Journal of Environmental Management 367 (2024) 122044

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Biochar-enhanced bioremediation of eutrophic waters impacted by algal blooms

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ARTICLE INFO

Handling editor: Raf Dewil

Keywords:
Eutrophic waters
Algal blooms
Biochar
Bioremediation
Environmental remediation

ABSTRACT

The permanent problem of formation of algal blooms in water polluted with nitrogen and phosphorus is one of the formidable environmental problems. Biochar has the potential to solve the issues related to eutrophication due to its special structure and ability to absorb the nutrients. Biochar's exceptional nutrient absorption capacity allows it to absorb excess nutrients, causing the algae to use fewer nutrients. This review deals with effective performance of biochar in reducing the effects caused by algal blooms and improving the environmental conditions. Besides, an analysis of the issues involved addresses the origins and consequences of nitrogen and phosphorus pollution, and the formation of algal blooms is also reviewed. It then delves deeply into biochar, explaining its properties, production methods, and their uses in environmental contexts. The review emphasizes that biochar can be effective in dealing with many challenges associated with environments affected by algal blooms, specifically focusing on the positive effects of biochar and algae to examine their roles in controlling algae growth. Finally, the review emphasizes new achievements and innovative ideas to foster sustainable aquatic ecosystems. The discussions emphasize the central role of biochar in managing nutrient-rich waters and algal blooms.

1. Introduction

When nutrients in aquatic ecosystems are abnormally high, there will be a sudden increase in algae and eventually algal blooms, causing environmental problem, known as eutrophication (Wang et al., 2022a). Understanding how the natural factors and human activities can interact with them is important. For instance, use of chemical fertilizers for agricultural lands may lead to the accumulation of nutrients such as phosphorus and nitrogen in water (Bhatt et al., 2023). Besides, when it rains heavily or urban sewage flows into lakes and rivers without treatment, large amounts of these nutrients are transferred to aquatic environments (Liu et al., 2021b). In addition, climate changes exacerbate this problem and causes changes in the pattern of precipitation, temperature, and the frequency of climatic phenomena, affecting the food cycle in aquatic environments (Glibert, 2020). Eutrophication directly increases the algal blooms, leading to rapid growth of phytoplankton, cyanobacteria, or microalgae (Rozemeijer et al., 2021). These algal blooms cause lesser light to reach aquatic fish and lesser oxygen in water. Also, due to their large volume, the free space for other organisms is reduced and biodiversity in water is reduced (Song et al., 2023). In addition, harmful cyanobacteria can sufficiently reduce the dissolved oxygen in water to disrupt the food webs of aquatic organisms, causing the dead zones in water (Yoon et al., 2021). To reduce harmful effects of eutrophication and algal blooms, it is necessary to use effective remediation techniques.

According to a recent study (Dai et al., 2023), the occurrences of algal blooms in eutrophic waters have surged by the spatial extent (+13.2%) and frequency (+59.2%) between 2003 and 2020. Nearly, 54% of lakes and reservoirs in Asia, 53% in Europe, 48% in North America, 41% in South America, and 28% in Africa are impacted by eutrophication (Ansari et al., 2010). As per recent satellite data, Fig. 1 illustrates the deterioration map of this issue in numerous lakes globally.

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https://doi.org/10.1016/j.jenvman.2024.122044
Received 23 April 2024; Received in revised form 26 July 2024; Accepted 27 July 2024
Available online 3 August 2024

Eutrophication is a complex problem, which is associated with many financial burdens. In the United States itself during 2009, damages to freshwaters from eutrophication amounted to more than $2.2 billion (Dodds et al., 2009). Annually, public health and commercial fisheries cost $25 million and recreation and tourism $29 million due to harmful algal blooms as well as $2 million in monitoring and management these costs (Shyam et al., 2022).

Biochar is a material that can be obtained from the decomposition of organic matters, which is rich in carbon (Wang et al., 2023) and this can improve water quality to correct the problems related to eutrophication (Wang et al., 2021). Due to its specific structure and ability to absorb nutrients, biochar has been used in practical solution to the problems related to eutrophication (Kończak and Huber, 2022). The biochar's exceptional adsorption capacity to nutrients allows it to take up surplus nutrients, repair them, and decrease their quantity, all of which will eventually cause the algae to use lesser nutrients (Cheng et al., 2022). By concentrating on phosphorus and nitrogen, biochar works as a natural filter to enhance the clarity and purity of water. Using biochar in water restoration techniques shows that it can limit the growth of dangerous algae (Ren et al., 2021). By reducing the availability of nutrients needed to algal growth, biochar indirectly prevents the algal blooms from forming (Cheng et al., 2023a).

This review highlights the utilization of biochar for the bioremediation of eutrophic waters impacted by algal blooms. This review also explores how the use of biochar can assist in addressing eutrophication to reduce the intensity and frequency of algal blooms. This method provides a new insight in the management and improvement of surface water quality that can be used as a sustainable and eco-friendly solution. Besides, the use of biochar can help to restore the soil around the water and lead to the overall improvement of the aquatic ecosystems.

2. Algal blooms and eutrophication

Algal blooms, which are commonly harmful algal blooms (HABs) are the complex phenomena in ecology. These events occur due to rapid increase in the number of phytoplankton, especially harmful species, in aquatic ecosystems. These are predominantly induced by the eutrophication of aquatic environments, a process characterized by the overabundance of nutrients in the system, including nitrogen and phosphorus (Anderson et al., 2021). Numerous phytoplankton species, each with distinct properties, are included in the algal blooms (Mercado et al., 2021). Comprehension of these species' life cycles, ecological niches, and dynamics is essential to understand how the algal blooms begin and grow. Certain algae, referred to as dangerous algae, can generate poisons that could endanger both human health and aquatic life (Ramesh et al., 2023).

Conventional agricultural practices such as the use of synthetic fertilizers and livestock farming can lead to the introduction of nutrients into water bodies, which are ultimately discharged into rivers through rainwater (Effiong et al., 2020). The proliferation of urban areas also intensifies the eutrophication. Nutrient-rich runoff can be discharged into adjacent rivers and lakes by impervious surfaces, sewage systems, and industrial activities in urban environments. To prevent urban eutrophication, efficient stormwater management is vital (Zhang et al., 2022). Phosphorus and nitrogen compounds present in untreated or partially treated sewage can introduce significant amounts of nutrients into aquatic systems and intensify eutrophication (Wang et al., 2014). Notwithstanding this, climate changes could also impact nutrient cycling. Nutrient release from the sediments is facilitated by the warmer waters, which in turn stimulates the algal growth (O'Neil et al., 2012). Natural sources such as volcanic eruptions (Andrade et al., 2021) or weathering of rocks (Parthasarathy et al., 2021) can contribute nutrients to aquatic ecosystems, but human activities often amplify these natural sources (Huang et al., 2014).

While the availability of nutrients is the principal determinant, algal blooms can be caused or exacerbated due to additional environmental conditions. Variations in light availability, hydrodynamics, and water temperature are some of the few examples. One area where climate

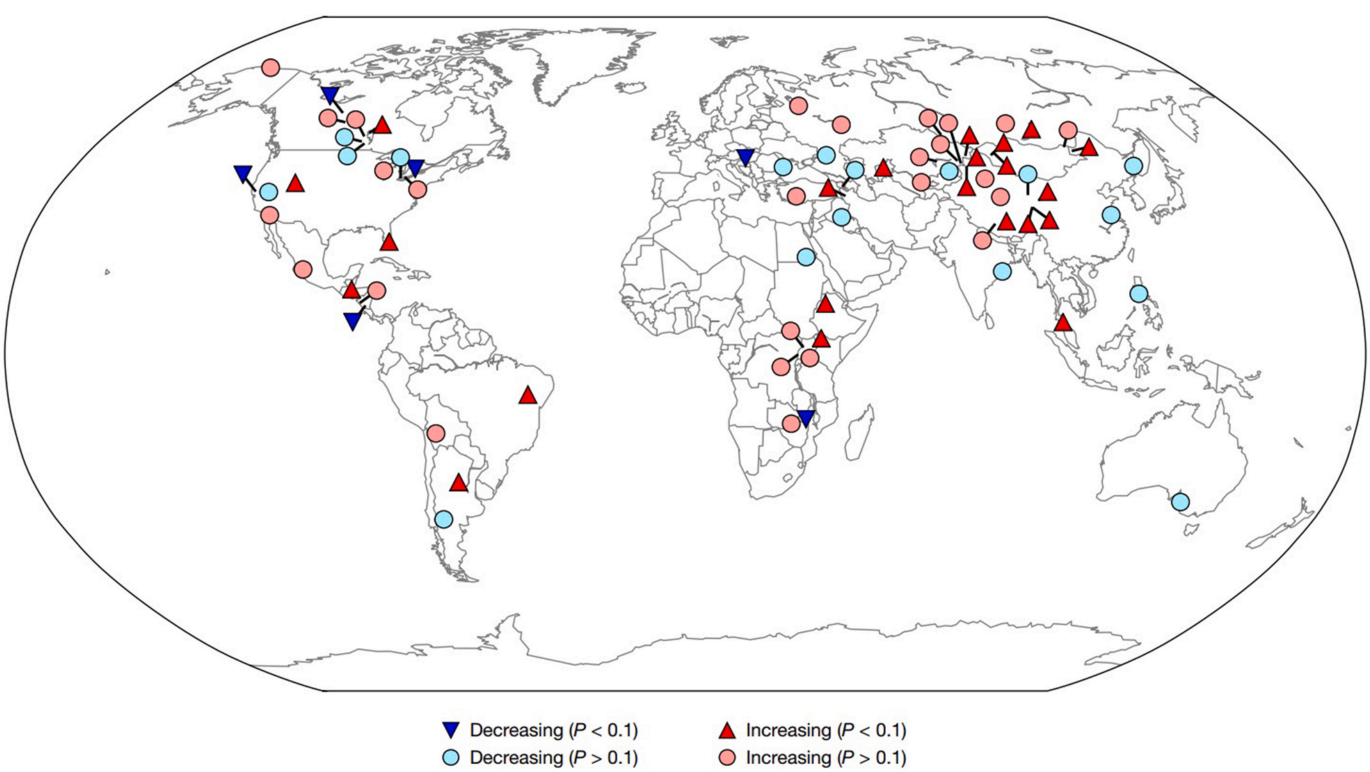

Fig. 1. Trends in lake bloom intensity distribution worldwide since the 1980s. P shows how reliable the data collected by the study is. If P < 0.1, it indicates that only less than 8% of lakes have shown a significant reduction in bloom intensity, Reproduction with permission from (Ho et al., 2019).

change has introduced further complications is by altering the environmental conditions that can promote the proliferation of algae (Glibert, 2020). Algal blooms can disrupt the food chain, induce hypoxia, or lead to anoxia by reducing the amount of dissolved oxygen in the water and competing with other organisms for the nutrients, leading to fish mortality, biodiversity loss, and environmental complications (Harrison et al., 2017). Furthermore, humans and wildlife may experience various health-related problems because of the exposure to toxins generated by the dangerous algae species (Smith et al., 2019).

In shallow lakes and ponds, alternative approaches to biochar applications to mitigate eutrophication encompass the sediment amendments, in-situ injection, and surface application. The surface application involves spreading the biochar directly onto water surface, providing a physical barrier to nutrient release and promoting the process of adsorption. In-situ injection entails directly injecting the biochar into the sediment or water column, facilitating its assimilation into the ecosystem (Patmont et al., 2015). Sediment amendments entail incorporating biochar into lake sediments to mitigate nutrient release (Amoah-Antwi et al., 2020).

2.1. Ecological and environmental impacts

Algal blooms, particularly the harmful ones, can significantly disrupt the delicate balance of aquatic ecosystems and trigger the ecological consequences. The overabundance of certain algal species, often microalgae or phytoplankton, can affect the dynamics of aquatic food webs. As these algae outcompete other organisms for nutrients, they become the primary food source for herbivorous zooplankton and filter-feeding organisms. Specific zooplankton populations may flourish due to this imbalance, which can affect fish and other higher-trophical levels. To make matters worse for the food chain, many grazers find certain algal species poisonous or unappealing (Amorim and do Nascimento Moura, 2021). For instance, durinbg 2021, the bloom of rapidophyte Heterosigma led to the death of more than 6000 tons of salmon fish in Los Lagos region (Mardones et al., 2023). Furthermore, aquatic environments can be physically altered by the algal blooms. Sunlight penetration into water column can be hindered by the dense growth of algae close to the surface of water. Submerged aquatic plants are vital to aquatic ecosystems as they can provide homes for various species, but this decrease in light may cause them to grow more slowly than usual. Fish and other creatures that rely on water plants for food and shelter may suffer due to declining plant mass (Zhu et al., 2021).

HABs, especially those caused by cyanobacteria known as blue-green algae, can produce toxins called cyanotoxins. These toxins include microcystins, anatoxins, saxitoxins, and cylindrospermopsins, which have different toxic effects. Toxins released by cyanobacteria can contaminate water sources and seriously endanger human health (Yang et al., 2022). Risks associated with consumption or contact with water contaminated by the presence of cyanotoxins include gastrointestinal disturbances, liver damage, neurological sequelae, and skin irritation (Nielsen and Jiang, 2020). Furthermore, aquatic life can be seriously affected by the ecological consequences of algal toxins as these toxins can lead to mass mortality in fish, aquatic diseases, and other aquatic organisms (Zhang et al., 2023). Table 1 summarizes the literature on ecological impacts of algal blooms.

Table 1
Ecological impacts of algal blooms.

Study Focus	Key Findings	Ref.
Altered food web	Algal blooms disrupt the balance of aquatic food webs by favoring herbivorous zooplankton, impacting water quality and fisheries production.	Danielsdottir et al. (2007)
Habitat changes	Algal growth near water surface inhibits seagrasses and submerged aquatic plant growth and affects aquatic habitats.	Imai et al. (2021)
Eutrophication	Excessive nutrient loading fuels algal blooms, changing aquatic ecosystem composition and nutrient cycling.	Ly et al. (2021)
Biodiversity loss	Harmful algal blooms cause deoxygenation of seawater, negatively impact the diversity of aquatic species, and alter ecological dynamics.	Brown et al. (2020)
Algal toxins	Cyanotoxins produced during blooms threaten fish and aquatic life, leading to mass mortalities and fish kills.	Rolton et al. (2022)
Oxygen depletion (hypoxia and anoxia)	Algal blooms can led to extensive hypoxia and significant mortality of benthic biota and fish.	Karim et al. (2002)
Decreasing water quality	Harmful algal blooms significantly reduce water quality by increasing pH, stratification, eutrophication, and reducing water transparency.	(Amorim and do Nascimento Moura, 2021)
Reduced light penetration	Phytoplankton bloom significantly reduced light penetration in the river water.	Gallegos and Jordan (2002)

3. Biochar: properties and applications

Biochar is a carbon-rich solid material produced by the thermal decomposition of plant biomass such as discarded plants and animal manure in a low-oxygen environment in the temperature range between 300 and 700 °C (Kumar et al., 2023). The notable characteristics of biochar is its high carbon content, primarily associated with the aromatic organic carbon (Liu et al., 2023a). This unique composition allows biochar to sequester carbon effectively, preventing its release into the atmosphere under favorable conditions, especially when integrated into the soil (Kumar et al., 2023). Biochar production typically involves large tank-like devices where biomass is loaded and subjected to pyrolysis, resulting in the conversion of biomass to biochar (Xue et al., 2022).

Physical and chemical properties of biochars are influenced by various factors, including the source of raw materials, pyrolysis unit conditions, heating rate, particle size, pyrolysis peak temperature, and duration (Sivaranjanee et al., 2023). The biochars exhibit a wide-ranging elemental composition, ash content, specific mass, porosity, pore size distribution, specific surface area, surface chemistry, water and ion adsorption capabilities, pH levels, and physical structure uniformity (Sinha et al., 2022). Introducing biochar might have unintended consequences in rare instances such as altering the pH levels or releasing the substances that could negatively affect the water quality. This could happen if the biochar used is not adequately characterized or if there are unfavorable interactions with other elements in water (Xiang et al., 2021).

Among the many diverse applications of biochar, its role in mitigating eutrophic waters impacted by the algal blooms has been the promising approach (Ou et al., 2023). Various biochars in different forms are available for applications, including powdered, granulated, or immobilized forms in materials such as beads or fabrics (Palansooriya et al., 2022). However, its applications in eutrophic waters and remediation of algal blooms encompass vital aspects such as nutrient adsorption, algal growth inhibition, water clarity improvement, toxin reduction, erosion control, and long-term carbon sequestration (Wu et al., 2022b).

Biochar is an excellent natural sorbent material for phosphorus removal from wastewater and other water-based natural sources (Sinha et al., 2022; Ly et al., 2023). Phosphorus removal can be highly sensitive to chemical makeup processes of water matrix, including the presence of competing ions and the overall pH conditions. Several recommendations for future research have been putforth to amplify environmental efficacy of biochar applications. These suggestions aim to streamline and augment the impact of biochar in addressing the challenges of phosphorus removal. The properties, in turn, are influenced by the factors such as biomass type, pre-treatment methods, and pyrolysis conditions during the production. Leveraging its extensive porous structure as a physical sorbent, biochar demonstrates remarkable effectiveness across various phosphorus concentrations. A proactive step towards avoiding the possible environmental problems of using biochar as a physical sorbent is due to its cost-effectiveness and is quite efficient (Fang et al., 2014; Nobaharan et al., 2021).

3.1. Synthesis methods of biochars

Biochar can be synthesized using a variety of methods. Since the physical and chemical properties of biochar are affected by the chosen synthesis method, it is necessary to choose the right approach depending on its intended application (Xue et al., 2022). In this section, several standard synthesis methods of biochar are discussed, each offering unique advantages towards producing biochars with distinct characteristics (Table 2).

Pyrolysis: This is one of the most common methods of producing biochar, which entails heating organic materials such as biomass, wood, and agricultural waste in an oxygen-limited atmosphere. Because no perfect oxygen is present, the organic matter cannot burn and transforms into a stable, high-carbon substance. The temperature and length of the pyrolysis dramatically influence the properties of the biochar. Higher temperatures typically result in more stable biochars with a higher carbon content. Biochar with an optimal surface area to porosity ratio has been typically produced by the slow pyrolysis at 300–700 °C (Manyà, 2012). Zhang et al. (2015) investigated the effects of different pyrolysis temperatures and heating durations on the properties of biochar made from lignosulfonate and straw. The results unveiled that temperature exerted a more substantial influence on the properties of the biochar than the duration of heating. Furthermore, their data clearly demonstrated that elevated temperatures increased both porosity and aromaticity of the resulting biochar during pyrolysis. Additionally, Bourke et al. (2007) reported that temperature affected the composition of biochar produced from pyrolysis process.

Gasification: This is another thermal conversion method that varies from the pyrolysis in terms of oxygen availability. In gasification, the organic feedstock is partially burnt by adding steam or oxygen in a controlled proportion, producing syngas—a mixture of hydrogen, carbon monoxide, and other gases. This technique yields biochar as a byproduct. Higher temperatures are frequently used for gasification, producing more stable biochar with less volatiles (You et al., 2017).

Hydrothermal carbonization (HTC): In hydrothermal carbonization, wet biomass is heated to high pressures and temperatures while being wet. This process works well with moist feedstocks such as algae and sewage sludge. Hydrothermal carbonization can create biochar with a high carbon concentration and distinctive surface characteristics. The characteristics of the biochar in hydrothermal carbonization can be controlled by adjusting the reaction conditions (Liu et al., 2013). In this regard, Kumar et al. (2011) utilized hydrothermal carbonization method to create the biochar from switchgrass, employing a precisely controlled temperature of 300 °C. These studies suggested that hydrothermal carbonization produces the biochar a carbon-neutral solution that can successfully remove several contaminants.

Microwave and electrical heating: Microwave or electrical heating techniques are employed for quick pyrolysis. These methods can effectively produce a particular-quality biochar to enable fine control over the heating rates, which are frequently used in applications needing specific properties of the biochars (Ye et al., 2019). Paunovic et al. (2019) produced a biochar by chemically activating the wild plum kernels with KOH using the microwaves. The study revealed that microwave irradiation significantly reduced the quantity of oxygen-containing functional groups in the biochar. This reduction, in turn, led to an increased adsorption capacity for various pollutants. Fig. 2 illustrates the microwave activation process utilized to produce biochar. This method involves using microwave energy to initiate specific transformations, leading to the creation of biochar.

Table 2
Biochar conversion techniques and process conditions.

Biochar Production Method	Experimental Conditions	Effect on Biochar Characteristics	Ref.
Pyrolysis	- Temperature	- Higher temperatures lead to increased surface area and porosity.	(Cantrell et al., 2012; Wang et al., 2020b)
	- Heating Rate	- Faster heating rates may result in biochar with a higher surface area.	
	- Feedstock Type	- Different feedstocks influence biochar properties (e.g., wood vs. agri-waste).	
	- Residence Time	- Prolonged residence times may enhance carbonization and affect porosity.	
	- Inert Gas Atmosphere	- Inert gases can impact biochar properties, e.g., nitrogen-enriched biochar.	
	- Final Pyrolysis Temperature	- Higher final temperatures influence biochar structure and stability.	
Hydrothermal Carbonization	- Temperature	- Higher temperatures can lead to increased carbon content.	(Liu et al., 2013; Kim et al., 2015)
	- Reaction Time	- Longer reaction times may result in biochar with enhanced stability.	
	- Pressure	- Higher pressures can affect the morphology and porosity of biochar.	
	- pH	- Acidic conditions can influence biochar properties.	
Gasification	- Gasification Temp.	- Higher temperatures can affect biochar composition and surface area.	You et al. (2017)
	- Gas Flow Rate	- Higher gas flow rates may influence the porosity and structure of biochar.	
	- Residence Time	- Longer residence times can affect the properties of the produced biochar.	
	- Steam/ Biomass Ratio	- The ratio can influence biochar yield and properties.	
	- Catalysts	- The presence of catalysts can alter biochar composition and properties.	

Biomass gasification with biochar production (BGBC): BGBC is a two-stage process where the biomass is first gasified, and then biochar is produced from the gasification residues. Maximizing the energy recovery from the feedstock while offering flexibility in biochar production is the goal of this approach (Yao et al., 2016).

Flash carbonization: Flash carbonization involves sudden pressure and temperature release after rapid biomass heating. As a consequence, organic matter breaks down, and biochar is created. Thanks to its high heating rate, biochar with particular qualities appropriate for various applications can be produced via flash carbonization (Meyer et al.,

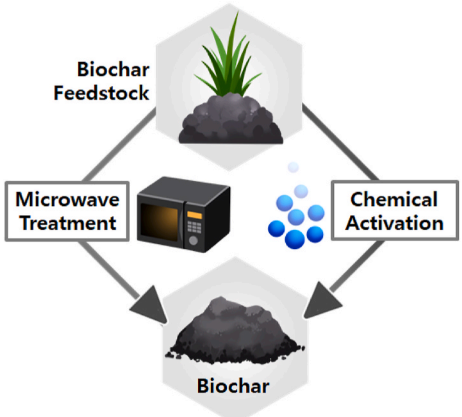

Fig. 2. Schematics of the critical steps and mechanisms involved in microwave activation for biochar production.

2011).

Fig. 3 presents various biochar synthesis methods, illustrating the diverse techniques transforming organic materials into these valuable carbon-rich materials. The diagram showcases the array of methods employed in biochar production, each with its unique approach to harnessing the potential of organic matter.

The capacity of slow pyrolysis to produce biochar with a high surface area and porosity guarantees improved contaminant adsorption, making it an attractive biochar preparation method in wastewater treatment applications (Zheng et al., 2023). Noteworthy for its effectiveness in nutrient retention, slow pyrolysis biochar proves beneficial in mitigating nutrient runoff and promoting the water quality (Carvalho et al., 2022). The porous structure of the method facilitates adsorption of a broad spectrum of organic and inorganic contaminants that are commonly found in water. Additionally, slow pyrolysis biochar supports carbon sequestration, providing an environmental advantage to mitigate climate change. However, when selecting a biochar preparation method, site-specific factors, feedstock characteristics, and local conditions should be considered to tailor the approach to unique challenges and objectives of any water restoration project.

There are a number of other different methods to estimate biochar, which include physical, chemical, and biological approaches (Leng et al., 2019). In the physical methods, surface area analysis using Brunauer-Emmett-Teller (BET) and microscopic imaging with transmission electron microscope (TEM) or scanning electron microscopy (SEM) have been used to observe the structure and morphology of biochars (Brewer et al., 2014). In chemical methods, Fourier transform infrared spectroscopy (FTIR) is used to identify the functional groups, elemental analysis using CHNSO analyzer to determine the elemental composition, and gas chromatography coupled with mass spectrometry (GC-MS) to identify the organic compounds (Xie et al., 2024). In biological methods, biodegradability tests are used to investigate the biodegradability of the biochars using the microorganisms, and microbial activity tests are used to measure microbial activities such as microbial respiration and enzyme production in the presence of biochar (Thies and Rillig, 2012). These methods can also be used in combination depending on the purpose of the study and specific characteristics of the biochars (Leng et al., 2019).

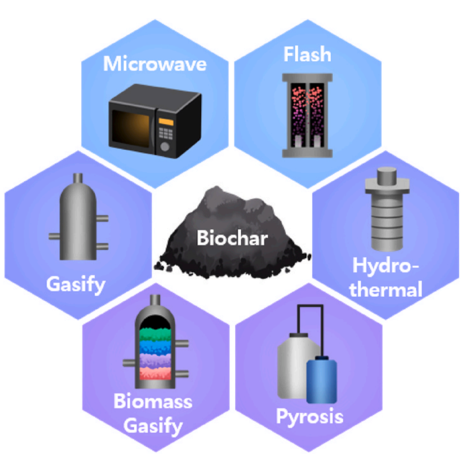

Fig. 3. Different methods of biochar synthesis from raw feedstock to improve bioremediation of eutrophic waters impacted by the algal blooms.

4. Nutrient management with biochar

Managing excess nutrients, particularly nitrogen and phosphorus in eutrophic waters impacted by the algal blooms is critical to environmental remediation (Anderson et al., 2021). With its remarkable nutrient adsorption capabilities, biochar has emerged as a promising tool in eutrophic water management due to its ability to reduce nutrient leaching. When applied in soils or sediment, biochar acts as a buffer, preventing excess nutrients from entering the water bodies. A significant factor in eutrophication, nutrient runoff can be mitigated by retaining the nutrients within the biochar-amended soil or sediment (Blanco--Canqui, 2019).

The presence of biochar in aquatic ecosystems can influence the nutrient cycling. Adsorption temporarily locks the nutrients, reducing their availability to aquatic organisms such as algae, which contributes to decreased algal blooms, thereby shifting the nutrient's dynamics within the ecosystem (Takaya et al., 2016). In addition, algal bloom frequency and severity can be affected by the biochar-induced decrease in nutrient availability (Bolton et al., 2019). Since the biochar is mainly characterized by its high surface area, porous structure, and negatively charged sites, all of which facilitate the adsorption of nutrients (Carey et al., 2015) as nutrient sorption onto the biochar occurs through several mechanisms:

Cation exchange: Negatively charged functional groups onto the surfaces of the biochar can attract and retain cations such as ammonium (NH_4^+) and metal ions (Šimanský et al., 2018).

Anion exchange: Biochar's positively charged sites can effectively adsorb anions, including phosphate (PO_4^-) and nitrate (NO_3^-) (Wang et al., 2022b).

Surface complexation: Nutrients can form complexes with biochar's surface functional groups, enhancing adsorption (Xiang et al., 2020).

Pore filling: The porous structure of biochar allows the physical trapping of nutrients within its pores (Masto et al., 2013).

In some cases, the application of biochars may exhibit synergistic effects when combined with other remediation strategies. By adsorbing and retaining the nutrients, biochar can can enhance the efficacy of other bioremediation techniques such as algal harvesting or introducing nutrient-removing organisms (Sforza et al., 2020). In this respect, Gong et al. (2019a) performed an analysis to determine biochar's nutrient adsorption capacities. This study obserevd that the most effective pores of the biochar for nutrient adsorption were within the range of 0.6–2 nm diameter. Further, it was observed that biochar produced at 600 °C in the presence of CO_2 exhibited the highest nutrient adsorption capacity. Notably, even after subjecting the biochar to five adsorption cycles, it retained over 40% of its initial nutrient adsorption capacity, indicating its considerable potential for reuse.

In efforts to decrease eutrophication in aquatic ecosystems, Konneh et al. (2021) examined the efficacy of biochar made from rice, coconut, and coffee husks to remove nitrates (NO_3-N) and nitrites (NO_2-N) from the slaughterhouse wastewater. This study evaluated the adsorbed nutrients' desorption efficiencies to determine if these enriched biochars could be used as slow-release devices for the fertilizers. These findings revealed that biochar produced from the coconut husk exhibited the highest adsorption capacities for NO_3-N and NO_2-N giving the values of

12.97 mg g^{-1} and 0.244 mg g^{-1}, respectively. Such an exceptional adsorption performance can be attributed to high porosity. In comparison, adsorption capacities of biochar fabricated from the rice husk were slightly lower showing 12.315 mg g^{-1} for NO_3-N and 0.233 mg g^{-1} for NO_2-N. Similarly, coffee husk biochar displayed adsorption capacities of 12.08 mg g^{-1} for NO_3-N and 0.218 mg g^{-1} for NO_2-N. For the rice husk biochar, the desorption efficiency of nitrates was 22.4%, while the coconut husk-derived biochar showed higher efficiency of 24.39%, and coffee husk-derived biochar exhibited an efficiency of 16.79%. As regards nitrites, rice husk biochar showed desorption efficiency of 80.73%, coconut husk-derived biochar demonstrated the highest efficiency of 91.39%, while that produced from the coffee husk-derived biochar showed adsorption capacity of 83.62%. These results suggest that biochars have the potential to be enriched with NO_3-N and NO_2-N that can be effectively utilized as slow-release formulations for the fertilizers. Additionally, the biochar's varying adsorption and desorption capacities provide insights into their potential uses in nutrient removal; of these, biochar made from coconut husks stands out as the most promising material owing to its high adsorption capacity.

In a recent study, Qu et al. (2020) developed a magnetic biochar decorated with $NaLa(CO_3)_2$ by the one-pot hydrothermal method that was used to remove the phosphate from eutrophic waters. This study involved the pyrolysis of corn straw at 800 °C in a tube furnace under nitrogen-flowing atmosphere to create the biochar as per the sceheme shown in Fig. 4. Batch adsorption experiments showed that pH affected the La-Fe-phosphate biochar's uptake, and its ability to increase the pH of the solution while at the same time removing the phosphates, further suggesting that it has enhanced the alkalinity. Further investigations about the adsorption mechanisms suggested phosphate binding to La-Fe-biochar resulting from electrostatic attractions and inner-sphere complexation via the ligand exchange (Fig. 4). Additionally, the phosphate adsorbed onto La-Fe-biochar was easily desorbed using NaOH solution, with a minor decrease in adsorption efficiency observed after five cycles. In another review (Kizito et al., 2015), it was suggested that although biochar has significant ability in nutrient management, its effectiveness can be influenced by factors such as biochar type, feedstock, and specific characteristics of the aquatic environments. However, long-term stability and potential nutrient release from the biochar under changing conditions require further research.

Table 3 summarizes the key studies on the application of biochar for nutrient adsorption in eutrophic waters impacted by the algal blooms, including the type of biochars used, application methods, and the results observed in each study.

Dynamic changes in algal communities are driven by the availability of nutrient, water temperature, light, pH, dissolved oxygen, competition, predation, habitat alterations, invasive species, and climate changes. When taken as a whole, these variables affect the diversity and abundance of aquatic algae, which in turn changes the dynamics of the community that may have ecological consequences. Monitoring and understanding these dynamics is crucial for effectively managing and mitigating the algal blooms and their consequences on water quality and the ecosystem health (Wells et al., 2015).

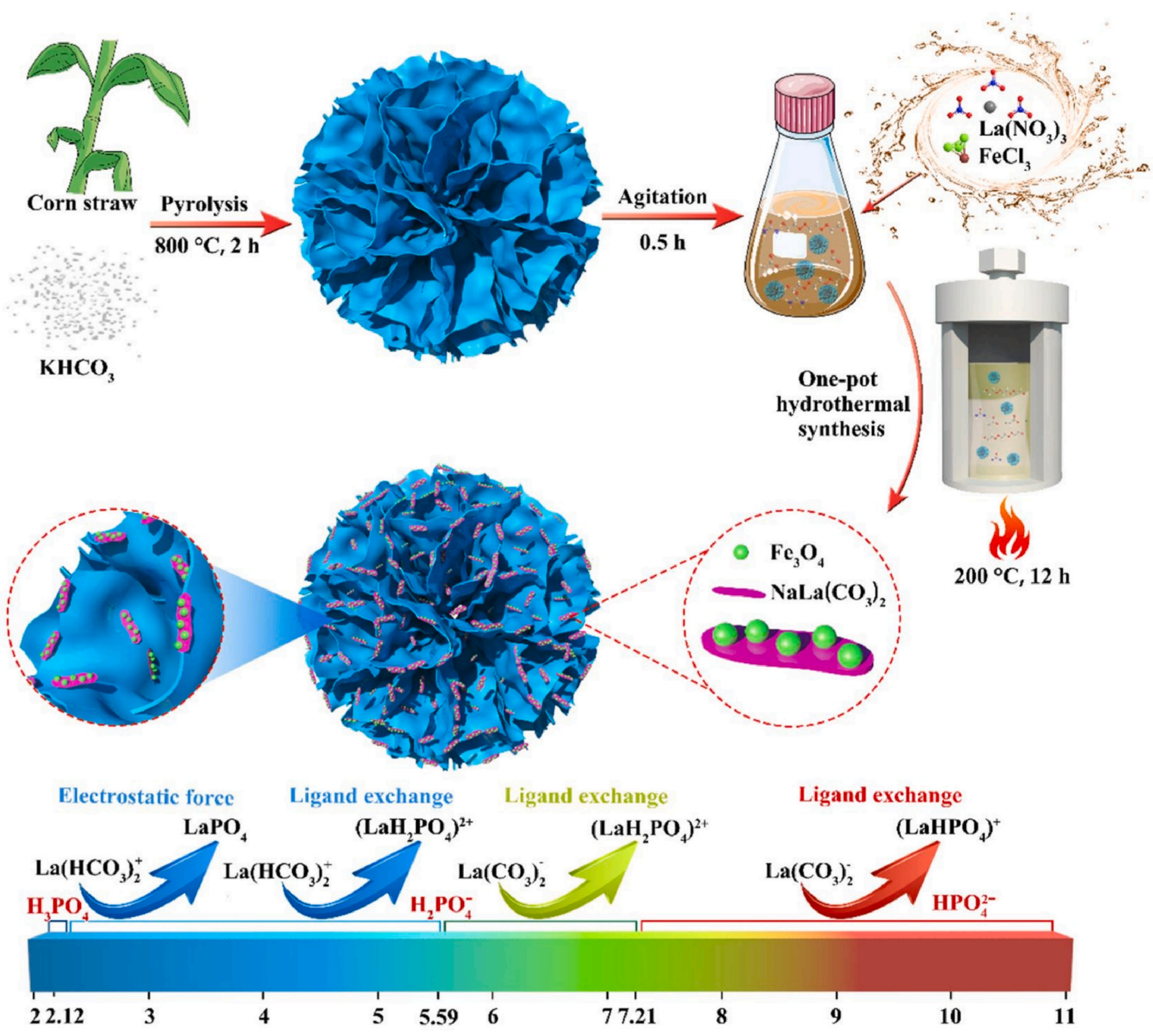

Fig. 4. Magnetic biochar decorated with $NaLa(CO_3)_2$ to efficiently remove phosphate from eutrophic waters, Reproduction with permission from (Qu et al., 2020).

Table 3
Recent studies on biochar for nutrient adsorption in eutrophic waters impacted by algal blooms.

Biochar Type	Synthesized Method	Application Method	Nutrient Type	Adsorption Capacity (mg g^{-1})	Kinetic	Isotherm	Ref.
Rrice straw	Carbonization	Laboratory application	NH_4^+-N	13.21–13.91	PSO	ND	Gong et al. (2019a)
			NO_3^--N	10.38–13.40	PSO	ND	
			P	12.18–12.42	PSO	ND	
			K	11.51–13.50	PSO	ND	
Oak wood, presscake	Hydrothermal carbonization	Laboratory application	PO_4–P	0–30	PSO	Freundlich	Takaya et al. (2016)
			NH_4–N	105.8–146.4	PSO	Freundlich	
Chipped hemp fibre	Pyrolysis	Watershed-scale application	PO_4–P	ND	ND	ND	Bolton et al. (2019)
Corn straw	Pyrolysis	Laboratory application	Phosphate	330.86	PSO	Langmuir	Qu et al. (2020)
Coconut husk	Carbonization	Laboratory application	NH_4^+	5.9	PSO	Low initial concentration: Freundlich	Thongsamer et al. (2022)
			NO_3^-	1.7	PSO	High initial concentration: Langmuir	
			PO_4^{3-}	6.7	PSO		
Eucalyptus wandoo	Pyrolysis	Synthetic stormwater	NH_3-N	100% (Adsorption removal)	PSO	Langmuir	Alam and AHM (2020)
			NO_2-N		PSO	Langmuir	
			PO_4-P		PSO	Langmuir	
Rice husk	Pyrolysis	Slaughterhouse wastewater	NO_3-N	12.315	ND	Langmuir	Konneh et al. (2021)
Rice husk			NO_2-N	0.233	ND	Langmuir	
Coffee husk			NO_3-N	12.08	ND	Langmuir	
Coffee husk			NO_2-N	0.218	ND	Langmuir	

PFO: Pseudo-first-order.
PSO: Pseudo-second-order.
ND: Not detected.
NO_3-N: Nitrate nitrogen.

5. Biochar-assisted algal bloom growth inhibition

The uncontrolled proliferation of harmful algal blooms significantly threatens the aquatic ecosystems, water quality, and human health (Brooks et al., 2016). Biochar's ability to adsorb and sequester nutrients from the water column can limit the nutrient availability to algae, subsequently inhibiting their growth (Hu et al., 2019). Several studies have demonstrated the efficacy of biochar in reducing the nutrient levels and impeding the algal bloom formation. For instance, in a study by Huang et al. (2023), the utilization of nanoscale biochar for the inhibition of *Chlorella vulgaris* growth was documented (Fig. 5). The research revealed that pyrolysis at 700 °C induced the most significant inhibition of algal growth and triggered the oxidative stress in microalgae. The study further attributed the temperature-dependent toxicity to factors such as biochar particle size and presence of carboxyl functional groups (–COOH). These investigations suggested how the biochar may increase the permeability of algae cell membranes by reducing the polyunsaturated fatty acids through the reactive oxygen species. Therefore, to understand the possible effects of biochar exposure on algal growth and aquatic ecosystems, it is necessary to understand these mechanisms.

Liu et al. (2023c) demonstrated the suppression of *Microcystis aeruginosa* growth using a metal-organic framework (MOF) with biochar (Fe_3O_4-Biochar@Cu-MOF-74) when exposed to visible light. These findings indicated that this MOF led to a considerable reduction of

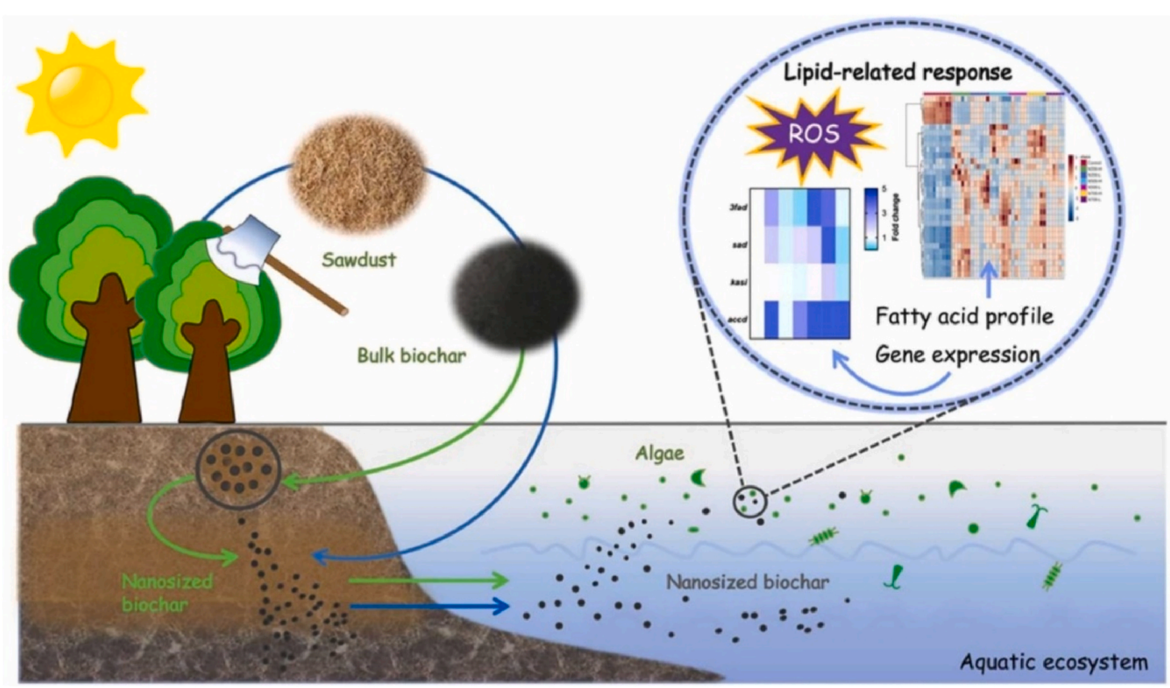

Fig. 5. Freshwater algal growth inhibition by nanosized biochar, Reproduction with permission from (Huang et al., 2023).

57.27% in chlorophyll-a content in *Microcystis aeruginosa*. The addition of biochar to MOF structure makes this composite more effective in absorbing organic nutrients and metabolic precursors, which are essential for the growth of microalgae such as *Microcystis aeruginosa*. This could substantially reduce the nutrient availability for algal species, directly hindering its growth. Besides, Li et al. (2019) investigated the application of a biochar-infused composite to investigate its prospective effectiveness in curbing the proliferation of harmful cyanobacterium *Microcystis aeruginosa*. The outcome of this demonstrated biochar's substantial capacity to restrain *Microcystis aeruginosa*'s growth, suggesting a considerable promise of this composite as an inhibitor for addressing the challenges associated with eutrophic water bodies.

Even though MOFs exhibit exceptional adsorption capabilities, their interactions with heavy metals lead to unintended consequences. Heavy metal concentrations in water could rise due to the release of metal(s) during MOF saturation or degradation, thereby harming the aquatic ecosystems and the people. In order to guarantee the effectiveness and environmental safety of MOF-based water remediation strategies, it is therefore crucial to have a thorough understanding of the fate and behavior of heavy metals within the MOF-water system (Gatou et al., 2021). In addition to its role in limiting nutrient availability, biochar's influence on algal community dynamics is a critical aspect of its application in eutrophic waters. Adding the biochar to eutrophic waters can alter its chemistry, changing the pH and releasing the organic compounds. Such changes, in turn, can affect the growth and competition of algal species. Biochar can thus shift the aquatic environment's physicochemical properties to favor some algal species while undermining the others. In addition, biochar can indirectly affect the dynamics of algal communities by encouraging the growth of beneficial microbes such as specific fungi and bacteria. These microorganisms may outcompete or interact with the algae in a manner that further shape the composition of the algal community (Zhu et al., 2019).

5.1. Mechanisms of biochar in algal bloom control

Because of its unique qualities, biochar can effectively stop the growth of algal blooms. Its large surface area, which offers plenty of binding sites for algae cells and their nutrients, is one of its essential characteristics. Biochar absorbs excess nutrients like phosphates and nitrates from eutrophic waterways suffering algal blooms (Novais et al., 2018). In addition to encouraging microbial colonization, biochar's porous structure also fosters a diverse microbial community. This capacity of the microbes to aid in organic matter breakdown and chemical synthesis inhibits the algal development that can amplify algal bloom inhibitory effects (Cheng et al., 2023b). One crucial mechanism underlying the biochar's potential to prevent the establishment of algal blooms is its capacity to absorb and immobilize nutrients. These nutrients, mainly nitrogen and phosphorus, can be absorbed by the biochar thanks to its large surface area and porous structure, which lowers the nutrients' availability to algae (Ren et al., 2021). The absorption capacity of biochar increased with an increase in pyrolysis temperature, thereby improving its ability to remove ammonium and phosphate ions from eutrophic water (Kończak and Huber, 2022).

Algal cell aggregation, facilitated by the surfaces of biochar particles, may hasten the settling rate of algae when biochar is added. Algal cells that come into contact with biochar may flocculate or group together. Because of the electrostatic interactions between biochar particles and algal cells, the amount of time algae spend in the water column is shortened, causing larger aggregates to develop and settle more quickly (Gao et al., 2023). Because biochar competes with algae for available nutrients, it can also disrupt their growth. Besides, the introduction of biochar into water has the potential to alter its pH and release organic molecules. These modifications may affect algae growth and provide an environment in which some algae species are less preferred than others (Zhu et al., 2019).

The influence of biochar extends to the microbial community in the water. Microorganisms that can be benefitted from the biochar amendments can indirectly affect the algal growth. For example, certain bacteria may outcompete or interact with algae, affecting their growth and success within the algal community (Cheng et al., 2022). There are two main mechanisms by which biochar affects the algal communities: direct interactions and microbial mediation. The addition of biochar to water sources creates an ideal environment for the colonization of microbes. Microorganisms that thrive in the presence of biochar can influence algal dynamics. For instance, certain bacteria may engage in mutualistic relationships with algae, providing essential nutrients or enhancing nutrient cycling, benefiting the algal community. On the other hand, microbial community can also exert inhibitory effects on algal growth. Microbes and algae compete for nutrients, which can suppress some species of algae and change the community's overall makeup. By fostering these microbial interactions, biochar plays a pivotal role in shaping the overall dynamics of algal communities in eutrophic waters (Liu et al., 2023b). In this regard, Cheng et al., examined the use of biochar in controlling eutrophication and removing the microcystins (MCs) in constructed wetlands (CWs). In this study, 40 cm hight 20 cm diameter cylindrical polyethylene microcosms modified with biochar were created. Two batch experiments were performed with a three-day operation period for each batch. The study involved the establishment of CWs with different biochar addition levels (0% (BC0-CWs), 10% (BC10-CWs), 20% (BC20-CWs), and 50% (BC50-CWs)) to assess the effectiveness of biochar-amended wetlands in managing eutrophication and microcystins pollution. The research findings indicated that introducing the biochar induced changes in the microbial community (Fig. 6) and led to varying degrees of improvement in removing NH_4^+-N and NO_3−-N. In addition, the study observed that addition of biochar increased the relative abundance of certain functional microorganisms, including *Burkholderiaceae, Micrococcaceae, Nitrospiraceae, Xanthomonadaceae, and Sphingomonadaceae*. These microorganisms play a role in inhibiting the growth of the algae in reducing water eutrophication. BC20-CWs and BC50-CWs have shown improved removal performance due to higher relative abundances of these microorganisms (Cheng et al., 2022).

6. Potential of biochar-enhanced bioremediation in eutrophic waters

Bioremediation is a promising approach to mitigate eutrophication by employing biological processes to remove excess nutrients and restore ecological balance (Lu et al., 2014). As a carbon-rich material, biochar has recently attracted interest for use in bioremediation techniques. Biochar's unique physicochemical properties are the valuable tools to enhance the performance of bioremediation techniques, such as phytoremediation, microbial remediation, and constructed wetlands (Sforza et al., 2020). In this comprehensive strategy, biochar is a multipurpose weapon in the fight against eutrophication. It improves the ability of constructed wetlands to remove the nutrients, increases the growth of beneficial microbes in microbial bioremediation, and helps phytoremediation systems retain the nutrients. Through its ability to support these natural processes, biochar plays a crucial role in improving water quality, decreasing nutrient pollution, and reducing the adverse effects of algal blooms on the aquatic ecosystems. Fig. 7 shows the ability of biochar to increase the efficiency of bioremediation to deal with eutrophication for long-term environmental cleanup.

6.1. Phytoremediation

Phytoremediation, a green approach for mitigating nutrient pollution, has demonstrated its effectiveness in harnessing the capabilities of plants to uptake excess nutrients from water bodies. However, the potential of phytoremediation systems to remove nutrients can be significantly enhanced through the strategic integration of biochar, a multifaceted carbon-rich material. Combining phytoremediation and

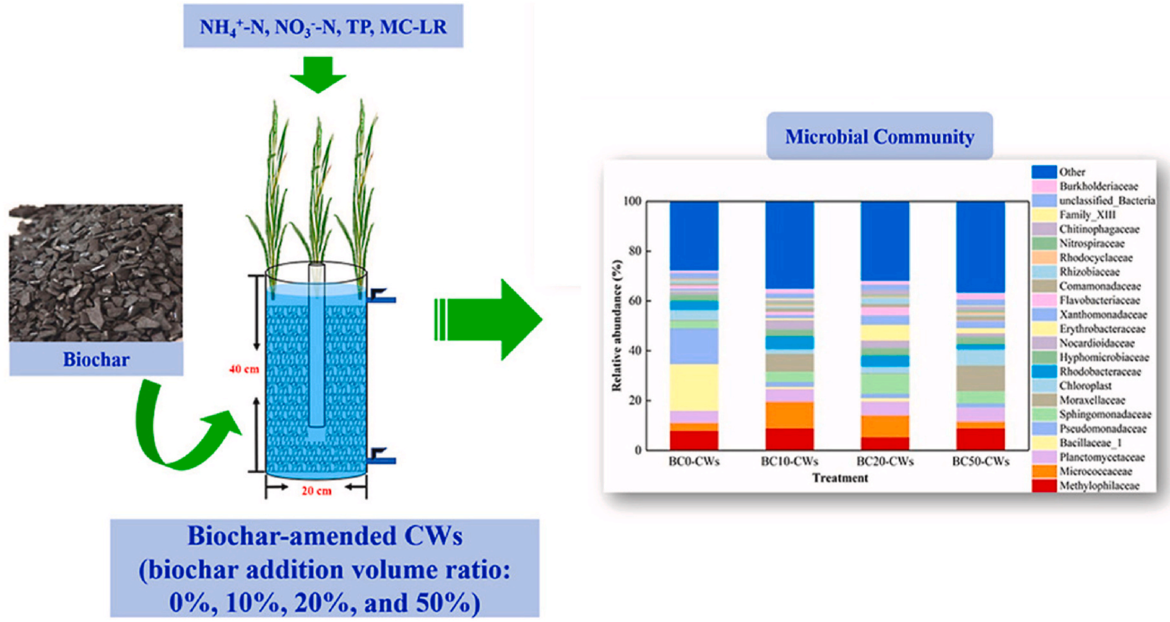

Fig. 6. Impact of biochar on algal communities for reducing of water eutrophication. Modified and reproduction with permission from (Cheng et al., 2022).

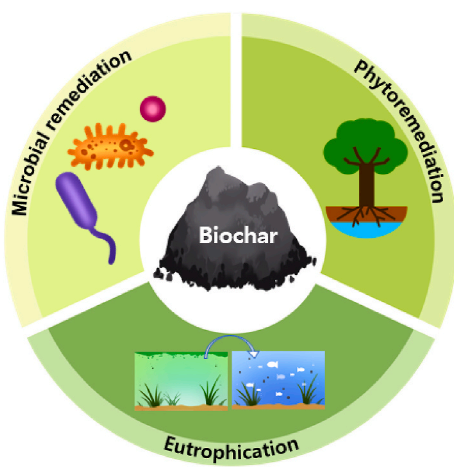

Fig. 7. The potential of biochar to enhance bioremediation of eutrophic waters.

biochar augments nutrient removal and brings about a range of additional advantages for sustainable environmental management (Gong et al., 2017). The capacity of biochar to improve the quality fo the soil is critical when using phytoremediation. Adding biochar to phytoremediation system as a soil amendment drastically changes the physicochemical properties of the soil (Zeng et al., 2013). Because of its porous structure, biochar retains nutrients and keeps them from leaking into the surrounding area. This characteristic of the biochar also applies to its use as a nutrient-retention agent in phytoremediation. Biochar improves the nutrient retention as well as its immobilization efficiency in phytoremediation systems by reducing the nutrient leaching (Gong et al., 2019b).

The favorable climate for plant development and nutrient uptake can be created when biochar is added to phytoremediation systems. Biochar is excellent for plant growth because it improves soil aeration and water-holding capacity. Stronger root systems in plants are promoted by the improved soil structure and increased nutrient retention. Because of their extensive root systems, these plants can penetrate deeper into the soil and access nutrients that would otherwise be inaccessible. The phytoremediation system's increased production of healthier plants results from the biochar's impact on soil quality (Zhang et al., 2020). The biochar fosters a mutually beneficial association between plants and advantageous soil bacteria. These microbes, which are crucial to the cycling of nutrients, have a home thanks to the porous nature of biochar. By assisting in mineralizing and transforming nutrients, these bacteria increase the availability of minerals for plant uptake. The cooperative relationship among microbes, plants, and biochar promotes a dynamic nutrient cycling mechanism in the phytoremediation system (Huang et al., 2018).

Beyond helping plants develop and retain nutrients, biochar has several other advantages. In addition to storing carbon in the soil, biochar also helps to reduce the greenhouse gas emissions. Because it tackles climate changes and nutrient pollution, biochar-augmented phytoremediation offers an environmentally sound and long-lasting solution (Evangelou et al., 2015). Biochar is an essential component of phytoremediation methods because of its synergistic effects on improved nutrient retention, optimal plant development conditions, and accelerated nutrient cycling. As the number of environmental issues linked to nutrient contamination continues to rise, phytoremediation and biochar provide a viable alternative for the efficient and sustainable removal of nutrients from impacted bodies of water (Ding et al., 2020).

6.2. Microbial remediation

Microbial bioremediation represents a powerful tool in the fight against nutrient pollution and the remediation of eutrophic waters. Using microorganisms' metabolic capacities, this strategy can efficiently lower the nutrient levels in aquatic environments. Nevertheless, microbial bioremediation could be significantly enhanced with the strategic incorporation of biochar, which provides numerous benefits to nutrient removal processes driven by microbes (Zheng et al., 2022b). Promoting microorganism growth and activity is one of the main ways that biochar improves microbial bioremediation. Because of its porous structure, biochar is a perfect home for beneficial microbial populations. These microscopic organisms, including fungi and bacteria, are essential to removing and transforming nutrients (Zhu et al., 2017). The intricate network of biochar pores provides a conducive environment for microbes, allowing them to thrive, proliferate, and perform crucial functions in nutrient cycling. A more efficient and rapid removal of nutrients is made possible by biochar by increasing microbial biomass (Wu et al., 2022a). Variety is essential to target and treat various nutrients and contaminants appropriately. These bacteria handle several pollutants simultaneously through a thorough and balanced bioremediation process (Mukherjee et al., 2022).

Biochar's role in denitrification processes is particularly noteworthy. Denitrification is a crucial method for removing nitrogen compounds from eutrophic waters, as it converts harmful nitrate (NO_3^-) into harmless nitrogen gas (N_2) (Liu et al., 2021a). Biochar can act as an electron donor for denitrifying bacteria, encouraging denitrification. Biochar improves nitrogen removal efficiency by providing denitrifying microorganisms with a readily available carbon source, promoting their growth and activity. Research has demonstrated that denitrification beds that incorporate biochar can remove excess nitrogen compounds from water bodies much faster and perform better overall (Zhang et al., 2021).

6.3. Constructed wetlands

Constructed wetlands are essential for effective nitrogen removal from eutrophic waters. A key component of artificial wetland design is mimicking the wetlands' inherent microbial activity, plant uptake, and sedimentation-based nutrient sequestration and modification capabilities. However, various methods have been explored to enhance their performance even further; one promising strategy is the incorporation of biochar into the substrates of wetland areas (Deng et al., 2021). The potential of biochar to improve artificial wetlands' restoration capacities has attracted much interest. Wetland substrates' ability to retain nutrients can be significantly enhanced by adding biochar, which will enhance the rehabilitation process as a whole (Gupta et al., 2016). Because biochar promotes denitrification and other processes that lower the concentration of nutrients in the water, it improves the natural wetland processes. It creates an environment that encourages the development and spread of beneficial microbes essential to the cycling of nutrients (Kasak et al., 2018).

Furthermore, the growth of marsh plants is ideally suited to the porous structure of biochar. Wetland plants' roots act as extra nutrient sinks, absorbing and storing more nutrients as they develop. Amended substrates with biochar provide a stable and productive environment for establishing and growing wetland plants, improving nutrient removal. A practical solution to the issues caused by algal blooms and eutrophic waterways can be achieved by combining microbial communities with biochar and wetland vegetation (Feng et al., 2020). The durability of biochar is one benefit of adding it to artificial wetlands. The long-term stability of biochar in soil and aquatic settings is well established. This durability makes biochar an attractive and reasonably priced long-term solution for nutrient removal from artificial wetlands. Biochar keeps the nutrient retention and microbial activity in the wetland steady and favorable as it ages and matures (Wang et al., 2020a).

Beyond removing the nutrients, adding biochar to artificial wetlands has other ecological advantages. Biochar can also support the overall health of wetland ecosystems by improving soil structure and providing habitats for a diverse range of microorganisms. In addition to their role in nutrient cycling, these microbes aid in organic matter decomposition and the degradation of various contaminants, enhancing the wetland's capacity to improve water quality (Zheng et al., 2022a). Because of its potential to foster microbial activity, promote the growth of vegetation in wetland areas, and provide a stable and long-lasting medium for nutrient retention, biochar is an excellent tool for environmentally sustainable restoration (Zhou et al., 2017).

7. Future directions and challenges

Even though there is a great potential for using biochar in bioremediation for eutrophic waters with algal blooms, its application has limitations. For example, the type of raw material for the generation of biochar may affect its efficiency, and also, biochar looses its absorbent properties over the time and needs continuous renewal. Besides, some nutrients and pollutants are not completely absorbed by the biochar and additional methods are needed. Hence, researchers should focus on optimizing the properties of the biochars because factors such as feedstock, production environment, and activation techniques affect its effectiveness in bioremediation. Future research should enhance the biochar's nutrient adsorption capacity, microbial support, and pH-buffering capabilities. Customizing specific water bodies is also essential, because nutrient concentrations, water chemistry, and algae species can vary significantly across eutrophic waterways. Besides, developing customizable biochar versions tailored to different conditions is crucial. Integrating biochar-enhanced bioremediation with conventional remediation techniques, such as chemical coagulation, algaecides, and sediment removal, could provide a synergistic approach to treating eutrophic water. Future studies should explore the potential benefits of combining these methods to improve these outcomes. Long-term monitoring and ecological consequences of biochar-enhanced bioremediation techniques must be investigated to assess their sustainability and potential unintended side effects. Additionally, the challenges posed by the climate changes, including higher temperatures, altered precipitation patterns, and increased frequency of extreme weather events, should be considered. Research must evaluate the adaptability of biochar-enhanced bioremediation under the changing climatic conditions to ensure its continued effectiveness.

8. Conclusions

Biochar-enhanced bioremediation is a versatile approach for addressing the eutrophication in water bodies impacted by toxic algal blooms. Its ability to adsorb and immobilize nutrients—especially nitrogen and phosphorus—and thereby prevent their release into the water makes it an effective tool for reducing algal overgrowth and excess nutrients. Biochar acts through surface adsorption, chemical interactions, and ion exchange. It also supports microbial populations by providing a conducive habitat for beneficial microorganisms, which is crucial in nutrient transformation and removal. Biochar promotes the growth of specific microbes that outcompete algae for nutrients, reducing algal biomass and the risk of harmful blooms. Additionally, its pH-buffering property helps to maintain stable, slightly alkaline conditions, promoting submerged vegetation growth, nutrient uptake, oxygenation, and aquatic habitat improvement. Overall, according to the United Nations, water scarcity is likely to increase as global temperatures rise due to climate change. It is necessary to follow the steps as per SDG 7 to ensure the universal access to safe and affordable drinking water sources by around 2030 by restoring the water-related ecosystems.

CRediT authorship contribution statement

Yasser Vasseghian: Writing – review & editing, Writing – original draft, Software, Project administration. **Megha M. Nadagouda:** Writing – original draft, Software. **Tejraj M. Aminabhavi:** Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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