off from pesticide application equipment further contribute to contamination.[68] These processes lead to the accumulation of harmful chemicals in water systems, adversely affecting aquatic ecosystems and human health. Pesticide pollution in water bodies has profound ecological and health impacts. It can cause immediate toxicity to aquatic life, leading to the decline of fish, amphibians, and invertebrate populations, and disrupts aquatic ecosystems' balance. Additionally, pesticides can bioaccumulate within the food chain, posing long-term risks to predators, including humans.[69-71] For communities relying on contaminated water sources, exposure can result in health problems such as neurological disorders, hormonal imbalances, skin irritations, and even increased cancer risk. Overall, pesticide pollution not only threatens biodiversity and ecosystem stability but also jeopardizes public health and the sustainability of water resources. To mitigate pesticide pollution in water, it is essential to adopt integrated pest management (IPM) practices that emphasize the use of biological control methods, crop rotation, and resistant crop varieties to reduce reliance on chemical pesticides. Additionally, implementing strict regulations on pesticide application, promoting the use of environmentally friendly and biodegradable pesticides, and ensuring proper handling, storage, and disposal of chemicals can significantly decrease runoff and leaching.[72] Establishing buffer zones along water bodies, practicing careful timing of pesticide application to minimize runoff during rain, and promoting awareness among farmers about safe pesticide use are also crucial. Regular monitoring of water sources for pesticide residues and encouraging sustainable agricultural practices further help protect aquatic ecosystems and safeguard public health. Addressing pesticide pollution in water requires coordinated efforts involving policy regulation, sustainable agricultural practices, public awareness, and scientific research to minimize environmental and health impacts.

7. Biochar-assisted removal of pesticide residues from water

Biochar-assisted removal of pesticide residues from water involves using biochar to adsorb and detoxify pesticide contaminants in water sources. This approach offers an eco-friendly, cost-effective, and sustainable solution for water purification, especially in agricultural runoff and contaminated water bodies. Here is **Table 4** below, summarizing notable cases where biochar has been used to remove pesticide residues from water. The utilization of biochars derived from various biowastes has shown promising results in the removal of pesticides from aqueous solutions, demonstrating their potential as sustainable and cost-effective adsorbents for water purification. For instance, switchgrass biochar, produced from switchgrass, has been tested for removing pesticides such as 2,4-D (2,4-Dichlorophenoxyacetic acid) and MCPA (2-methyl-4-chlorophenoxyacetic acid), achieving removal efficiencies ranging from 50% to 90%, indicating its considerable capacity to adsorb these herbicides.[73] Similarly, dairy manure biochar has been employed to effectively remove atrazine from water, with an approximate removal efficiency of 77%, highlighting its applicability in agricultural runoff treatment.[74] Rice husk biochar, made from rice husks, has demonstrated high efficacy in removing pesticides like atrazine, dimethoate, diuron, and chlorfenvinphos, with removal efficiencies reaching up to 97.6% for diuron and chlorfenvinphos, and around 61% for atrazine and dimethoate. Date pit biochar also proved effective, with removal efficiencies of about 56% for atrazine and an impressive 95.4% for other pesticides. Sugarcane bagasse biochar, derived from sugarcane residues, achieved approximately 60.8% removal efficiency for atrazine and 90.8% for other pesticides like dimethoate, chlorpyrifos, and malathion, further showcasing its potential in pesticide remediation.[75] Corn cob biochar, produced from corn cobs, demonstrated a broad-spectrum removal capacity, effectively adsorbing multiple pesticidesincluding atrazine, dimethoate, malathion, diazinon, diuron, profenofos, chlorfenvinphos, cyprodinil, ethion, and chlorpyrifos with efficiencies ranging from 40% to 93%.[76] Potato peel biochar was successfully used to remove chlorpyrifos from water, with a removal efficiency of approximately 72%.[77] Coconut shell biochar, especially when modified with phosphoric acid, exhibited exceptional performance in removing diazinon, reaching a removal efficiency of 98.96%, making it highly effective for specific organophosphate pesticides.[78] Biochars produced from agricultural residues such as bush, wheat straw, peanut, and corn have also shown notable effectiveness in removing pymetrozine, with efficiencies exceeding 70%.[79] Peanut shell biochar has been employed to remove imidacloprid from water in both acidic and neutral conditions, achieving removal efficiencies between 35.7% and 63.6%.[80] Sugarcane filter cake biochar has been used to adsorb thiamethoxam, with about 70% removal efficiency, further emphasizing the versatility of biowaste-derived biochars in pesticide removal applications.[81] Lastly, walnut shell biochar, modified with boric acid, has demonstrated high efficacy in removing pesticides such as tricyclazole, propiconazole, imidacloprid, and thiamethoxam from real water samples, with removal efficiencies exceeding 70%.[82] Collectively, these studies underscore the potential of various biowaste-based biochars as sustainable, efficient adsorbents capable of addressing diverse pesticide contaminants in water, offering an environmentally friendly alternative to conventional treatment methods.

Table 4. Notable cases where biochar used to remove pesticide residues from water

Biochar type / Source	Target pesticides	Water type	Removal efficiency	References
Switchgrass	2,4-D & MCPA	Aqueous solution	50 to 90%	85
Dairy manure	Atrazine	Aqueous solution	77%	86
Rice husk	Atrazine+Dimethoate & Diuron+Chlorfenvinphos	Water	61 & 97.6%	87
Date pit			56 & 95.4%	
Sugarcane bagasse	Atrazine+Dimethoate & Chlorpyrifos+Malathion		60.8 & 90.8%	
Corn cob	Atrazine, Dimethoate, Malathion, Diazinon, Diuron, Profenofos, Chlorfenvinphos, Cyprodinil, Ethion & Chlorpyrifos	Aqueous solution	40 to 93%	88
Potato peel	Chlorpyrifos	Aqueous solution	72.06%	89
Coconut shell (Phosphoric acid-modified)	Diazinon	Aqueous solution	98.96%	90
Bush+Wheat straw+Peanut+Corn	Pymetrozine	Aqueous solution	>70%	91
Peanut shell	Imidacloprid,	Acid and neutral solution	35.7 to 63.6%	92
Sugar cane filter cake	Thiamethoxam	Wastewater	70%	93
Walnut shell (boric acid modified)	Tricyclazole, Propiconazole, Imidacloprid & Thiamethoxam	Real water	>70%	94

8. Research and development trends

Research on biochar has been rapidly expanding, reflecting its growing recognition as a sustainable solution for soil enhancement, carbon sequestration, and waste management. Current trends focus on optimizing production techniques to tailor biochar properties for specific agricultural and environmental applications, understanding its long-term effects on soil health and crop productivity, and evaluating its role in mitigating greenhouse gases. There is also increasing interest in exploring the use of diverse feedstocks, including agricultural residues and waste materials, to improve economic viability and sustainability. Additionally, interdisciplinary studies are examining the environmental impacts, potential risks, and policy frameworks necessary for large-scale implementation. Overall, biochar research continues to evolve towards integrating its benefits into climate-smart agriculture and sustainable land management practices.[83-84] The development trends of biochar are increasingly focused on optimizing production methods for higher efficiency and environmental sustainability, integrating biochar into circular economy models through waste valorization, and expanding its application beyond agriculture to areas like water treatment, construction materials, and energy storage. Advances in feedstock diversification, pyrolysis technologies, and functionalization techniques aim to enhance biochar's soil amendment properties and carbon sequestration capacity. There is also growing research on large-scale deployment and policy frameworks to promote sustainable practices, alongside efforts to better understand long-term environmental impacts. Also, biochar development is moving toward more sustainable, multifunctional, and commercially viable solutions to address climate change, soil degradation, and resource management challenges.[85-86]

9. Regulatory and safety considerations

Standards for pesticide levels in water are established by various regulatory agencies to protect public health and the environment. For example, the U.S. Environmental Protection Agency (EPA) sets Maximum Contaminant Levels (MCLs) for specific pesticides in drinking water, such as atrazine (3 ppb) and glyphosate (no federal MCL, but state-specific guidelines). The World Health Organization (WHO) and the European Union also provide guidelines and regulations, including maximum residual levels (MRLs) for pesticides in drinking water and surface waters. These standards are based on toxicological data, acceptable daily intakes, and environmental considerations, and they aim to limit human exposure to harmful pesticide residues while ensuring water safety. Disposal or regeneration protocols for spent biochar involve assessing its contamination levels and potential environmental impacts. If biochar is contaminated with toxic substances or pollutants, it should be disposed of safely through designated waste management facilities, avoiding release into the environment. For biochar that remains relatively clean, regeneration can be achieved by processes such as thermal treatment (pyrolysis or calcination) to restore its adsorption capacity, or chemical washing to remove impurities. It is essential to monitor the biochar's properties post-regeneration to ensure it is safe for reuse, especially in agricultural applications. Proper protocols help prevent environmental contamination, promote resource recycling, and optimize the sustainability of biochar use. To ensure no secondary pollution from biochar use, it is essential to carefully select feedstocks that are free from contaminants such as heavy metals, pesticides, or other toxic substances. Proper production processes should be employed, including controlled pyrolysis temperatures and conditions, to minimize the formation of harmful compounds like polycyclic aromatic hydrocarbons and dioxins. Regular testing and quality assurance protocols are crucial to monitor the biochar's chemical composition and safety standards. Additionally, applying biochar at appropriate rates and in suitable environments helps prevent potential leaching of contaminants into soil and groundwater. Implementing these measures ensures that biochar contributes positively to soil health without introducing secondary pollution risks.[87-91]

10. Future perspectives

The future perspectives of biochar are promising, with ongoing research focusing on optimizing production methods, feedstock selection, and application strategies to maximize its environmental and agricultural benefits. Advances in technology could enable more efficient, low-energy, and scalable production processes, making biochar more accessible and cost-effective. Integrating biochar into sustainable land management and climate mitigation policies holds potential for significant carbon sequestration and soil health improvement. Furthermore, exploring its use in innovative fields such as wastewater treatment, renewable energy, and as a component in composite materials could expand its applications. However, realizing these potentials requires addressing current limitations related to standardization, long-term impacts, and economic viability through continued research, policy support, and stakeholder engagement. This work confirms the high importance of applied sciences in different fields as reported before in scientific papers.[92-107]

11. Conclusion

Biochar-based technologies present a promising and sustainable approach for the removal of pesticides from water sources. Due to its high surface area, porosity, and functional groups, biochar effectively adsorbs various pesticide compounds, reducing their concentration and mitigating environmental and health risks. Additionally, biochar is derived from renewable biomass, making it an environmentally friendly and cost-effective option compared to conventional treatment methods. Research indicates that optimizing biochar production conditions (such as feedstock selection, pyrolysis temperature, and surface modifications) can enhance its adsorption capacity for specific pesticides. Additionally, biochar-based systems can be seamlessly incorporated into existing water treatment frameworks, providing a flexible solution for managing agricultural runoff, industrial effluents, and contaminated water sources.

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