Kumar *et al. Biochar* (2025) 7:94
https://doi.org/10.1007/s42773-025-00486-8

Biochar

**REVIEW** **Open Access**

# Harnessing biochar for nitrate removal from contaminated soil and water environments: Economic implications, practical feasibility, and future perspectives

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## Abstract

Anthropogenic activities contribute to excessive nitrate ($NO_3^-$) concentrations in water and soil ecosystems and negatively impact the environment and human health. The current debate and major challenges associated with biochar application are aimed to minimize the negative impacts of $NO_3^-$, and advance agricultural and environmental sustainability. Critical discussion on practical applicability for $NO_3^-$ removal from contaminated soil–water and cost–benefit analysis for scaling up biochar applications are yet to be discussed. Therefore, this review emphasizes the practical applications and feasibility of biochar in $NO_3^-$ removal via treating naturally contaminated soil and water environments. Naturally contaminated groundwater and stormwater have been treated with different filter materials to achieve $NO_3^-$ removal up to ~ 70–100% due to electrostatic attraction, ligand formation, precipitation, and electrochemical reduction. Incorporating biochar as a soil amendment to overcome ex-situ challenges for $NO_3^-$ retention in soil ecosystems is discussed using various in-situ remediation techniques. Soil column studies for $NO_3^-$ retention and leaching using pristine and modified biochar contribute to improved $NO_3^-$ management. Further, considering interference with existing wastewater treatment plant operations, the critical evaluation of $NO_3^-$removal using biochar integrated with constructed wetlands for robust and high treatment efficacy has been summarized. Considering the economic implications of biochar, cost–benefit analysis for $NO_3^-$ abatement via the polluter pay principle, the implementation of subsidies for pollution control, and different denitrification techniques for restoration, reduction of non-point source pollution, and scaling up biochar applications at commercial scale have been explored. Importantly, this review concludes with future perspectives on biochar applications to agricultural surface and subsurface flows, mesocosm-constructed wetlands, and soil column experiments. Overall, raw and engineered biochar can be effectively implemented for $NO_3^-$ removal from contaminated soil and water ecosystems. Lastly, this study recommends policy interventions for biochar applications for nutrient management and environmental sustainability in the agricultural sector.

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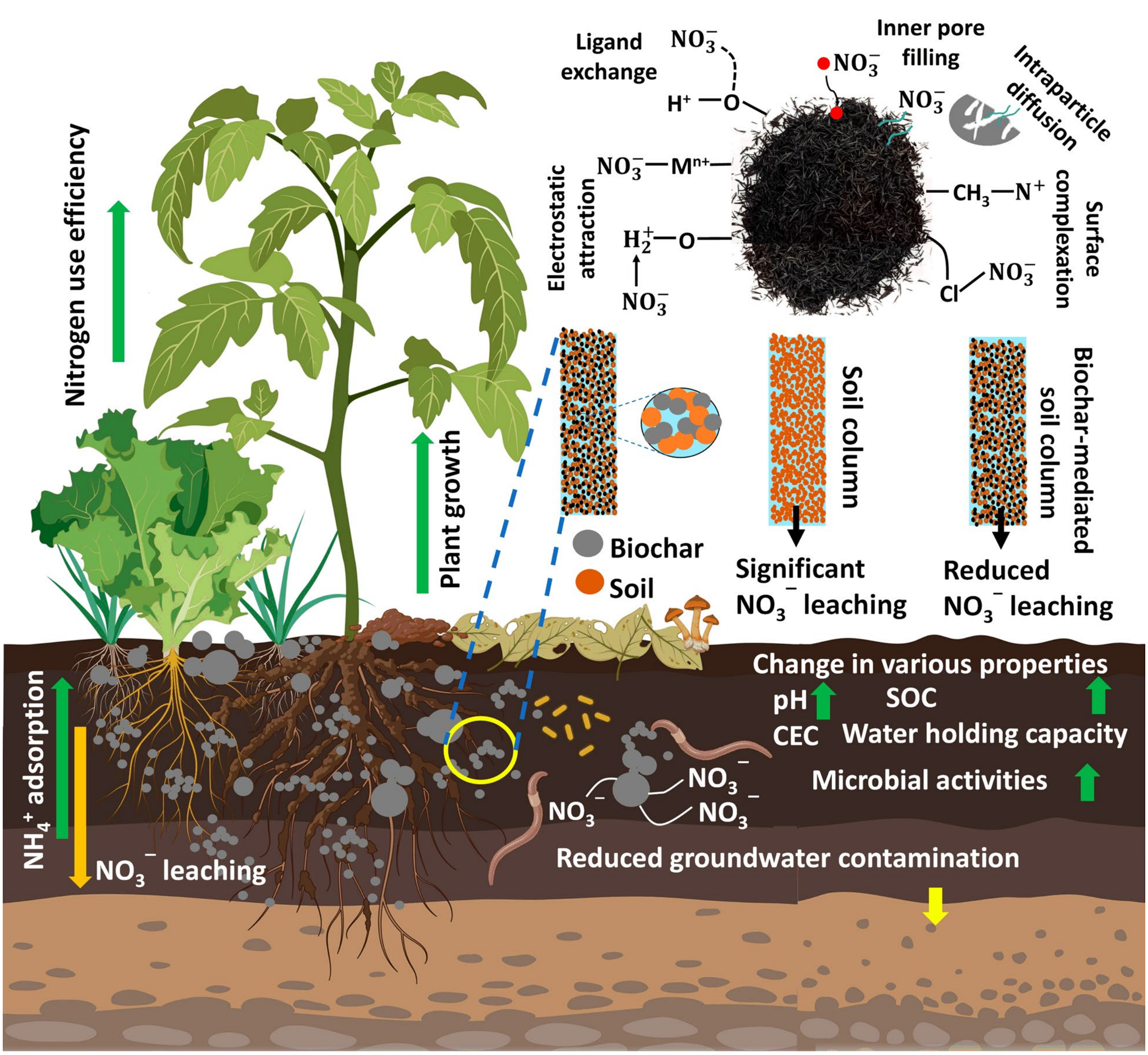
## Highlights

- Biochar reduces nitrate ($NO_3^-$) loss from contaminated soil and water environments.
- Soil column studies reported effective $NO_3^-$ retention for agricultural sustainability.
- Integrated biochar-constructed wetlands were used for $NO_3^-$ removal at an industrial scale.
- Treatment costs and constraints were summarized for practical applications.
- $NO_3^-$ abatement via polluters pay principle and subsidies interventions are summarized.

**Keywords** Adsorption, Nutrient management, Groundwater, Soil column experiments, Constructed wetland, Sustainable agricultural practices

## Graphical Abstract



## 1 Introduction

Excessive application of fertilizers and pesticides leads to the loss of various organic and inorganic pollutants from agricultural landscapes to groundwater aquifer systems and surface water bodies. Agricultural soils with high levels of nutrients (Lee et al. 2019a, b; Schulte-Uebbing et al. 2022; Zou et al. 2022), pesticides (Rillig et al. 2023; Tang et al. 2021), and organic & inorganic contaminants (Hou et al. 2020; Matej-Łukowicz et al. 2023; Naderi Beni et al. 2023; Tóth et al. 2016) are the major sources of pollutants, which pollute surface and sub-surface ecosystems due to improper irrigation practices, contaminated surface runoffs, and infiltrating water (Abbasi & Sepaskhah 2023; Tian et al. 2023; Wang et al. 2019b, 2023b). Further, excessive applications of fertilizers and pesticides to soils result in bioaccumulation of these toxic pollutants in plants and their transport in the food chain (Kumar et al. 2022; Roodt et al. 2023; Tooker & Pearsons 2021; Wang et al. 2022a). FAOSTATS (2022) stated global fertilizer use is approximately 133 kg N $ha^{-1}$ $year^{-1}$. Besides, FAO (2017) underlined that global demand for fertilizer use increased from 184 metric tons (MT) in 2015 to 200 MT in 2020, and hence, a 42% increase in $NO_3^-$ emissions has been reported, which is a potential source of water pollution.

Nitrate ($NO_3^-$), which is one of the inorganic nitrogen ions, is significantly abundant in groundwater with high soluble affinity in water sourced from anthropogenic activities, e.g., agricultural and industrial actions globally, as shown in Fig. 1 (Abascal et al. 2022; Verma et al. 2023). Excessive $NO_3^-$ levels in the natural environment cause eutrophication in water bodies, resulting in plant and algal growth, harmful to fish and other aquatic living species (Singh & Craswell 2021; Wurtsbaugh et al. 2019). Considering child health, high doses of $NO_3^-$ consumption have severe health effects, which cause "*blue baby syndrome*" or "*infant methemoglobinemia*" and stomach cancer (Majumdar 2003). Prolonged exposure to elevated $NO_3^-$ levels could heighten the risk of developing non-Hodgkin lymphoma (Wongsanit et al. 2015; Yu et al. 2020). The maximum permissible limit for $NO_3^-$ concentration for drinking water is 50 mg $L^{-1}$, which is set by the European Union (EU) Drinking Water Directive (98/83/EC) (EU 2020) and the World Health Organization (WHO 2011). Likewise, the United States Environmental Protection Agency (USEPA) has set $NO_3^-$ limit for drinking water to 10 mg $L^{-1}$ in the United States (USEPA 2016).

Primary techniques for $NO_3^-$ remediation are (i) separation-based technologies (electrocoagulation, membrane-based remediation techniques, capacitive deionization, reverse osmosis, ion exchange, and adsorption), and (ii) reduction-based technologies (biological denitrification process and chemical reduction) (Abascal et al. 2022; Richa et al. 2022; Xin et al. 2021). Several conventional and advanced techniques, such as chemical reduction (Sanchis et al. 2021), electrodialysis (Belkada et al. 2018), ion exchange (Duan et al. 2020), biological method (Liu et al. 2020; Pang & Wang 2021), reverse osmosis (Epsztein et al. 2015; Yılmaz & Sahinkaya 2023), and adsorption (Ahmed et al. 2023; Priya et al. 2022), have been used to remove $NO_3^-$. Among all techniques, $NO_3^-$ removal via adsorption process has been reported as the most effective and possesses advantages over other methods due to least undesirable by-products, waste disposal, low-cost investments,

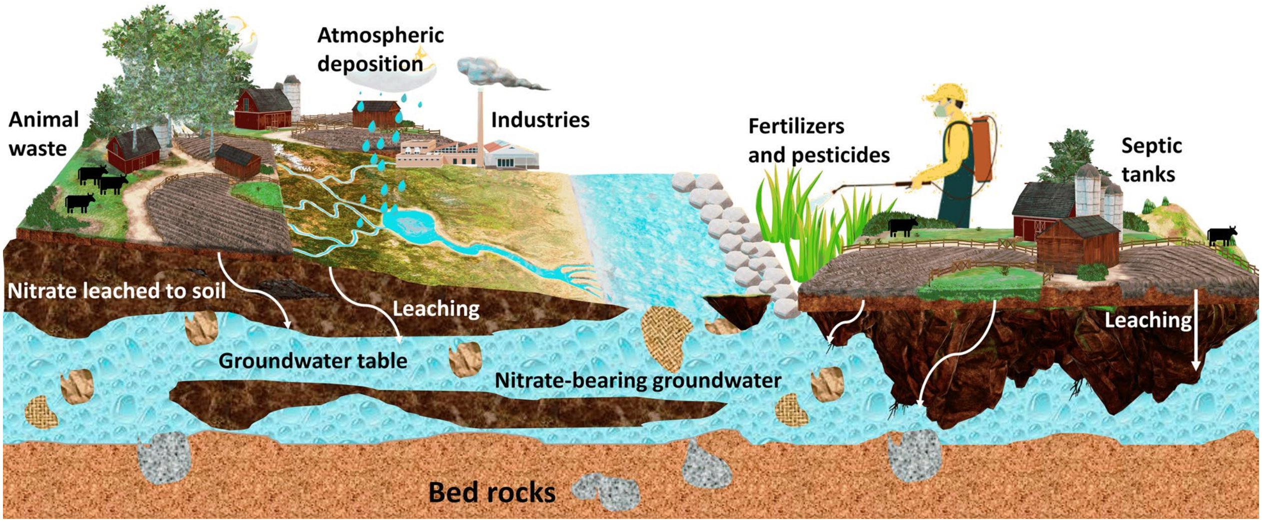


**Fig. 1** Schematizing various sources for nitrate pollution in groundwater and soil ecosystems

and eco-friendliness (Abascal et al. 2022; Choudhary et al. 2022; Priya et al. 2022; Singh et al. 2022; Verma et al. 2023). Adsorption studies on $NO_3^-$ removal have reported the use of various adsorbents, such as clay, zeolite, carbon nanotubes, silica, alumina, chitosan, cellulose nano-fibers/crystals, metal hydroxides, agricultural wastes, biochar, etc. Nitrate adsorption has been performed as a function of multiple factors, which include, but are not limited to, pH, residence time, initial $NO_3^-$ concentration, adsorbent dosage, temperature, and adsorbent selectivity (Ahmed et al. 2023; Bhatnagar & Sillanpää, 2011; Ge et al. 2024; Liu et al. 2022c; Pei et al. 2024; Priya et al. 2022; Zhang et al. 2023b).

Considering the better performance and environmental advantages, selecting suitable adsorbents for $NO_3^-$ removal is essential, as adsorbents can possess high adsorption capacity at low-cost investments. Biochar is one of the promising adsorbents, which is a renewable carbon material obtained from the pyrolysis of various biomasses and has a porous structure and high affinity for contaminants, which can be effectively used for $NO_3^-$ removal from wastewater, as shown in Fig. 2 (Chang et al. 2023; Zhang et al. 2023b) and could help retain $NO_3^-$ in soil for the long term (Chandra et al. 2020; Hagemann et al. 2017). Besides this, several studies have reported that biochar obtained from various biomasses and agricultural wastes can help

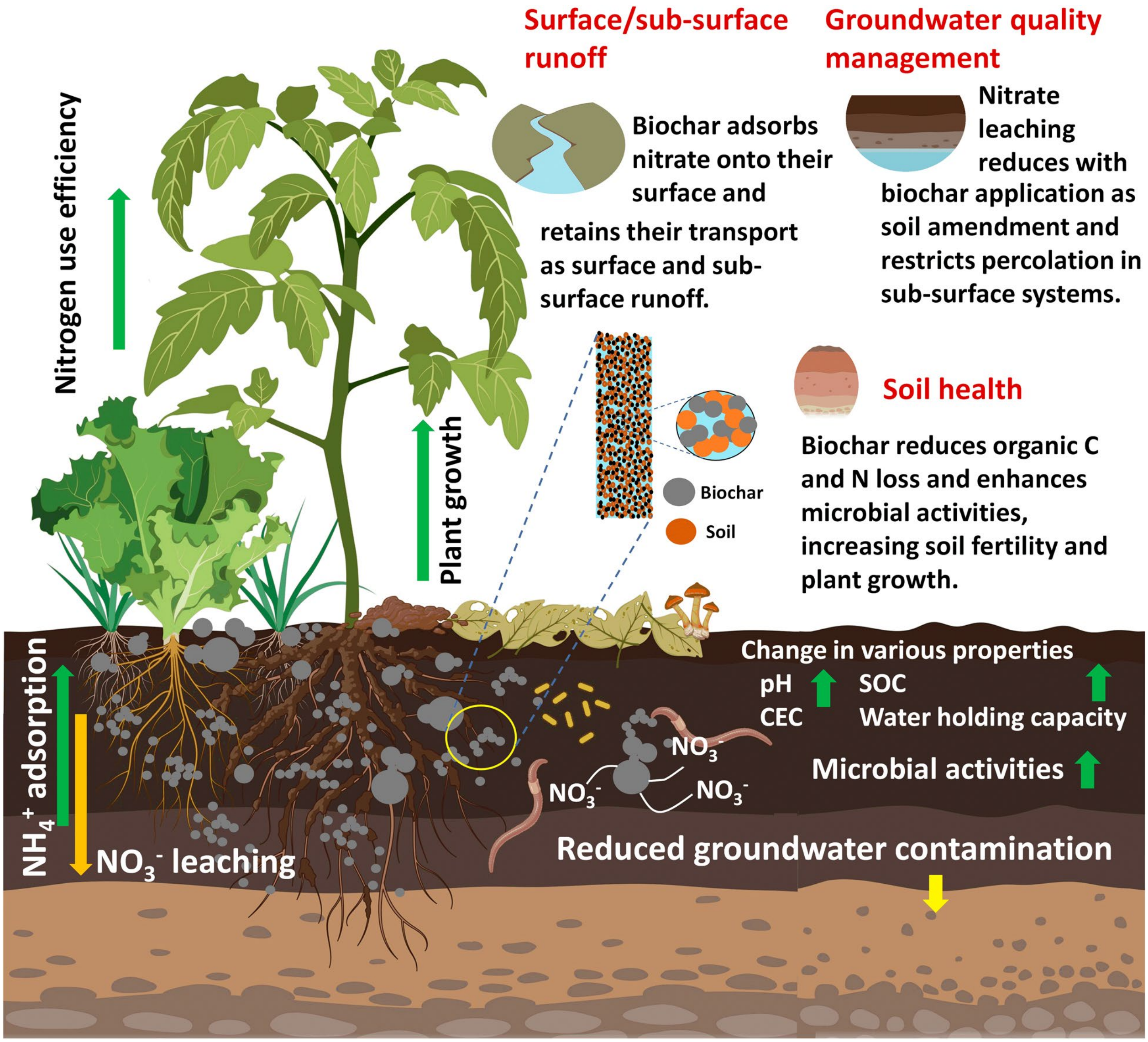


**Fig. 2** Biochar application as soil amendment for nitrate removal and associated mechanisms and consequences

remove contaminants from contaminated soil and water ecosystems (Abhishek et al. 2022; Beesley et al. 2014; Bhatnagar & Sillanpää, 2011; Cooper et al. 2023; Das et al. 2023; Jiang et al. 2023). Recently, Ahmed et al. (2023) emphasized activated carbon applications in removing $NO_3^-$ from contaminated/wastewater samples, in which raw and modified or composite activated carbon adsorbents were analyzed comparatively based on their removal performance. Various studies have reported that activated carbons, which are obtained using physical and chemical modifications of biochar, possess higher adsorption performance than raw biochar precursors (Demiral & Gündüzoğlu 2010; Hafshejani et al. 2016; Kilpimaa et al. 2014, 2015; Najmi et al. 2020; Wang et al. 2021b; Zhang et al. 2023b). Previous reviews on removing inorganic nitrogen using raw/modified biochar have been summarized, in which critical discussion focused on batch sorption experiments (Dai et al. 2020; Jellali et al. 2022; Yin et al. 2017). However, no review exists on the critical discussion on practical applicability and feasibility for $NO_3^-$ removal via raw/modified biochar-amended saturated column experiments, in-situ remediation approach, constructed wetlands, real/natural contaminated groundwater/stormwater treatment, and cost–benefit analysis for scaling up biochar applications. $NO_3^-$ removal from naturally contaminated groundwater and wastewater via raw/modified biochar is challenging, though in-depth investigations are yet to be reported. Thus, a critical comprehensive review of $NO_3^-$ adsorption via raw and modified biochar is necessary to understand the current state-of-the-art with respect to sustainable agricultural practices and to advance environmentally sustainable goals.

Therefore, the overall goal of this review paper is to discuss $NO_3^-$ removal from wastewater and naturally contaminated groundwater and soil ecosystems using various raw and modified biochars to mimic the feasibility of biochar for $NO_3^-$ removal in natural environments. This paper covers critical discussion and challenges related to (a) practical applicability in the treatment of $NO_3^-$-contaminated environments, (b) in-situ remediation and integrating conventional and advanced techniques with biochar, and (c) economic analysis of $NO_3^-$ abatement, considering direct and indirect benefits, such as reduction in $NO_3^-$ concentration, reduction in treatment cost, restoring groundwater quality, and ecosystem services. Lastly, this review also investigates cost–benefit analysis for biochar synthesis and performance cost analysis, and concludes with future perspectives and recommendations for $NO_3^-$ removal using biochar.

## 2 Nitrate sources and distribution

Nitrate is a ubiquitous contaminant in groundwater due to its high water solubility and mobility through the soil profile (Abou Zakhem & Hafez 2015; Filter et al. 2024). The $NO_3^-$ is sourced from landscapes under various land uses, geological deposits of $NO_3^-$ salts (Gupta et al. 2015), igneous rocks, plant symbioses, and cyanobacteria (Abascal et al. 2022), and heterotrophs (Gutiérrez et al. 2018). Besides, anthropogenic sources, such as point sources, which include sewage, septic systems, and industrial wastewater; and non-point sources, namely atmospheric deposition and agricultural fertilization, lead to $NO_3^-$ contamination in surface water, groundwater, and soil, as shown in Fig. 1 (Anornu et al. 2017; Cho et al. 2015; Filter et al. 2024; Su et al. 2013; Verma et al. 2023; Yeganeh and Bazargan 2016). For example, Statista (2021) reported that worldwide fertilized croplands contributed to 60% of the groundwater $NO_3^-$ contamination, followed by domestic wastewater and septic tanks (22%), industrial waste (6%), and deforestation (5%) in groundwater in 2018. In recent years, anthropogenic activities have been the main reason behind the rapid increase of $NO_3^-$ in waterbodies (Abascal et al. 2022; Verma et al. 2023; Xin et al. 2019). Thus, $NO_3^-$ commutes to surface and groundwater bodies through surface runoff and leaching, which leads to the increase in the $NO_3^-$ concentration in waterbodies and ultimately returns to the soil through $NO_3^-$-intensified fertilizer applications in irrigation (Andreo-Martínez et al. 2020; Rubio-Asensio and Intrigliolo 2024; Verma et al. 2023; Zhang et al. 2024).

Groundwater nitrogen (N) hydrochemistry has been studied in numerous works in recent years. Abascal et al. (2022) summarized that groundwater at 292 locations in Africa, Asia, Europe, and the USA is contaminated with high $NO_3^-$ concentrations. In the Asian continent, India, Palestine, Saudi Arabia, and regions of China and Pakistan have witnessed mean $NO_3^-$ concentrations above WHO standards. Recently, Verma et al. (2023) have also analyzed high $NO_3^-$ concentrations of up to 2000 mg $L^{-1}$ among different states in the Indo-Gangetic Plains of India. Among 71 regions in the European continent, 22 areas have maximum values above WHO standards. Moreover, the maximum $NO_3^-$ concentrations in Duero (Spain) and Malta is above 200 mg $L^{-1}$ (Abascal et al. 2022). Most of the countries in Africa, such as the Democratic Republic of the Congo, Mozambique, and Zimbabwe, have severe $NO_3^-$ pollution, with mean concentrations ranging from 52 to 775 mg $L^{-1}$ in groundwater (Barbieri et al. 2019; Kapembo et al. 2016; Muzenda et al. 2019).

## 3 Practical applicability in the treatment of contaminated environments

### 3.1 Real/natural contaminated groundwater/stormwater treatment

This section summarizes biochar applications in treating $NO_3^-$-contaminated groundwater and stormwater to understand how efficiently biochar can be scaled up commercially, depending on feedstock types and physicochemical properties. Natural $NO_3^-$-contaminated groundwater, with 43.6 mg $L^{-1}$ levels in China, was treated using raw biochar and modified biochar (nZVI/BC), which reported that $NO_3^-$ levels were reduced to 9.5 mg $L^{-1}$ (78.2% removal efficiency) using nZVI/BC, whereas raw biochar showed negligible remediation at pH 6.8 (Wei et al. 2018).

Several studies have reported $NO_3^-$ removal for stormwater management using multi-layered bioretention (Alam et al. 2022; Hsieh et al. 2007; Reddy et al. 2014; Teymouri et al. 2023; Wang et al. 2017; Zhang et al. 2019). For example, for urban stormwater management, Reddy et al. (2014) have implemented different filter materials, such as calcite, sand, zeolite, and iron filings, to remove $NO_3^-$, which showed removal efficiency of 39–65%, 40–70%, 42–77%, and 74–100%, respectively. In this study, dominating $NO_3^-$ adsorptive mechanisms were electrostatic attraction established between the adsorbent surface and $NO_3^-$, whereas exceptionally high removal efficiency was observed for iron filings due to electrochemical reduction, ligand formation, and precipitation. Recently, Alam et al. (2022) investigated the fate and transport of $NO_3^-$ using recycled concrete aggregate and crushed glass, rice husk, and layered media using column experiments at low/high flow conditions, which possessed low adsorption efficiency of up to 30% at the low flow rate, i.e., reactive behavior and 25% at high flow rates, i.e., adsorptive behavior for rice husk and recycled crushed glass, respectively. Conversely, Teymouri et al. (2023) observed no significant reduction in $NO_3^-$, pH, and total dissolved solids, whereas COD, TSS, and turbidity were reduced using lignite pervious concrete from stormwater. Besides, Valenca et al. (2021) have observed major challenges in $NO_3^-$ removal via stormwater control measures, where design (e.g., flow rate, retention time, size of ponds from average to watershed scale, etc.), climatic factors (temperature, rainfall intensity, etc.), and microorganisms contribute to uncertainty in $NO_3^-$ removal (Fig. 3). For example, retention pond design significantly affects $NO_3^-$ removal, but in the case of bioremediation, climatic conditions are more significant for remediation. In the case of $NO_3^-$ bioremediation, native plants showed more adaptability to remove $NO_3^-$ in tropical climates than in other environments. This study by Valenca et al. (2021) incorporated different amendments, such as organic amendments (compost, mulch, and other organics), mixed media, biochar, and iron-based amendments, to investigate $NO_3^-$ removal compared to control media (sand/soil). Results stated that iron-based media mixture and organic amendments showed positive $NO_3^-$ removal, whereas no significant change in $NO_3^-$ removal was observed for biochar amendment (Valenca et al. 2021). In this study, biochar possesses negative electro-kinetic potential, which enhances electrostatic repulsion, i.e., net negative surface charge density onto biochar surfaces. Compared with $NO_3^-$ removal using vegetation, it has been observed that other N species, such as $NH_4^+$ and total dissolved N, have shown more positive $NO_3^-$ removal than $NO_3^-$ and total N. Thus, based on the application of amendments and vegetation types, it can be summarized that the transformation of $NO_3^-$ into different N species and their complexities particularly with respect to pH-dependent, surface charge density, and redox potential, challenge $NO_3^-$ removal from stormwater control measures (Valenca et al. 2021).

### 3.2 In-situ remediation of nitrate

Removal of $NO_3^-$ in groundwater has various challenges and limitations, such as the denitrification process governed by pH, regional temperature, electron availability, and complex and heterogeneity of aquifers (Valenca et al. 2021; Henri and Harter 2022; Liu et al. 2022a, 2025). Thus, in terms of large-scale application and source control, the challenges and limitations being addressed in this section cover how in-situ remediation of $NO_3^-$ can be performed with the help of biochar. Biochar possesses characteristics such as a large surface area, well-developed pore structure, high carbon content, abundant oxygen-containing functional groups, and high cation exchange capacity that make it favorable for $NO_3^-$ adsorption (Ahmad et al. 2014). The physicochemical properties of biochar, including the sorption capacity and selectivity, are influenced by the biochar feedstock material and production temperature (Hassan et al. 2020; Mukome et al. 2013). Elements present in biochar can also contribute to its adsorption capabilities (Wang et al. 2020a, b; Yin et al. 2018). Biochar, with its unique properties, has emerged as an excellent material for the waste treatment process. In the field of catalysis, biochar materials have shown excellent performance in a wide range of reactions, including transesterification, catalytic reforming, gasification, hydrolysis, electrochemical reactions, photocatalysis, and oxidation (Lee et al. 2019b). Chew and Zhang (1998) investigated in-situ $NO_3^-$ remediation via electrokinetic coupled with zero-valent iron (ZVI) from contaminated groundwater, where 54–87%

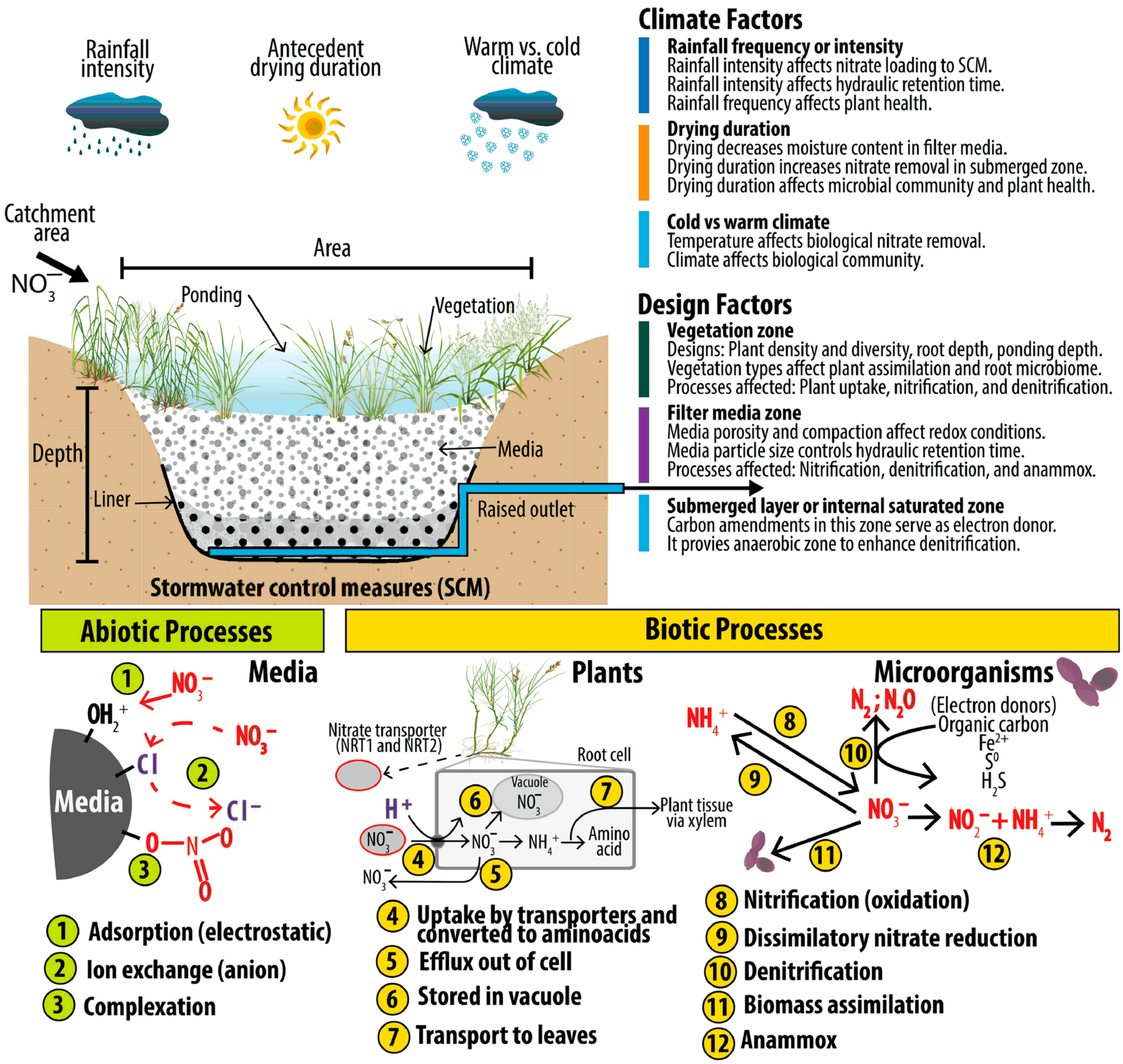


**Fig. 3** Nitrate removal using stormwater control measures under different climatic and design factors affecting biotic and abiotic processes. Reprinted with permission from Valenca et al. (2021), License Number 5610871467579

of $NO_3^-$–N transformation was observed at various voltages. In comparison, only 25–37% of $NO_3^-$–N was transformed for controlled experiments using an electro-kinetic approach. Recently, nano-ZVI modified biochar has been used for $NO_3^-$ removal from controlled contaminated water, with removal efficiencies ranging from 97% to 89% for varying pH 5 to 10, respectively, and the NO3$^-$–N transformation has been reported where biochar acts as a carrier for electron transfer from nZVI ions to yield high $NO_3^-$ removal (Liu et al. 2022a). Zhao et al. (2022) have summarized various in-situ remediation techniques and their principles, along with on-field challenges due to unpredictable hydro-geological conditions. Ex-situ remediation approaches require external power and workforces in the treatment of contaminated groundwater aquifer systems, whereas in-situ remediation has advantages over ex-situ in terms of overcoming the challenges at on-field scale via integrated denitrification with carbon materials and sequencing batch reactor (He et al. 2018), bioremediation (Safonov et al. 2018), phytoremediation (Shyamala et al. 2019), biological permeable reactive barrier (Gibert et al. 2019), bio-electrochemical system (Vidotto et al. 2020), and hydrogenotrophic denitrification (Duffner et al. 2022).

Fewer studies have been reported on the in-situ biochar application for $NO_3^-$ removal (Ashoori et al. 2019; Cooper et al. 2023). For example, regarding $NO_3^-$–contaminated stormwater (0.8–13.7 mg $L^{-1}$), Ashoori et al. (2019) have reported that woodchips amended with pine wood biochar dropped $NO_3^-$ levels $< 0.05$ mg $L^{-1}$ in stormwater collected from Santa Rosa Creek Sub-basin, California, USA. In alignment with the above-stated challenges, Ghorbani et al. (2019) implemented rice husk biochar as soil amendments to two different soils, clay and loamy sand, to investigate $NO_3^-$ leaching in greenhouse environments and wet-dry cycles. This study reports a reduction in $NO_3^-$ leaching in clay soil compared to loamy sand at 1–3% biochar application rates due to significant soil properties improvement and enhancement in cation exchange capacity and water holding capacity of soils. Similarly, Yao et al. (2012) have also reported that biochar from Brazilian pepperwood and peanut hull reduced $NO_3^-$ leaching in sandy soil by 34%. Recently, Cooper et al. (2023) synthesized self-functionalized biochar from *Pinus ponderosa,* which possesses Fe particles on its surface, resulting in higher $NO_3^-$ retention in soil than in control conditions due to Fe-redox chemistry. This study demonstrated that biochar particles exposed to soil minerals undergo self-surface functionalization over time, which can be beneficial for nutrient retention and soil profile management. Still, many challenges were observed from the abovementioned studies, which are yet to be reported with respect to understanding the applicability of biochar for stormwater treatment in any watersheds, depending on the various factors (e.g., runoff coefficients, land use and land cover, precipitation (annual rainfall volumes), soil physiochemical properties, soil types, etc.) for $NO_3^-$ removal, along with other anions/cations, organic pollutants, and so on.

### 3.3 Nitrate removal through biochar integration to constructed wetlands

Typically, several traditional techniques, including chemical reduction (Fu et al. 2014), photocatalytic breakdown (Anderson 2011), electrochemical $NO_3^-$ removal (Li et al. 2010), ion exchange (Samatya et al. 2006), reverse osmosis (Schoeman & Steyn 2003), and electrodialysis (Elmidaoui et al. 2001), have been implemented to remove $NO_3^-$ from contaminated groundwater. As stated above, these traditional methods are not economically viable due to their comparatively elevated installation and operational expenses during wastewater treatment (Gao et al. 2015). Thus, integrating biochar interference in existing wastewater treatment plants (WWTPs) can effectively address $NO_3^-$ removal in constructed wetlands to mitigate by-product formation and release of polluted wastewater into natural ecosystems. In this regard, constructed wetlands can play a significant role because of their robustness, low cost, low energy consumption, easy operation, and exhibiting high treatment efficacy (Li et al. 2017a, b; Wang et al. 2018; Wu et al. 2014), and are used widely for treating wastewater containing N and P.

Constructed wetlands (CWs) can be categorized into two types based on their hydraulic characteristics, such as free water surface (FWS) CWs and subsurface flow (SSF) CWs (Fig. 4). Moreover, depending on the direction of water movement, SSF-CWs can be further divided into vertical flow (VF) and horizontal flow (HF) CWs (Yang et al. 2023). VF-CWs are inclined towards enhancing the transfer of oxygen to facilitate nitrification, whereas HF-CWs encourage the formation of oxygen-deprived areas, promoting denitrification due to water saturation (Yalcuk and Ugurlu 2009). Moreover, soil types and other environmental conditions can play a significant role in the denitrification process in biochar-applied soil; for example, N transformation processes are critically affected by soil water content (5–30%), particularly in wet conditions for sandy soil, biochar increased denitrification (Hale et al. 2023). Furthermore, biochar can potentially enhance the activity of the dihydroxyacetone (DHA) enzyme in calcareous soils due to an increased amount of soluble carbon and microbial biomass within the soil (Karimi et al. 2020). DHA plays a crucial role as an oxidoreductase enzyme, contributing significantly to the breakdown of organic matter by microorganisms (Liu et al. 2022b; Xiao et al. 2020). Higher DHA activity corresponds to a faster breakdown of organic compounds to produce electrons, which, in turn, enhances electron transfer system activity in biochar-applied CWs. Consequently, this could increase electron transfer, thereby increasing denitrification efficiency (Guo et al. 2023). Thus, in soil, CWs can be effectively integrated with biochar, which facilitates nitrification and promotes denitrification to address emerging challenges in $NO_3^-$ removal and contribute to sustainable agricultural practices.

The primary application of CWs is to retain nutrients and organic matter present in domestic and municipal sewage, as well as in managing stormwater and agricultural runoff (Gao et al. 2018). The mechanisms involved in N removal during wastewater treatment within CWs encompass various processes, including ammonia ($NH_3$) volatilization, nitrification, denitrification, nitrogen fixation, uptake by plants and microorganisms, mineralization, conversion of $NO_3^-$ to $NH_3$, anaerobic ammonia oxidation, fragmentation, sorption, desorption, burial, leaching, and others, as shown in Fig. 4a (Gao et al. 2018). In conventional CWs, the primary $NO_3^-$ removal method

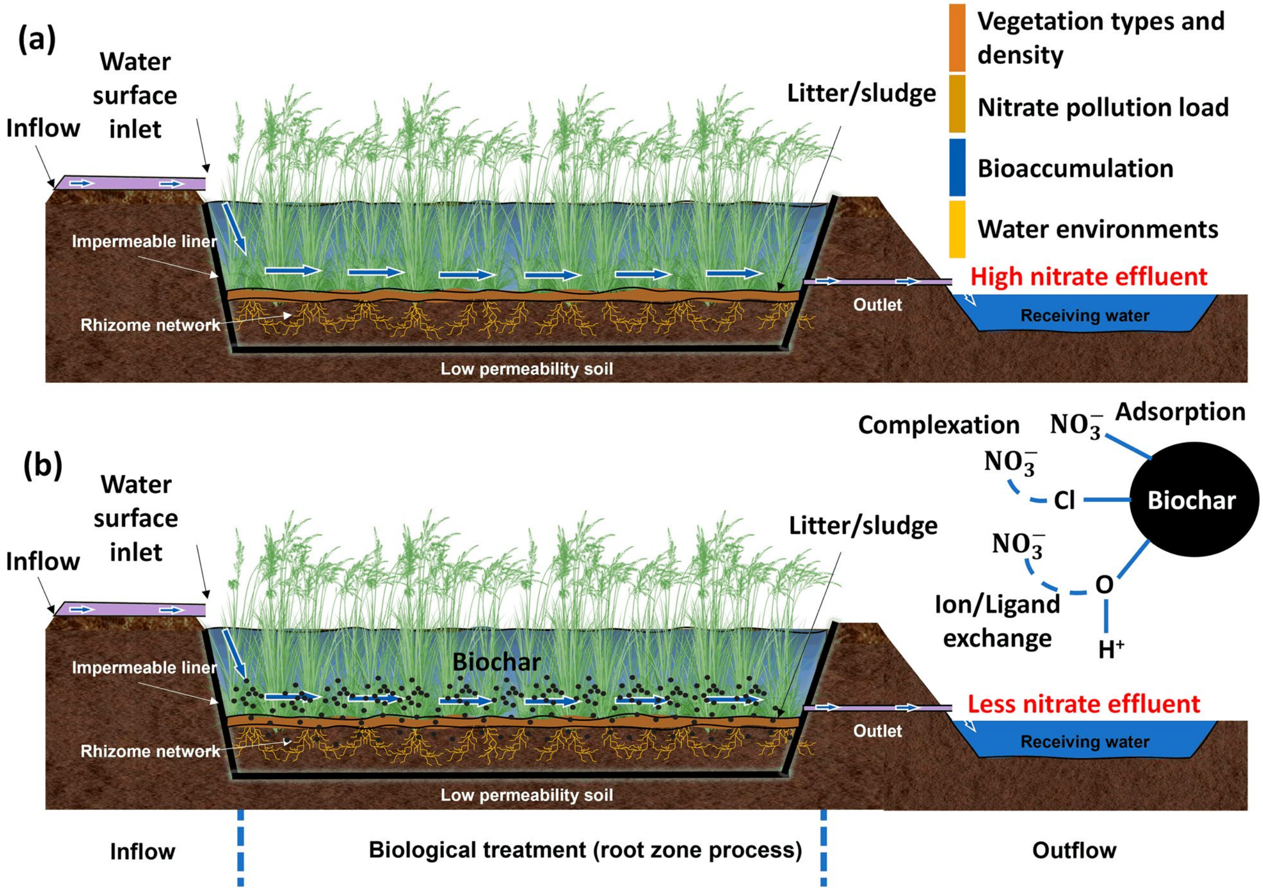


**Fig. 4** Schematic diagram representing nitrate removal and associated mechanisms through **a** constructed wetland and **b** constructed wetland integrated with biochar

is predominantly dependent on heterotrophic denitrification. Heterotrophic denitrification relies on organic constituents as sources of electrons, which convert $NO_3^-$–N into nitrogen gas ($N_2$) (Cecconet et al. 2018), nitrous oxide ($N_2O$), or nitric oxide (NO) (Sparacino-Watkins et al. 2014). However, the scarcity of available carbon compounds in the treated wastewater from WWTPs poses challenges to promoting significant heterotrophic denitrification processes within CWs (Wang et al. 2019a; Zhang et al. 2018). The removal of $NO_3^-$–N during water treatment is impeded because of the scarcity of electron donors, which would occur if the C/N ratio in the influent is low (Li et al. 2019). To improve the nitrogen removal efficiency of low carbon-to-nitrogen ratio (C/N) wastewater in CWs, previous studies have explored carbon-rich solid materials that can compensate for the deficiency in carbon sources or electron donors and enhance the biological denitrification process (Yuan et al. 2020). However, a significant portion of the readily consumable organic matter undergoes microbial breakdown, leaving limited remaining organic content for microbial denitrification within CWs. This scarcity of natural organic matter results in unsatisfactory $NO_3^-$ removal efficiency (Jia et al. 2021). In earlier investigations, carbon sources derived from agricultural wastes (Hang et al. 2016), synthetic carbon sources (Zheng et al. 2021), and ferric-carbon materials (Zheng et al. 2019), were utilized as electron donors within CWs to bolster nitrogen removal efficiency. Nonetheless, the inconsistent rate of electron donor release from these solid materials did not align with changes in $NO_3^-$–N levels in WWTP tailwater (Zhong et al. 2021), which causes water color, smell, and toxicity in plants (Arrivabene et al. 2015; Ju et al. 2014). Moreover, an excessive release of carbon could potentially lead to the risk of secondary pollution (Hang et al. 2016; Jia et al. 2018).

Biochar application to the CWs can solve these problems by adsorbing iron along with the simultaneous removal of oxyanion pollutants and reducing the water colority, as shown in Fig. 4b (Brassard et al. 2016; Gao et al. 2019; Lawrinenko et al. 2017; Sizmur et al. 2017; Yang et al. 2018; Zhou et al. 2017). Pereira et al. (2011)

reported that biochar comprises 21%–49% labile carbon, which could potentially compensate for the scarcity of carbon compounds in influents characterized by a low C/N ratio. This, in turn, could enhance the progress of the denitrification process (Pereira et al. 2011). Chand et al. (2022) experimented with $NO_3^-$ removal using CWs with three treatments, namely SB: substrate + biochar; SBP: substrate + biochar + *Colocasia esculenta* plantation; SP: substrate + *Colocasia esculenta* and reported that the highest adsorption was found in the SPB reactor at 57.85% followed by 48.94%, and 40.23% in SB and SP, respectively. Moreover, Chand et al. (2021b) used *Colocasia esculenta*-based vertical subsurface flow constructed wetland packed with heterogonous gravels and cattle dung biochar with three treatments, namely SB [medium + biochar (10% *v*/*v*)]; SBP (medium + biochar + *Colocasia*); SP (medium + *Colocasia*), to investigate the $NO_3^-$–N removal efficiency, and stated that the removal rate of $NO_3^-$–N was maximum in SBP (81.7%), followed by SP (57.6%), and SB (30.9%). However, the $NO_3^-$–N removal difference between SBP and SP was insignificant ($p = 0.42$). Chand et al. (2021a) also experimented with the combined application of biochar and *Typha latifolia* plantation and applied three treatments (SB: substrate + BC; SBP: substrate + BC + P; and SP: a substrate + P) for $NO_3^-$ removal. The authors stated that the SPB reactor (64.05%) removed a significant amount of $NO_3^-$, followed by the SB (48.94%) and SP (45.03%) reactors. This can be explained by the fact that the reduction of $NO_3^-$ primarily results from substrate adsorption, plant uptake, and microbial degradation (Chand et al. 2022; Kumar and Singh 2017). Therefore, $NO_3^-$ reduction within the Submerged Plant Bed (SPB) system can be attributed to the presence of biochar and *Colocasia*. This contribution is facilitated by both adsorption and the simultaneous promotion of plant uptake (Kasak et al. 2018; Zhi and Ji 2014). Wang et al. (2022b) experimented with NaOH-modified corn straw biochar for $NO_3^-$ removal from CWs and reported that the application of NaOH-modified biochar with plants has a higher $NO_3^-$ removal rate (> 80%) than that of unmodified biochar with plants. This is because alkali-modified feedstocks provide a favourable environment for growing denitrifying microorganisms, thereby increasing the denitrification rate (Gu et al. 2021). Besides, Jia et al. (2020) constructed three horizontal subsurface flow wetlands, namely (HSCWs) C-HSCW (quartz sand + soil), B-HSCW (quartz sand + soil + unmodified biochar), and FeB-HSCW (quartz sand + soil + Fe-modified biochar), for treating the low C/N tailwater discharged from the wastewater treatment plant and stated that FeB-HSCW had the maximum $NO_3^-$–N removal efficiency of 95.3% under the hydraulic retention time of 96 h with low influent carbon–nitrogen ratio (2.5). Moreover, Fe-modified biochar remarkably improved the N removal rate of 2.52 g N/($m^3$·d) through microbial activities, which is much higher compared to other treatments. In the FeB-HSCW treatment, the nitrogen removal was mainly attributed to microorganisms, which accounted for 92.69% of the total removal, while substrate storage and plant uptake contributed 2.97% and 4.34%, respectively (Jia et al. 2020). Electrostatic adsorption is the primary purification mechanism when biochar is applied in the CW without plants (Wang et al. 2022b). Moreover, the biochar pores filtration and hydrogen bonding hydrophobic interaction, π–π interaction, and sedimentation also act as the functions of nitrogen removal from CWs treated wastewater (Nguyen et al. 2021; Wang et al. 2021a). On the other hand, application of biochar is used as a substrate in the CWs with plants to stimulate the growth of microorganisms (Jiang et al. 2022; Wang et al. 2020a, b). Lastly, CWs can be effectively integrated with biochar for wastewater purification, considering substrate adsorption, plant uptake, and microbial degradation to address the need for a clean and safe water supply.

## 4 Soil column studies for nitrate retention and leaching

Fixed-bed column studies have been performed to understand the $NO_3^-$ retention and leaching behavior in the soil profile, as nutrients can leach into the subsurface environment and contaminate groundwater. Yao et al. (2012) investigated $NO_3^-$ leaching in soil columns, wet-packed with 2% wt. of sandy soil and biochar obtained from Brazilian pepperwood and peanut hull. The results of this study reported an approximate reduction of 34% in $NO_3^-$ leaching using both pepperwood and peanut hull biochar, and further, 34.7% and 14.4% of $NH_4^+$ leaching, and 20.6% and 39.1% of phosphate leaching using Brazilian pepperwood and peanut hull biochar, respectively. Several studies reported on $NO_3^-$ reduction in soil columns using *Acer pseudoplatanus* biochar (Angst et al. 2013), pine and hardwood biochar (Bock et al. 2015), and biochar-augmented woodchip biofilters (Berger et al. 2019) amended in soil columns have reported enhanced $NO_3^-$ leaching, due to active sites available onto biochar surface relative to unamended soil. Similarly, Pratiwi et al. (2016) applied 4% (w/w) of rice husk biochar in loamy soil column experiments to quantify $NH_4^+$, $NO_3^-$, and phosphate leaching and retention. In this study, biochar helped reduce $NO_3^-$ and $NH_4^+$ leaching by 23% and 11%, respectively, whereas phosphate leaching in loamy soil increased by 72% compared to the control treatment. Considering raw biochar application, Kameyama et al. (2012) reported 5% less $NO_3^-$ leaching using 0–10% (w/w) sugarcane bagasse biochar-amended soil compared to non-amended soil. From this study, it was observed that $NO_3^-$ was weakly bonded with biochar in soil columns and easily desorbed with flowing distilled water through columns. Zheng et al. (2013) observed that $NO_3^-$ and $NH_4^+$ leaching reduced after the application of biochar (0–5% w/w) in soil columns, resulting in the high bioavailability of nutrients in soil planted with maize and thus, potentially decreasing nitrogen demand for plant growth. Similar results were observed in sandy loam soil using rice chaff biochar with an application rate of 0–10% (Yoo et al. 2014) and in sandy soil using 0–10% (w/w) pine wood biochar (Sika and Hardie 2014). However, 0–2% (w/w) holm oak biochar amended to Acrisol and Calcisol soils at different rates was reported to have no influence on $NO_3^-$ leaching, whereas $NH_4^+$ leaching was significantly in the range of 0.05–0.09 mg $g^{-1}$ and 0.21–0.24 mg $g^{-1}$ for Acrisol and Calcisol soils, respectively (Teutscherova et al. 2018). Nitrate removal using lignocellulosic waste, brewer spent grain (BSG), modified *N*,*N*-dimethylformamide (DMF), and epichlorohydrin has been performed for fixed-bed column experiments to treat synthetic $NO_3^-$ wastewater and dairy effluent, with adsorption capacities of 22.65 and 14.4 mg $g^{-1}$, respectively. Less $NO_3^-$ adsorption capacity has been observed for dairy effluent due to clogging of column systems, where adsorption might be influenced with coexisting ions and intraparticle diffusion (Stjepanović et al. 2019).

Fixed-bed continuous flow test experiments are required when designing models for large-scale water treatments, representing the breakthrough curves for $NO_3^-$ sorption using polyaniline biochar (PANIBC). The breakthrough point obtained at $C_f/C_i$ is closer to 0.1, where the column initiates to become saturated, and the exhaustion point, where $C_f/C_i$ is closer to 0.9 at complete saturation. For $NO_3^-$ removal, the column capacities obtained from mass balance calculations were 72 mg $g^{-1}$, which has been implemented for the removal of $NO_3^-$ from lake water (Herath et al. 2021).

Sawdust-ZVI co-pyrolyzed biochar blended with zeolite in columns is applied for $NO_3^-$ removal in two columns. Thus, for $NO_3^-$ removal, $NH_4^+$ was observed during $NO_3^-$ reduction using sawdust-ZVI biochar (Han et al. 2021). In this study, in an acidic medium (pH 2), approximately 71% of $NO_3^-$ was observed to be transformed, but $NH_4^+$ was not removed using sawdust-ZVI biochar. Besides, adsorption experiments were performed using sawdust-ZVI blended with zeolite, where $NH_4^+$ was completely adsorbed, which shows that zeolite removed the $NH_4^+$ produced after the $NO_3^-$ reduction reaction. Besides, it was observed that $NO_3^-$ reduction and $NH_4^+$ production are simultaneously pH-dependent, as only 33% of $NO_3^-$ was reduced at $pH > 7$ (Han et al. 2021).

Batch and dynamic column experiments were performed for $NO_3^-$ removal using date palm biochar, which reported that biochar had adsorption capacities of 4.18–4.39 mg $g^{-1}$ (Fseha et al. 2022). Considering biochar modification, Li et al. (2022) synthesized raw biochar (ECL-BC) from an invasive plant, *Erigeron canadensis* L., and further modified it with Lanthanum (La/ECL) and La-coupled cationic surfactant [cetyltrimethylammonium chloride] (La/CTAC-ECL). After that, La/ECL and La/CTAC-ECL were used for $NO_3^-$ removal via fixed-bed column studies, filled with 20% and 50% biochar by volume, under the influence of initial $NO_3^-$ concentrations, flow rates, filler height, the particle size of filler, and porosity and permeable coefficients, where La and CTAC have improved physiochemical characteristics of biochar. La/CTAC-ECL has shown a maximum $NO_3^-$ removal capacity of 18.99 mg $g^{-1}$ at varying conditions, such as flow rate of 15 mL $min^{-1}$ influent at filler height of 10 cm and filler particle size of 0.8–1.2 mm for an initial $NO3^-$ concentration of 50 mg $L^{-1}$, via surface adsorption, pore filling, and ion exchange mechanisms compared to ECL and La/ECL adsorbents.

The application of woodchips as bioreactor and biochar has shown significant efficiency for $NO_3^-$ removal (Rahman et al. 2021). For example, dairy runoff was treated in biofilters amended with biochar in different ratios in the column analysis for nitrogen species removal. Dairy manures were diluted with regular water and remained in the solution overnight to prepare dairy runoff. Porous media, e.g., sand and biochar (20–50% vol.) mixed with sand at varying flow rates of 255–420 mL $h^{-1}$, were investigated to understand the change in water quality and to assess hydraulic performance. In this study, both biochar-amended columns reported negative NOx effluent; however, positive removal efficiency was reported for total ammonia nitrogen, total nitrogen, and dissolved organic nitrogen (Rahman et al. 2021). Further, Teixidó et al. (2022) performed pilot-scale column experiments to remove $NO_3^-$, phosphate, and other trace organic pollutants from stormwater runoff. In this study, column filter media were sand, biochar (1% w/w), and MnOx-coated sand mixed in different compositions (Fig. 5a). For $NO_3^-$ removal purposes, two different pre-treatment conditions, the iron-enhanced filter and the iron-enhanced filter, followed by the woodchip bioreactor, have been applied to process through different column conditions (Fig. 5b). In this study, 98% of $NO_3^-$ was removed via woodchip bioreactor pre-treatment with a flow rate of 18 mL $min^{-1}$, and thus, effluent flows through WBM, WMB, WMX, and WCt have shown removal efficiency as $C/C_o$. At the same time, columns (BM, MB, MX, and Ct) received effluent with a flow of 90 mL $min^{-1}$ from an iron-enhanced filter for $NO_3^-$ concentrations of

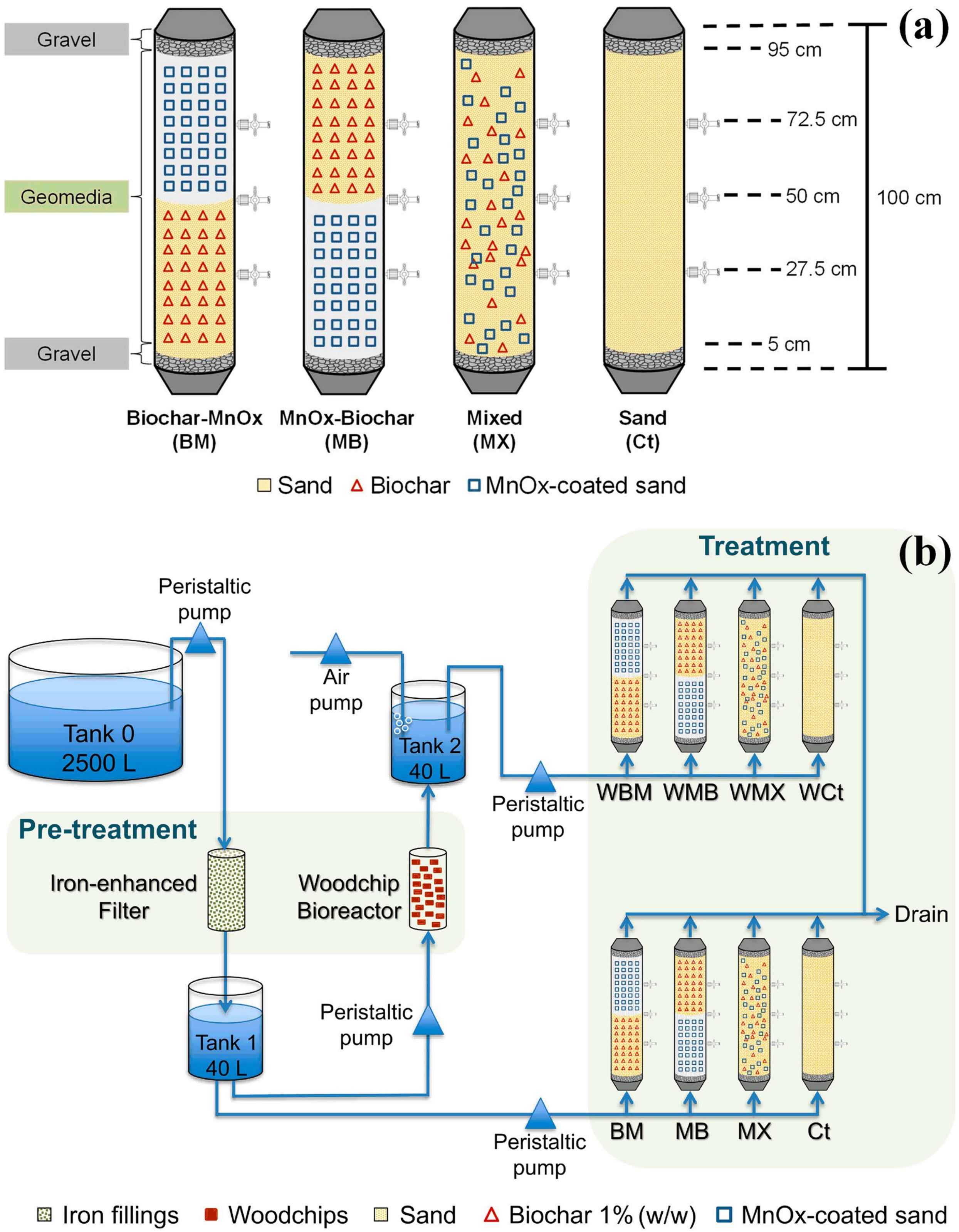


**Fig. 5** **a** Composition of column fillings using sand, biochar, and MnOx-coated sand, and **b** set up for the flow of nitrate via an iron-enhanced filter and woodchip bioreactor under different treatments. Adopted from Teixidó et al. (2022)

$2.6 \pm 0.4$ mg $L^{-1}$ (here BM = biochar-MnOx, MB = MnOx-Biochar, MX = Mixed, Ct = Sand, and W stands for woodchip prefix in WBM, WMB, WMX, and WCt).

Looking at the increase in flow rates, studies have shown that adsorption capacities decrease significantly due to reduced interaction time of biochar-$NO_3^-$ in column experiments. For example, Fseha et al. (2022) showed that an increase in flow rates from 5 to 10 mL $min^{-1}$ at fixed bed depth and $NO_3^-$ concentrations resulted in decreased adsorption capacities for $NO_3^-$, 4.13 to 1.10 mg $g^{-1}$, using date palm biochar. Similarly, with increased $NO_3^-$ concentrations, mass transfer rates onto date palm biochar increased, rapidly attaining equilibrium and saturating the active sites on the biochar surface. While considering the biochar application rate, Jin et al. (2016) reported that the total time of $NO_3^-$ effluent leached out of the column increased with respect to controlled experiments. An increase in biochar application rates leads to higher activated sites available in soil for $NO_3^-$ interaction, decreasing $NO_3^-$ concentrations in leachate. Besides, Parvage and Herbert (2023) explored implications of hydraulic residence time (HRT) for $NO_3^-$ leaching in column experiments, leading to higher removal efficiencies of 90% and 95% for woodchips and woodchips + biochar (2:1) at higher HRT (5 days), respectively, compared to lower HRT (2 days). In this study, the removal efficiency was reported to decrease up to 79% for high flow rates of $NO_3^-$ through column due to less biochar–$NO_3^-$ interactions.

Conversely, in column studies, Eykelbosh et al. (2015) found negligible impact on $NO_3^-$ leaching due to biochar application (5% dry weight) in Brazilian sugarcane soil, whereas dissolved organic carbon was reported to have decreased significantly. Later on, Kanthle et al. (2016) investigated $NO_3^-$ leaching in Inceptisol soils influenced by *Zea mays* stalks biochar, finding that $NO_3^-$ leaching decreased with an increase in soil organic carbon due to increased $NO_3^-$ adsorption and water retention significantly. These studies provide insight into investigating $NO_3^-$ leaching in soils, considering various particulate matter and changes in dissolved organic carbon in soil with varying biochar application rates.

Considering practical feasibility and regenerative properties, several studies have reported that biochar possesses significant reusability for consecutive adsorption, which depends on environmental conditions. For example, biochar-supported aluminum goethite has demonstrated significant removal efficiency of 82.1% after ten regeneration cycles, with a slight decrease in adsorption capacity compared to the first sorption, for 50 mg $L^{-1}$ of $NO_3^-$ removal at a neutral pH solution (Wang et al. 2022a, b, c). Further, oil tea shell biochar regenerated using 0.1 and 1 M HCl showed $NO_3^-$ removal efficiency of 51.4% and 65.3% in the second regeneration cycle, respectively (Mehmood et al. 2022). Commercial biochar has been utilized for $NO_3^-$ removal, but removal efficiency dropped by 18% in the seventh regeneration cycle (He et al. 2023). Lychae peel biochar modified with calcium ferrite magnetic nanocomposite has been utilized for $NO_3^-$ removal, which showed a decrease in removal efficiency from 98.3% to 52.9% with five consecutive regeneration cycles (Le et al. 2023). Besides, co-synthesized biochar from guava seeds/beetroot peels modified with Mg/Al hydroxide has been regenerated using 0.1 M HCl and has shown a decrease in removal efficiency from 93.2% to 70% in fifth regeneration cycles (Mahmoud et al. 2024). Recently, ammoniac-grafted iron-modified biochar was regenerated using 0.1 M NaOH, which dropped $NO_3^-$ removal by 14%, i.e., from 89% to 79%, after six regeneration cycles (Yan et al. 2025). Overall, different biochars demonstrated significant removal potential for $NO_3^-$ removal, indicating that biochar can be effectively utilized for scaling up at an industrial scale.

## 5 Nitrate–biochar interaction mechanisms

Generally, $NO_3^-$ removal using biochar-based materials is observed in acidic environments due to abundant positive surface charge density onto biochar surfaces, which encourages $NO_3^-$ attraction electronically. In addition, biochar modification, with $M^+$ ions, enhances surface charge density, as metallic substitution attracts $NO_3^-$ more effectively onto biochar. Thus, the point of zero charges (pzc), either for raw or modified biochar, suggests the electro-kinetic potential of biochar surface, below which surfaces are positively charged, and above which surfaces are negatively charged (Fig. 6). For example, Dewage et al. (2018) synthesized magnetic biochar, and showed modified biochar possessed a $pH_{pzc}$ of 11, whereas raw biochar had a $pH_{pzc}$ of 8–9. Here, magnetic biochar possesses high $pH_{pzc}$ due to basic adsorbent characteristics and also dominates the properties of $Fe_3O_4$ in solution, resulting in a $pH_{pzc}$ of 11. Thus, surface charge density above pH 11 produces negative potential on modified biochar surfaces, which reduces $NO_3^-$ adsorption due to electrostatic repulsion at biochar-$NO_3^-$ interfaces in aqueous solutions. Thus, maximum $NO_3^-$ adsorption was observed at pH 2–9 due to electrostatic attraction between modified biochar surfaces and $NO_3^-$ (Dewage et al. 2018). Wang et al. (2021b) have reported that $NO_3^-$ adsorption using Mg/Al-modified biochar derived from wood waste decreases with an increase in pH of solution due to electrostatic repulsion. In contrast, wood waste biochar showed slightly increased adsorption capacity with increased pH, but further decreased adsorption capacity in an alkaline medium. Moreover, adsorption kinetics were performed

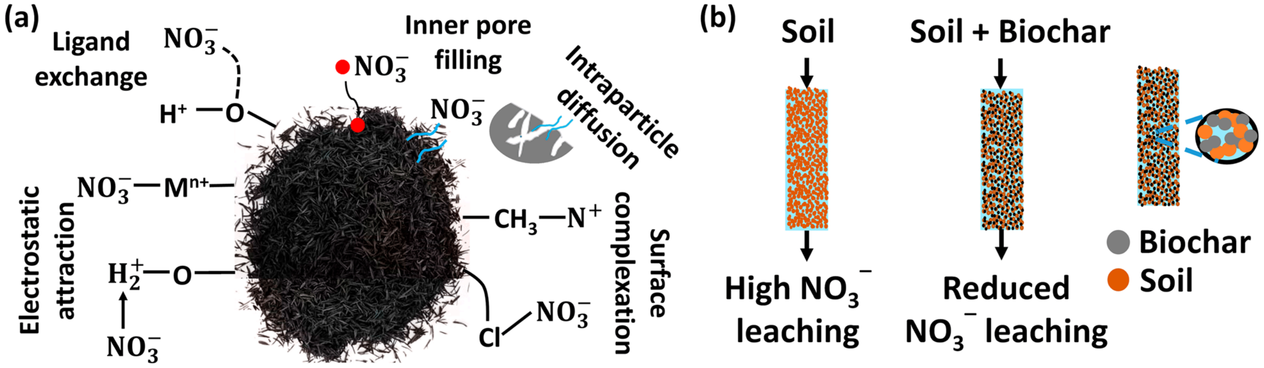


**Fig. 6** Biochar–nitrate interactions at **a** batch sorption experiments and **b** transport and deposition of biochar and nitrate in leaching effluents from saturated porous media

using pseudo-first-order, pseudo-second-order, Elovich, and intraparticle diffusion, in which pseudo-second-order kinetic was best-fitted and showed large adsorption kinetic gradient at Mg/Al-modified biochar- $NO_3^-$ interfaces. Further, $NO_3^-$ adsorbed on biochar surfaces passes through inner pores, where $NO_3^-$ adsorption gradually decreases with decreased kinetics after equilibrium is attained. Thus, Mg/Al-modified biochar showed heterogeneous $NO_3^-$ adsorption via surface adsorption, liquid film diffusion, and intraparticle diffusion. In this study, biochar surfaces were modified by $Mg^{2+}$ and $Al^{3+}$ ions, and $NO_3^-$ adsorption was interfered with via competitive $NH_4^+$, as multiple co-existing ions are present in actual aquatic environments (Wang et al. 2021b).

Like Mg/Al-modified biochar, Mehmood et al. (2022) synthesized $ZnCl_2$-Tea oil shell-synthesized biochar and showed that $NO_3^-$ adsorption capacity decreased with an increase in pH from 2 to 7; however, maximum $NO_3^-$ adsorption has been observed at pH 9. Basically, at high pH, $NO_3^-$ and hydroxide ions compete with each other, which leads to reduced adsorption onto biochar surfaces. Whereas, at pH 9, high adsorption was observed due to biochar modification, as –$CH_3$–$N^+$ complexation (Fig. 6a). Besides, adsorption kinetic followed pseudo-second-order, i.e., chemical adsorption and intraparticle diffusion, i.e., film diffusion and intra-particle diffusion at the $NO_3^-$-biochar interface (Mehmood et al. 2022). The primary reason behind $NO_3^-$ removal using Al-substituted goethite-based biochar is $pH_{pzc}$ of 8.75, which prefers significant adsorption at pH 4–8 and large surface charge density onto biochar surface due to $Al^{3+}$ functional groups. Along with the influence of pH, Wang et al. (2022c) reported that increased ionic strength reduces $NO_3^-$ adsorption capacity using Al-modified biochar. Due to ionic strength, it could be possible that biochar particles attached, as the hydrodynamic diameter of biochar increases with increasing NaCl strength in aqueous solutions (Wang et al. 2022c). Wang et al. (2023a) reported $NO_3^-$ adsorption using cetyltrimethylammonium bromide (CTAB)-modified MgFe-LDHs biochar composites via electrostatic attraction for $pH < pH_{pzc}$ and electrostatic repulsion for $pH > pH_{pzc}$; still, $NO_3^-$ adsorption was observed due to ion exchange and surface complexation formed in the interaction between CTAB-modified MgFe-LDHs biochar composites and $NO_3^-$ at aqueous solution interface. Similarly, Shin et al. (2023) have shown an enhancement in recovery and selectivity for $NO_3^-$ removal using Mg/Al-modified biochar derived from coffee ground waste biomass via ligand exchange and static surface complexation. In $NO_3^-$ and modified biochar interactions, ligands formed onto biochar surface due to –OH functional groups attached with $NO_3^-$ and further interaction mechanisms shifted to electrostatic surface complexation formation and anion exchange (Fig. 6a).

In column experiments, raw and modified biochar are transported through saturated porous media under varying hydrodynamic conditions to investigate the transport and deposition of biochar (Ma et al. 2023). During transport experiments, biochar is retained in saturated porous media, either attached to sand via adsorption or blocking the flow passage, depending on solution pH, biochar particle size, ionic strength, organic matter, and electro-kinetic potential of biochar and sand (Cao et al. 2023). The deposition of biochar in saturated porous media acts as a filtration system for pollutants under varying environmental conditions (Cao et al. 2021; Kumar et al. 2023; Tong et al. 2020; Zhu et al. 2021). Size blocking, i.e., the ratio of the diameter of biochar particle ($d_b$) to pore diameter ($d_p$), is one of the major factors which govern biochar deposition. A large value of the ratio, $d_b/d_p$, restricts biochar transport and may fail as a filtration system as well as retain biochar at certain positions in saturated porous media in column experiments (Liu et al.

2023). For example, Li et al. (2022) have synthesized raw biochar (ECL-BC), La/ECL-BC, and La-coupled cationic surfactant La/CTAC-ECL to perform $NO_3^-$ removal via fixed-bed column studies at varying initial $NO_3^-$ concentrations, flow rates, filler height, particle size of filler, and porosity and permeable coefficients, which reported $NO_3^-$ removal via surface adsorption, pore filling, and ion exchange mechanisms (Fig. 6b).

In batch sorption experiments, Wang et al. (2021b) reported $NO_3^-$ adsorption via surface adsorption, liquid film diffusion, and intraparticle diffusion using Mg/Al-modified biochar, as a heterogeneous sorption process, in which $NH_4^+$ interfered with $NO_3^-$ adsorption as multiple co-existing ions are present in actual aquatic environments. Conversely, zeolite-blended sawdust-ZVI co-pyrolyzed biochar was applied in column experiments at an acidic medium (pH 2), where $NH_4^+$ transformation was observed during $NO_3^-$ reduction where zeolite facilitate sorption in removing the $NH_4^+$ produced after the $NO_3^-$ reduction reaction compared to sawdust-ZVI biochar. Thus, $NO_3^-$ reduction and $NH_4^+$ transformation are simultaneously pH-dependent factors, which must be considered in varying environmental conditions (Han et al. 2021).

## 6 Cost–benefit analysis and scaling up biochar applications at commercial scale

Nitrate pollution in surface and groundwaters caused by agricultural activities is a complex and unresolved issue. Significant challenges include developing a biochar technology in such a way that can be optimized to address emerging challenges in $NO_3^-$ removal at low cost with effective removal efficacy, compared with other $NO_3^-$ removal techniques. Cost–benefit of $NO_3^-$ removal or treating contaminated water resources using biochar has significance in terms of scaling biochar application for commercial purposes and treatment performance at low cost. However, potential limitations and constraints in large-scale applications of biochar for wastewater treatment and soil amendment, particularly in terms of consequences on natural ecosystems, have yet to be summarized. Therefore, François and Youssef (2022) have investigated $NO_3^-$ abatement via economic (cost–benefit) analysis of $NO_3^-$ input–output in different agricultural fields in France. In this work, abatement for $NO_3^-$ pollution and cost–benefit analysis have been determined by considering direct and indirect benefits, such as reduction in $NO_3^-$ concentrations, reduction in treatment cost, increase in fishing production, recreational ecosystem services, etc. The findings of this study showed how the implementation of cost abatement (standard policies/rules, i.e., polluters pay principle and subsidies on pollution control) via reforestation, organic farming, reduction in non-point source pollution, etc., can help in understanding the cost–benefit from the reduction in $NO_3^-$ pollution, e.g., less eutrophication, restoration of $NO_3^-$-free aquatic environments and also decrease in drinking water treatment cost. Rinaudo and Aulong (2014) defined how cost–benefit analysis through the contingent valuation method would help in groundwater remediation for large regional aquifers by considering two scenarios: restoring drinking water and natural groundwater quality levels. From this study, the net present value for both scenarios was Euro 224 and Euro 340 million, respectively, which shows a high willingness to pay at a regional scale for restoring natural groundwater quality levels over 10 years. In another study, Yadav and Wall (1998) employed best management practices (BMPs) for $NO_3^-$ reduction in the groundwater of the Garvin Brook watershed region, where fertilizers, livestock manure, and legumes were primary sources of $NO_3^-$ contamination. Three different scenarios were considered: first, with $NO_3^-$ concentration of more than 10 mg $L^{-1}$ in domestic wells (35%) and subjected to fall below 10 mg $L^{-1}$ (Current Scenario); second, rural domestic wells are set to have $NO_3^-$ concentration of 10 mg $L^{-1}$ for 35% of wells, and others are subjected to have concentrations in the range of 3–10 mg $L^{-1}$, which would increase above 10 mg $L^{-1}$ in future (Future Scenario 1); and third: $NO_3^-$ levels of 3–10 mg $L^{-1}$ in all wells, assumed to have $NO_3^-$ concentration more than 10 mg $L^{-1}$ in future (Future Scenario 2). Benefit–cost (B/C) analyses have reported that current scenarios have a B/C ratio of 6 years, whereas B/C ratios are 5 and 4 for Future Scenarios 1 and 2, respectively, by considering the total cost of BMPs the same for all three practices. However, in this study, a major limitation of restoring groundwater quality and reduction in non-point source pollution was not considered for cost–benefit analysis.

Khera et al. (2021) determined $NO_3^-$ treatment costs using biological treatment, anion exchange, and point-of-use treatment approaches. This study demonstrates that the centralized anion exchange treatment approach is cost-effective compared to point-of-use and biological treatment methods for low influent $NO_3^-$ levels, with a design flow of 0.12 to 10 million gallons per day (mgd). Whereas, for higher $NO_3^-$ influents, the biological treatment method was the most cost-effective treatment approach for design flow of 3.5 mgd and above. In 2007, the University of Minnesota investigated the cost of $NO_3^-$ remediation, $100–200 per individual per year from municipal water treatment via reverse osmosis, anion exchange, and distillation treatment systems (Minnesota Legislature, 2007; https://www.house.mn.gov/comm/docs/CostofNitrateContaminationtoPublicSuppliers2007.pdf). Lewandowski et al. (2008) have investigated

$NO_3^-$ in drinking water wells in Minnesota and found costs of remediation \$190 per year to replace bottled water, \$800 to buy and install $NO_3^-$ removal system with additional maintenance costs, and \$7200 for having a new well, determined based on a survey among those who adopted to buy bottled water, installing treatment system and a new private well.

Considering $NO_3^-$ treatment cost comparatively among different treatment methods, Juntakut et al. (2020) analyzed $NO_3^-$ in the groundwater of Nebraska, where wells are significantly contaminated with high $NO_3^-$ levels. In this study, $NO_3^-$ treatment costs were estimated to be lower, \$4–164 per year for each household via reverse osmosis (RO) point-of-use (POU), whereas ion exchange and distillation methods were found to be more expensive than RO POU. In addition, Juntakut et al. (2020) reported that the RO POU approach for $NO_3^-$ treatment is the most expensive for water supply at the community level. In contrast, the biological treatment approach is less expensive than RO POU due to lower initial costs and operation & maintenance costs. Mathewson et al. (2020) have investigated the economic costs and diseases caused by high $NO_3^-$-contaminated drinking water consumption and their consequences in terms of adverse birth outcomes in Wisconsin, USA. In this study, groundwater is the primary source of drinking water in Wisconsin, where most cases are of very low birth weight and preterm birth, and two cases of neural tube defects due to $NO_3^-$ exposure pose medical costs of \$23–80 million per year. Similar results for the majority of cases of very low birth weight, preterm birth, and neural tube defect were observed by Temkin et al. (2019) for the entire USA. Considering $NO_3^-$-attributed diseases, such as different cancers, due to high $NO_3^-$ consumption, the burden of medical expenditure for the entire USA is \$250 million to \$1.5 billion. Lin et al. (2023) have also reported $NO_3^-$-attributed health concerns, such as preterm birth and neural tube defects associated with $NO_3^-$ in drinking water investigated in New Zealand. In addition, other health concerns, such as congenital disabilities, congenital heart defects, gestational age infants, etc., are found to be inconsistent.

Pirsaheb et al. (2016) have compared RO with electrodialysis for $NO_3^-$ removal from contaminated drinking water in Golshahr, Mashhad, and reported that cost per cubic meter treatment via RO method was \$0.27 along with maintenance and operation cost of \$0.47 for 15 years and total present cost of $NO_3^-$ treatment was \$0.73, which was estimated to be 2.3, 1.9, and 2.98 times higher than RO system for electrodialysis system. Earlier, Sahli et al. (2006) also treated $NO_3^-$ from surface and groundwater via the electrodialysis method, which costs \$0.17 per cubic meter, with additional costs for membrane replacement and power consumption of \$0.05. Recently, Karamati-Niaragh et al. (2019) evaluated the costs of $NO_3^-$ removal, along with its operational costs via continuous electro-coagulation method under alternating current and direct current modes, which were estimated to be \$54 and \$29, respectively, based on their electrode and energy consumptions. Alguacil-Duarte et al. (2022) have assessed two different denitrification techniques, RO and eco-granular water (EGW) technology, via aerobic granular sludge, which costs \$1.60 and \$0.91, respectively, for producing 1 $m^3$ of drinking water. In this study, environmental impact assessment, in terms of ozone formation and depletion, eutrophication, acidification, and ecotoxicity, was investigated for both RO and EGW technologies, where EGW possessed less impact per cubic meter of producing drinking water than RO. In addition, the denitrification-anammox with urea hydrolysis (U-PD-Anammox) process was applied for treating $NO_3^-$-contaminated wastewater, which produced low-carbon and sludge after treatment, which cost \$0.44 per ton, significantly lower than conventional denitrification (\$0.90 per ton) (Zhang et al. 2023a). White et al. (2022) have applied in-situ surface flow woodchips bioreactors, which reduced $NO_3^-$ runoff in the range of 18% (non-ideal hydrological condition) to 73% (ideal hydrological conditions), which cost \$13.14 per kg of $NO_3^-$ removal by considering surface/subsurface and overland flow events. Karamati Niaragh et al. (2017) conducted techno-economic analysis of $NO_3^-$ removal efficiency, achieving 61.70% using continuous flow electrocoagulation under the influence of various determining factors, such as $NO_3^-$ influent, flow rate, pH solution, and current density, which cost \$1.28 per g of $NO_3^-$ removal.

Considering the similar determining factors above-mentioned, Tounsi et al. (2022) treated real wastewater using a continuous electrocoagulation process, which showed $NO_3^-$ removal efficiency of approximately ~ 42.83% and a cost of \$2.30 per $m^3$ of drinking water supply production. Pan et al. (2020) have synthesized amine-functionalized biogas residue, which was implemented to remove $NO_3^-$ and phosphate from contaminated surface water. In this study, 82% of nitrate-phosphate was removed via continuous adsorption–desorption, with adsorption capacities of 64.12 mg $g^{-1}$ and 34.40 mg $g^{-1}$ for $NO_3^-$ and phosphate, respectively. In this regard, the synthesis cost for the production of modified biogas residue was \$2.89 per kg, which indicates that low-cost adsorbent is readily available for the treatment of contaminated surface water. Yapıcıoğlu and Yeşilnacar (2023) have optimized energy cost for $NO_3^-$ removal using agricultural waste biomass (pistachio shells) derived biochar for treatment of contaminated groundwater in arid and semi-arid regions, along with the treatment of boron, fluoride, lead, and iron as well. In this study, energy costs were estimated using data envelopment analysis in terms of the energy cost indicator (ECI) of drinking water treatment plants, which shows that lead is a highly energy-intensive treatment process, whereas $NO_3^-$ costs the lowest energy investments. Lekene et al. (2023) synthesized an activated carbon/chitosan composite, which showed an effective adsorption capacity of 58 mg $g^{-1}$ at pH 3 for $NO_3^-$ concentrations of 200 mg $L^{-1}$. In addition, adsorbent synthesis cost was also estimated by considering chemical costs, energy consumption, washing, and drying, altogether coming up with a cost of \$1.85 per g of composites, which showed low synthesis cost is attributed to the significant adsorption capacity for $NO_3^-$ removal. Overall, from the above discussion, applications of biochar technology in $NO_3^-$ removal have been observed to be more cost-effective in terms of sustainable use of agricultural wastes as biochar, which contributes to advancing environmental sustainability goals.

## 7 Future studies and perspectives

Based on the discussion summarized in this review, it has been concluded that several challenges and knowledge gaps still exist that future research and directions should focus on the field of biochar applications for $NO_3^-$ removal for clean and safe water supply to improve soil health, and nutrient retention, particularly in the context of advancing environmental sustainability and sustainable agricultural practices:

- For non-point source pollutants loss via surface runoff and subsurface flows, future studies should consider biochar applications to maintain optimum $NO_3^-$–N levels in the field and reduce leaching and fertilizer demand for plant growth.
- Selection of feedstock biomass, by considering adsorptive behavior towards $NO_3^-$ in aquatic and soil environments, needs to be explored further under varying pyrolysis conditions and physicochemical properties. Biochar derived from different feedstocks applied to soil helps in plant growth, and $NO_3^-$–N presence governs GHG emission and retention of nutrients, which is unpredictable but can be considered for future studies.
- To date, costs for $NO_3^-$ removal through various techniques have been presented in different units or indicators. Besides, no such study on biochar synthesis for application in $NO_3^-$ removal and performance and maintenance costs of wastewater treatment unit, has been reported for contaminated synthetic water or naturally contaminated groundwater, to facilitate a better understanding of economic cost and benefit analysis.
- $NO_3^-$ and $NH_4^+$ recovery from N and their interdependent exchange depend upon surrounding environments, which must be considered, especially during in-situ remediation of $NO_3^-$ leaching and reduction to $NH_4^+$.
- $NO_3^-$ removal is directly proportional to the organic matter present in the soil. Thus, biochar application with varying organic matter should be investigated for $NO_3^-$ retention and cycling. Fixed-bed dynamic experiments need to be performed for biochar application to understand clogging and retention under different water chemistries, thereby elucidating $NO_3^-$–biochar interactions.
- Transport and retention of $NO_3^-$ in saturated and unsaturated column experiments should be investigated to explore the potential mechanisms between porous media (e.g., sand) and $NO_3^-$, which must be followed by biochar application as potential adsorbents at varying pH, ionic strength, organic matter, co-existing ions, and so on.
- Biochar integrated with biofilters can be efficiently applied in stormwater management before it leaches into groundwater aquifers and sub-surface soil systems for a cost-effective $NO_3^-$ removal, along with comprehensive life-cycle assessment, techno-economic analysis, and resource recovery management, for long-term monitoring systems.
- Policy interventions should be incorporated to facilitate in situ biochar application in agricultural soil for nutrient management, enabling biochar to minimize $NO_3^-$ leaching and maintain desired nutrient levels and act as slow-release fertilizer for crops.

## 8 Conclusions

This review summarizes the potential efficacy of biochar for effective $NO_3^-$ removal, both technically and economically, and possesses diverse environmental and agricultural applications. Moreover, comprehensive analysis emphasized the practical feasibility of raw/modified biochar for $NO_3^-$ removal via treatment of naturally contaminated groundwater and stormwater via in-situ applications. This study critically summarized the challenges and advantages of using different types of biochar, considering various feedstocks, pyrolysis conditions, mixing media, and solution chemistry (i.e., pH-dependent, surface charge potential, and redox potential) for $NO_3^-$ removal. Not only effective $NO_3^-$ removal in wastewater treatment, but biochar can also retain $NO_3^-$ in the soil profile, improving soil physico-chemical properties and nutrient management, ultimately contributing to efficient nutrient cycling/transformation and reducing GHGs emissions. Cost–benefit analysis reveals economic implications for $NO_3^-$ removal among different techniques, promoting sustainable and effective management strategies, which can be scaled up commercially via biochar integration to CWs, depending on feedstock types and physico-chemical properties. The review summarized various constraints, such as abatement for $NO_3^-$ treatment, cost–benefit analysis considering same price unit to scale up with respect to avoid challenges in comparing investment–outcomes analysis among different techniques, implementation of polluters pay principle and subsidies in $NO_3^-$ removal, and reduction from contaminated soil and water environments, which are yet to be explored. Lastly, this review concluded with worthwhile in-depth future recommendations and studies on monitoring and managing non-point sources of nutrients and other pollutants in soil and water ecosystems based on biochar applications for sustainable agricultural practices and advancing environmental sustainability goals.

**Acknowledgements**

This work was supported by the National Science Foundation (award #2316278), United States Department of Agriculture (USDA)-Agricultural Research Services under a non-assistance cooperative agreement (58-6010-2-005), USDA-NIFA Hatch Project (ALA014-2-19254), and the Alabama Agricultural Experiment Station.

**Author contributions**

Rakesh Kumar: conceptualization, methodology, investigation, writing—original draft, resources. Atiqur Rahman: Data curation and Formal analysis. Jasmeet Lamba: writing—review & editing, formal analysis, supervision, project administration, and funding acquisition. Sushil Adhikari: writing—review & editing, formal analysis. Henry Allen Torbert: writing—review & editing. The author(s) read and approved the final manuscript.

**Funding**

This study was funded by USDA-ARS (58-6010-2-005); USDA-NIFA Hatch (ALA0 14-2-19254); National Science Foundation (2316278).

**Data availability**

No data were used for the research described in the article.

## Declarations

**Competing interests**

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.

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Received: 17 October 2024 Revised: 14 May 2025 Accepted: 20 June 2025
Published online: 19 August 2025

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