Environ Monit Assess (2024) 196:425
https://doi.org/10.1007/s10661-024-12595-1

REVIEW

Biochar imparted constructed wetlands (CWs) for enhanced biodegradation of organic and inorganic pollutants along with its limitation

Ruba Munir · Amna Muneer · Bushra Sadia · Fazila Younas · Muhammad Zahid · Muhammad Yaseen · Saima Noreen

Received: 2 November 2023 / Accepted: 30 March 2024 / Published online: 4 April 2024

Abstract The remediation of polluted soil and water stands as a paramount task in safeguarding environmental sustainability and ensuring a dependable water source. Biochar, celebrated for its capacity to enhance soil quality, stimulate plant growth, and adsorb a wide spectrum of contaminants, including organic and inorganic pollutants, within constructed wetlands, emerges as a promising solution. This review article is dedicated to examining the effects of biochar amendments on the efficiency of wastewater purification within constructed wetlands. This comprehensive review entails an extensive investigation of biochar's feedstock selection, production processes, characterization methods, and its application within constructed wetlands. It also encompasses an exploration of the design criteria necessary for the integration of biochar into constructed wetland systems. Moreover, a comprehensive analysis of recent research findings pertains to the role of biochar-based wetlands in the removal of both organic and inorganic pollutants. The principal objectives of this review are to provide novel and thorough perspectives on the conceptualization and implementation of biochar-based constructed wetlands for the treatment of organic and inorganic pollutants. Additionally, it seeks to identify potential directions for future research and application while addressing prevailing gaps in knowledge and limitations. Furthermore, the study delves into the potential limitations and risks associated with employing biochar in environmental remediation. Nevertheless, it is crucial to highlight that there is a significant paucity of data regarding the

Highlights
- Application of biochar-augmented constructed wetlands.
- Investigating the diversity of biochar feedstock, the impacts of heating and temperature variations, and optimizing conditions as a substrate.
- CW system design criteria with biochar.

R. Munir · M. Zahid · S. Noreen (✉)
Department of Chemistry, University of Agriculture,
Faisalabad 38000, Pakistan
e-mail: saima_bashir03@yahoo.com

A. Muneer
Department of Physics, Government College Women
University, Faisalabad 38000, Pakistan

B. Sadia
Centre of Agricultural Biochemistry and Biotechnology
(CABB), University of Agriculture, Faisalabad 38000,
Pakistan

F. Younas
School of Environmental Science and Engineering,
Shandong University, Qingdao 266237, China

M. Yaseen
Department of Physics, University of Agriculture,
Faisalabad 38000, Pakistan

influence of biochar on the efficiency of wastewater treatment in constructed wetlands, with particular regard to its impact on the removal of both organic and inorganic pollutants.

Keywords Biochar · CW system design criteria · Inorganic material · Organic compounds · Microbial communities

Abbreviations

CWs	Constructed wetlands
CFW	Constructed floating wetland
TSS	Total suspended solids
BOD_5	Biochemical oxygen demand
SSF-CWs	Sub-surface flow constructed wetlands
FWF-CWs	Free water surface flow constructed wetlands
HF-CWs	Horizontal flow constructed wetlands
VF-CWs	Vertical flow constructed wetlands
DO	Dissolved oxygen
CWMs	Constructed wetland microcosms
AOX	Adsorbable organic halogen
EW	Emergent wetland
CWEs	Constructed wetland ecotechnologies
CEC	Cation exchange capacity
HRT	Hydraulic retention time
HLR	Hydraulic loading rate
COD	Chemical oxygen demand
TN	Total nitrogen
N_2O	Nitrous oxide
TP	Total phosphorus
EC	Electrical conductivity
VBF-CW	Vertical baffle flow constructed wetland
E-BHFCWs	Electrolysis-integrated, biochar-amended, horizontal (sub-surface) flow constructed wetlands
AC	Activated carbon
VF-FWS-CWs	Vertical flow and free water surface constructed wetland system
IRCWs	Integrated recirculating constructed wetlands

Introduction

Water is an essential substance on Earth, and its presence is vital for all living beings, including humans, animals, and plants, as it is necessary for their survival. It is worth noting that approximately 71% of the Earth's surface is covered by water. However, it is alarming that only 2.5% of this vast quantity constitutes fresh water, which is suitable for consumption and other essential uses (Narayan & Srivastava, 2019). Water as a chief requisite of life is confronting worldwide issues of scarceness and underground and ground water contamination with natural reserves of water depletion. Natural reserves of freshwater are depleting at an alarming rate, surpassing any previous records. Disturbingly, estimates suggest that by the year 2025, approximately two-thirds of the global population will be grappling with water scarcity issues (Hoffman, 2019). Additionally, there is a projected increase of 37% in primary energy consumption. These statistics paint a grim picture of the challenges ahead in terms of both water availability and energy demands (Narayan & Srivastava, 2019).

Wastewater can contain a wide range of pollutants, depending on its source, such as textile, domestic, or municipal wastewater. These pollutants can be classified as organic or inorganic and can originate from both point and non-point sources. In the case of inorganic substances, several contaminants, including arsenic, antimony, copper, cyanide, chromium, fluorine, lead, and mercury, are responsible for water resource contamination. These substances can enter water bodies from both point sources, such as industrial discharges, and non-point sources, such as agricultural runoff. It is important to note that plumbing systems can also contribute to water contamination. Leaks, improper disposal of hazardous substances, or outdated infrastructure can introduce pollutants into the water supply. Therefore, addressing these issues and improving plumbing systems are crucial steps in preventing water contamination and ensuring the availability of clean and safe water resources (Sharma & Bhattacharya, 2017). Currently, wetlands are the most suitable technology for treating wastewater for irrigation reuse. Wetlands offer advantages such as effective contaminant removal, lower energy requirements, and lower maintenance costs. Constructed wetlands (CWs) are proficient treatment systems that are suitable for wastewater treatment with less energy consumption, less infrastructure requirement, minimum maintenance, less operational cost, and friendly nature to the environment. Moreover, the extended lifetime and minimal administrative requirements of CWs are also factors that explore the importance of CWs (Sehar & Nasser, 2019).

CWs are the engineered ecosystems that are constructed and function for wastewater treatment by operating the simultaneous biological, physical, and chemical processes that occur in the natural wetlands. From a technical perspective, the design, operation, maintenance, and construction of CWs have evolved from traditional approaches to include numerous new configurations and technical advancements. These include biological and amendment techniques aimed at enhancing pollution removal efficiency. As a result, CW technology has significantly expanded its application to treat secondary and tertiary effluents, including those generated by industrial wastewater (Wu et al., 2019). One example of an innovative application is the use of constructed floating wetlands (CFWs) to enhance habitats for aquatic waterfowl. CFWs have various other applications as well, including improving the quality of airport runway runoff, treating sewage and wastewater discharges, enhancing farming and agriculture practices, reducing algal blooms, and improving the water quality of mine tailings (Lucke et al., 2019).

Biochar is recognized as a beneficial media amendment due to its ability to enhance plant growth, retain nitrogen in agroforestry systems, and remove nutrients from wastewater. Consequently, it finds application in domestic wastewater treatment. Additionally, biochar contains a high concentration of organic carbon, making it valuable for improving the biological and physicochemical properties of soil. It serves as a soil conditioner, boosting microbial activity, nutrient availability, crop production, soil organic matter, and water retention (Mohan et al., 2014; Zheng et al., 2020). CW's impending biochar utilization is due to its large surface area, high porosity, and cation exchange capacity. These characteristics have the advantage of the contaminant's attachment and adsorption ability of biofilm, which improves the contaminant's degradation. Another significant characteristic of biochar is its ability to alleviate exhaustion. Being nutrient-rich, biochar is utilized as a soil amendment, helping to mitigate the disposal problem of exhausted materials. By reprocessing waste biomass, biochar can enhance both economic aspects and environmental sustainability. Previous studies have shown that the incorporation of biochar in CWs significantly enhances their capacity for removing coliforms, total suspended solids (TSS), and biochemical oxygen demand (BOD_5) (Kizito et al., 2017). However, little information is available on advanced organic and inorganic pollutant elimination. The primary goal of this manuscript is to address the existing knowledge gap in the use of biochar in CWs for wastewater treatment. It presents novel insights into this underexplored field, shedding light on the potential advantages of biochar-based treatment methods. Additionally, the manuscript goes beyond a mere review by outlining future research avenues and practical applications, thus contributing to the progression of scientific knowledge and highlighting the path forward for further investigations. This dual focus on filling knowledge gaps and providing guidance for future exploration aligns with the fundamental process of advancing scientific research.

The classification of CWs is dependent on three key factors. Firstly, the water level of the CW system determines whether it falls under the category of subsurface flow constructed wetlands (SSF-CWs) or free water surface flow constructed wetlands (FWF-CWs). Secondly, the water movement direction within the system is taken into account. Lastly, the presence and type of macrophytes (aquatic plants) in the CW system are considered during classification (Almuktar et al., 2018; Vymazal, 2014). Furthermore, CWs can also be categorized based on their purposes such as wastewater purification, habitat creation, and flood control, as stated in a few recent studies (Vymazal, 2014) (Fig. 1).

However, there are currently no specific criteria for selecting the most suitable CW system (hybrid, horizontal flow, or vertical flow) for treating specific types of wastewater. Hybrid CWs, on the other hand, combine two or more similar or dissimilar vertical flow (VF) or horizontal flow (HF) systems to achieve higher efficiency in pollutant removal. CWs are considered environmentally friendly, cost-effective, and low-energy engineering solutions. In our study, we combined the advantages of green nano-biochar composites and CWs to enhance dye degradation and obtain optimal results Table 1 provides an overview

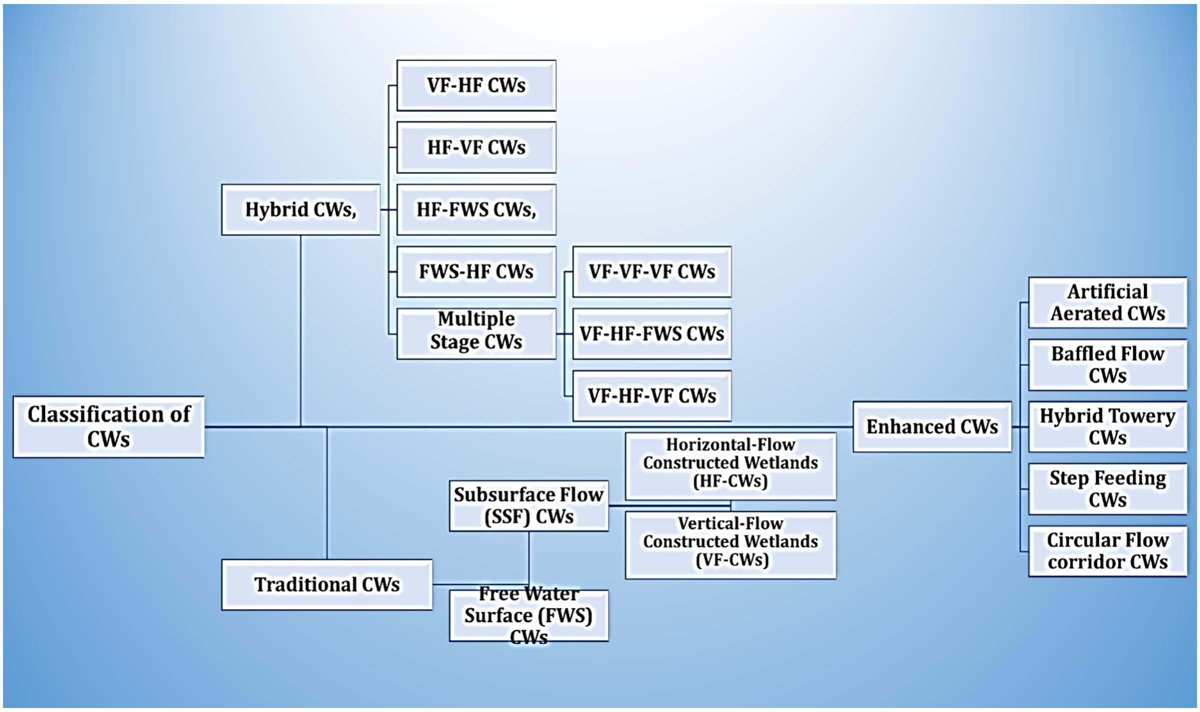

Fig. 1 Flowchart and types of constructed wetland

Table 1 Benefits and drawbacks of VF and HF wetlands

	Type	
	Vertical flow wetlands	Horizontal flow wetlands
Advantages	• Demand for smaller area • Decent oxygen supply • Better nitrification • Good SS and organics removal, simple hydraulics • High purification • Improved performances as compared to HF beds because of water drifts from upper to lower surface which can improve oxygen mixing	• Longer flowing distance • Nutrient gradient establishment, efficiency in the removal of organics and SS • Denitrification process • Humic acids formation for nitrogen, phosphorus removal
Disadvantages	• Shorter stream distances • Low denitrification • High demands • Low nitrate removal • Loss of the performances especially P removal	• Demand for high area • Clogging problems • Transformation of sulfur can be affected by sensitivity of nitrification • Loss of P performance removal • Fastidious hydraulics control necessary for the optimal supply of oxygen • Low oxidation of ammonium • Uniform wastewater passage throughout saturated media is quite complex (dead zones presence)

of the advantages and disadvantages of VF and HF wetlands (Saeed & Sun, 2012).

Biochar as substrate for CWs

The mode of production is very important for biochar since it directly affects plant growth and microorganisms. Media that is cast-off in the CWs are also called aggregate or substrate. CW media might be rocks, gravel, sand, or organic material like compost and soil, which provide primary support to microorganisms and plant growth, improving the biodegradation of pollutants and hydrology mechanisms (Meng et al., 2014). Moreover, wetland substrates eliminate pollutants from wastewater by ion exchange, adsorption, precipitation, and complexation improving the effluent quality to meet standards of agriculture reuse. Nevertheless, the wetland substrate's chemical composition affects the efficiency of the system (Ge et al., 2015).

The parent feedstock plays a significant role in determining the physicochemical characteristics of biochar. This is due to the variations in the structural and chemical compositions of the biomass used. Typically, the composition of the parent feedstock includes lignin, cellulose, hemicellulose, and minerals. These components contribute to the unique properties of the resulting biochar, such as its carbon content, surface area, porosity, and nutrient content. Therefore, careful consideration of the feedstock selection is essential in order to obtain biochar with desired characteristics for specific applications (Li et al., 2016). One of the major challenges in biochar production is dealing with various biomass sources that have different physical and chemical properties, making their conversion into biochar a complex task. For instance, selecting the appropriate feedstock for biochar production is crucial to ensure its effective application in soil and water remediation processes (Table 2). The choice of feedstock directly impacts the quality and characteristics of the resulting biochar, influencing its suitability for specific remediation purposes. Therefore, careful consideration and evaluation of feedstock selection are essential for successful biochar production and subsequent application in environmental remediation (Zheng et al., 2020). Furthermore, utilizing waste feedstock for biochar production avoids competition with energy crops and food production on arable lands. This is crucial considering the existing threats to their sustainability due to land degradation and reduction. Therefore, ensuring the sustainable and responsible selection or supply of biomass is a critical prerequisite in both biochar application and production. Careful consideration should be given to the sources of biomass to ensure their environmental and socio-economic viability, taking into account factors such as availability, renewability, and impact on food security. Making informed choices in biomass selection is essential for promoting the sustainable and responsible use of biochar (Zheng et al., 2020).

Biochar is chiefly comprised of nitrogen, carbon, hydrogen, oxygen, and other mineral elements instigated from the biomass feedstock (Liu et al., 2018). These elements significantly influence the reactions of decarboxylation, dehydration, and demethylation during pyrolysis, resulting in the formation of diverse products and species within biochar. Various types of biochar exhibit wide ranges of mass percentages for elements such as phosphorus, silicon, sulfur, iron, and nitrogen. The elemental composition of biochar is dependent on the nature of the biomass feedstock and the temperature of the pyrolysis process. Inorganic elements like magnesium, phosphorus, potassium, and calcium act as direct sources of plant nutrients in the soil (Bolan et al., 2023). They also play a role in the immobilization or removal of contaminants such as organic pollutants and heavy metals in soil and water. Additionally, these elements contribute to biochar's carbon retention and stability, making it effective for carbon sequestration purposes (El-Naggar et al., 2019).

Complex and copious pores in the biochar are retained in the soils and make available space for microbe expansion, defending the microbes from the adverse outer environment and decreasing the competition for microbes' survival (Tan et al., 2017). The biochar surface is exceedingly variable due to its heterogeneous composition. It is because of the main interfaces where there are many biological and chemical interactions present. Generally, surface properties usually include the surface functional charge, groups, hydrophobicity and hydrophilicity, structure of pore and surface area, and surface free radicals. Among these, the functional group surface plays perilous roles in applications and the biochar properties as

Table 2 Contaminant removal efficiency of biochar prepared under various conditions in treating various types of wastewater in CWs

Feedstock	CWs	Heating Temp	Condition	BC and substrate	V. ratio	Purpose	Reference
Bamboo	VF-CWs	500 °C	Anaerobic	BC/fine gravel	1:1	Lower C/N	(Zhou et al., 2018b)
Oil mallee/wheat Chaff	EW	550 °C	–	BC/soil	0.5 or 5% (w/w)	Soil cadmium	(Zhang et al., 2013)
Corn cob	CW (lake wetland)	450 °C	Anaerobic	Straw/rotten veg./cont. soil/wheat bran/BC	7%	contaminated soil	(Ye et al., 2019)
Coconut shell	CWs	300 °C	Limited oxygen supply	BC/soil	–	Turbidity, TDS, BOD_5, and COD	(Vijay et al., 2019)
Pine chips/swine manure solids	CWs muck	350 °C	–	BC/Lauderhill muck	10%	Wetland mucking	(Novak et al., 2015)
Bamboo and wood	Pilot-scale CWs systems	Pyrolysis	–	BC/mortar and sand	–	Nutrients from sewage	(Saeed et al., 2019b)
Wheat straw	Wetland	450 °C	Anoxic pyrolysis	BC/top 20 cm of the soil	0, 20, 40 and 60 mg ha^{-1}	Saline-alkali soil (halogen source)	(Cui et al., 2019)
Cattail harvested from the CW's	CWs	300 °C	Under nitrogen flow (99.9%)	Gravel/BC	4:1	GHG COD, NH_4^+–N, TN	(Guo et al., 2020a)
Sewage sludge and pruning trees	CWs (metal-polluted wetlands)	500 °C	–	Mine soil/BC	6% d. w	Acidic soil treatments	(Álvarez-Rogel et al., 2018)
Acacia auriculiformis bark	VF-FWF-CWs	500 °C	Anoxic conditions	Sand, BC, sandy soil, and gravel	1:4:2:1	Dormitory sewage	(Nguyen et al., 2020)
Coconut shell (CS)	CWs	300 °C	–	Sand, gravel, and soil mixed with the CS	–	Domestic wastewater	(Vijay et al., 2017)
Bamboo	SSF-CWs	500 °C	Anaerobic conditions	Gravels and BC	1:1	Synthetic wastewater	(Zhou et al., 2018a)
Bamboo	E-BHFCWs	800 °C for 48 h	Anaerobic conditions	Quartz rock/bio-ceramic/BC	Mixed evenly	Removal of N and P	(Gao et al., 2018)
Maize husk	VF-CWs	500 °C	Anaerobic	BC/fine gravel/sand/soil	–	Reactive Golden Yellow MERL (Yellow 145) dye	(Munir et al., 2023)

functional materials, for instance, an adsorbent or soil conditioner.

The pore-size distribution of biochar is categorized into macropores (50 nm), mesopores (2–50 nm), and micropores (<2 nm), based on the diameter of biochar. Micropore plays a significant part in the adsorption capacity, while macropores turn into a suitable place for the enormous diversity of soil microorganisms and root hairs, because the pore-size distributions and nutrients are imprisoned in biochar that can be engrossed by the plants through the nutrient uptake mechanisms (De Rozari et al., 2015). Chemical adsorption is involved in the hydroxyl groups or water displacement from calcium and iron oxide surfaces by ligand-exchange reactions through the phosphate ions, which form an insoluble metal phosphate. Iron-based functional groups were identified on the surface of biochar; subsequently, they had been in the CWs for 7 months (Bolton et al., 2019).

CW system design criteria with biochar

Several parameters, such as the appropriate selection of vegetation, the composition of the media, and the hydraulic conditions within the system, including hydraulic retention time (HRT) and hydraulic loading rate (HLR), are essential for designing wetlands to achieve optimal removal efficiencies. These parameters play a crucial role in ensuring the most efficient removal of contaminants in wetland systems.

Vegetation in CWs

Wetland vegetations are reported to be the main factor that influences the wetland's water quality. As a chief biological component, the plant operates as a purification intermedium of the reactions by the enhancement of a diversity of the elimination processes and the direct utilization of nitrogen (N), phosphorous (P), and many other nutrients**.** The plantation is one of the vital parameters for the determination of the CW performance that, as a plant, rhizosphere not only delivers the microbial growth surface to stimulate microbial activity but also serves as a carbon source. For the enhancement of the treatment efficiency of the wastewater, the selection of the plant should have considerable characteristics such as stem densities, biomass, extensive root and root hair network, and proper adaptation to the conditions of extreme climate (Vymazal, 2013).

In comparison to control systems without biochar, biochar amendment in CWs can significantly boost plant development, producing higher biomass of both above- and below-ground portions. This effect may be primarily explained by the improvement in media porosity brought about by the addition of biochar, which favors plant development by enhancing oxygen conditions. Biochar substrates, which accommodate a huge number of degrading microbes, may increase the effectiveness with which macrophytes in CWs exploit nutrients. Biochar can absorb plant growth inhibitors (e.g., harmful pollutants) in CWs, lowering phytotoxicity (Kasak et al., 2018).

Different biochar that is used is also specific for the plant selection that it must be capable of growing in it, such as the tree of Melaleuca angelica that can be grown in biochar of chipped hemp fiber (Bolton et al., 2019). Furthermore, biochar media may stimulate the root aerenchyma tissues and macrophyte porosity in CWs, allowing for just an increase in root oxygen loss and, therefore, the stimulation of aerobic microbial metabolism, including organic oxidation, nitrification, and methane oxidation. The increased plant growth in CWs brought on by the addition of biochar is advantageous for the removal of nutrients and organic matter by plant absorption, oxygen release, organic exudate secretion, and the availability of additional sites for microbial attachment on the plant rhizosphere, which might further augment N removal by plant harvesting, even if this contribution seems insignificant (Deng et al., 2021). In terms of metal removal in CWs, biochar inclusion can minimize metal absorption by aquatic plants because biochar's significant binding capability lowers metal bioavailability, reduces metal phytotoxicity, and stimulates plant development. Furthermore, Fe-modified biochar amendment in CWs was reported to inhibit pesticide absorption by *C. alternifolius* (Jia & Yang, 2021).

The utilization of biochar as a growth medium for plant screening has garnered increased attention in recent years, owing to its distinctive attributes and potential advantages for plant development. Biochar is a carbon-rich substance derived from organic matter via a process known as pyrolysis, and it can serve as an efficient and sustainable medium for various plants. Several noteworthy features and benefits of employing biochar as a growth medium for plant screening are outlined below. Biochar possesses a considerable surface area and a porous structure that enables it to retain essential nutrients and moisture. This capability facilitates the consistent and stable provision of nutrients to plants, thereby diminishing the necessity for frequent fertilization. Biochar also has the capacity to absorb and gradually release water, aiding in the maintenance of optimal moisture levels for plant roots. This feature is particularly advantageous in regions where water availability fluctuates. The porous nature of biochar enhances soil aeration, reducing the likelihood of root rot and promoting robust root development. Additionally, it facilitates the exchange of gases between roots and the surrounding atmosphere (Yu et al., 2023).

Another advantage of biochar is its ability to stabilize soil pH, making it particularly beneficial in soils that are excessively acidic or alkaline. It serves as a buffer, averting rapid pH fluctuations. Biochar, being a stable form of carbon, can contribute to carbon sequestration, thus aiding in mitigating climate change when employed in agriculture. Furthermore, biochar enhances soil structure and reduces compaction, enabling plant roots to penetrate the soil more easily and access essential nutrients and moisture. Some research even suggests that biochar may have the potential to suppress certain soil-borne pathogens, lowering the risk of plant diseases (Osman et al., 2022). The utilization of biochar as a growth medium promotes the recycling of organic waste materials, ultimately decreasing the need for landfill disposal and reducing environmental pollution. Importantly, biochar exhibits remarkable stability in the soil, and its beneficial effects endure over an extended period, diminishing the necessity for frequent replacement of the growth medium. Moreover, biochar can be produced from a variety of source materials, allowing growers to tailor its properties to suit specific plant species and growth conditions (Knox et al., 2018).

There are diverse types of plant species that can grow in the biochar such as biochar-based CWs like *Typha latifolia* (coconut shell), *Oenanthe javanica* (bamboo) (Vijay et al., 2017; Zhou et al., 2018a), *Cyperus alternifolius* root stock (bamboo) (Gao et al., 2018), and *Phragmites australis* (common reed) (agricultural wastes) (Abedi & Mojiri, 2019). The effectiveness of two plant species, *Cymbopogon citratus* and *Melaleuca quinquenervia*, was evaluated in the removal of BOD_5 (biochemical oxygen demand) and coliforms. Additionally, measurements of anthracene and phenanthrene concentrations in the stems, leaves, and roots of *T. orientalis* indicated the involvement of phytotransformation and phytoextraction processes in the removal of these contaminants (Wang et al., 2019). The ornamental plant *Canna* sp. has shown remarkable potential for nutrient removal and organic matter in hybrid infiltration systems with free water surface (FWS) conditions. Similarly, FWS *Colocasia esculenta* has proven effective in treating municipal wastewater, while rice noodles have demonstrated sufficient adsorption capacity for various contaminants including chemical oxygen demand (COD), total suspended solids (TSS), organics, total Kjeldahl nitrogen (TN), cadmium, copper, chromium, lead, and zinc (Nguyen et al., 2020).

Constructed wetland substrate selection

Substrates, that is also referred to as the support matrix/material, media, and filling material, are one of the chief components in the CWs. They are extensively recognized for their important role (as a carrier for the biofilm development, as a medium for plant growth in the wetland, and as an adsorbent for pollutant immobilization) in CWs, especially for non-biodegradable pollutant removals like organic toxic metals and xenobiotics (Yang et al., 2018). At present, the common and typical fillers include gravel, zeolite, coal ash, limestone, and industrial by-products. Some prior studies have already proved that diverse substrates have diverse abilities for water purification (Lu et al., 2016). Therefore, the verdict of a low-cost and appropriate filler for the enhancement of effluent treatment in the CWs is a serious issue.

The substrate is a significant design parameter in the CWs particularly SSF-CWs, due to an appropriate medium for growing plants, and can also permit an efficacious crusade of the wastewater. Furthermore, sorption on the substrate can play the most important role in the absorption of numerous pollutants like phosphorus (Ju et al., 2014). The substrate selection is resolute in the hydraulic permeability terms and capacity of the pollutant's absorption. Low hydraulic conductivity results in clogging in the systems, which sternly decreases the effectiveness of the system, and the substrate's low adsorption also affects the long-term CW performance for pollutant removal. The substrates that are repeatedly used mainly contain artificial media and industrial and natural material by-products, like gravel, sand, and clay (Wu et al., 2015). Novel composite biochar (NCB) addition has been examined in the non-aerated vertical baffle flow constructed wetland for the polluted treatment of water (Meng et al., 2019).

Biochar proves to be a versatile and effective tool in wetland applications, demonstrating its utility when used alone or in combination with other substrates. When employed in isolation, biochar's benefits include enhanced soil quality, improved water retention, and increased nutrient availability, creating a favorable environment for wetland plant growth. Furthermore, biochar amendment has been shown to significantly boost macrophyte growth and nitrogen removal efficiencies in CWs, making it an efficient and cost-effective approach for wastewater treatment while mitigating greenhouse gas emissions (Xiang et al., 2022). When combined with various substrates like sand, soil, or organic matter, biochar can yield synergistic benefits by enhancing soil properties, microbial activity, and nutrient cycling, which is especially valuable in wetland ecosystem restoration (Hu et al., 2022). However, the choice of whether to use biochar alone or in combination depends on the unique objectives and conditions of the wetland project, often necessitating site-specific testing and expert guidance to ensure its optimal effectiveness (Deng et al., 2021).

In CW systems, the addition of biochar composites, which include biochar combined with various metal oxides, has shown a significant improvement in the removal of dyes from wastewater compared to the control group, which lacks biochar (Phiri et al., 2024). Biochar composites (CuO/BC, MgO/BC, ZnO/BC, MnO_2/BC) indicated that copper oxide/biochar (CuO/BC) composite achieves the highest color removal efficiency, with 95.52% at a maximum hydraulic retention time (HRT) of 60 days. It is exceptionally effective in adsorbing and removing dyes from the wastewater. Magnesium oxide/biochar (MgO/BC), following closely, demonstrates a color removal efficiency of 92.88%. The addition of magnesium oxide to biochar significantly enhances its dye-removal capabilities. ZnO/BC is also effective, with an 88.08% color removal efficiency. Zinc oxide combined with biochar provides a favorable medium for dye adsorption and removal. Manganese oxide/biochar (MnO_2/BC) composite achieves an 84.08% color removal efficiency. Manganese oxide, when combined with biochar, contributes to improved dye removal. Biochar (BC) alone: when biochar is used by itself, it demonstrates a color removal efficiency of 77.92%. Biochar is known for its porous structure and high surface area, making it a capable adsorbent for dye removal. However, the results clearly show that the addition of metal oxides further enhances its performance. Control (without biochar): in the control group, where no biochar is used, the color removal efficiency is the lowest at 56.4%. This highlights the crucial role that biochar plays in enhancing dye removal in CW systems (Munir et al., 2023).

The utilization of sewage sludge and cattail litter as raw materials for biochar production has proven to be highly effective in enhancing the advanced treatment of secondary effluent in CWs (Qi et al., 2024). The results revealed remarkable improvements in total nitrogen removal efficiency with the implementation of sludge biochar CWs (SBC-CWs) and cattail biochar CWs (CBC-CWs) when compared to a control group devoid of biochar. SBC-CWs achieved an impressive total nitrogen removal efficiency of 91%, underscoring the capacity of sewage sludge–derived biochar to significantly reduce total nitrogen levels in the treated effluent. Similarly, CBC-CWs demonstrated substantial success with an 81% removal rate, showcasing the value of cattail biochar in enhancing total nitrogen removal within the CW system. In contrast, the control group, without biochar, attained a total nitrogen removal efficiency of 67%, serving as a reference point for the notable advancements brought about by the incorporation of biochar in the CWs (Zheng et al., 2022). This approach not only enhances the quality of treated wastewater but also offers an eco-friendly means of repurposing sewage sludge and cattail litter, traditionally considered waste materials, into valuable resources for water treatment and environmental remediation (Yadav et al., 2023). Adsorbent material rice husk is used in a CW, an engineered structure to increase textile industry effluent encompassing reactive black dye (RB) in amalgamation with phytoremediation and bioremediation (Saba et al., 2015). Biofilm molded in the macrophyte rhizomes and roots as well as in the media of substrate plays a significant role in the biogeochemical and biodegradation transformation of the varied nutrients, toxic substances, and organic materials (Sharma, 2022). Some examples are given in Table 2 along with preparation conditions.

Hydraulic load rate (HLR) and hydraulic retention time (HRT)

Hydrology is a primary factor in the consolation of wetland function, and the flow rate should also be controlled by the achievement of suitable treatment performance. The optimal HRT and HLR designs show a significant part in the elimination efficiency of the CWs. Better HLR elevates wastewater passageway through media, which reduces optimal contact time. Optimum HLR also can satisfy irrigation standards like COD and BOD_5 levels with the HLRs of 0.04 to 0.06 m/d having 64% and 88% removable rates which satisfied irrigation standards. Biochar also plays a significant role in this parameter like HSSF-CWs with chipped hemp fiber having an HLR of about 0.023 m/day (Bolton et al., 2019). The optimal HRT and HLR may vary depending on the specific treatment objectives and influent characteristics. Increasing the HLR can increase the treatment capacity of the wetland but may also decrease the treatment efficiency. Buffer zones within the wetland can provide additional contact time for water and biochar, especially for hard-to-treat contaminants. Properly placed baffles, distribution pipes, or other hydraulic control structures can help prevent preferential flow paths and minimize short-circuiting (Minakshi et al., 2022).

Another important parameter is contact time because it directly affects the removal of pollutants as well as the microbial community that might be established in the CWs. After all, longer HRT provides a higher contact time for microbial activities to remove the contaminant. Biochar consists of chipped hemp fiber in HSSF-CWs and has a retention time of 5.1 for phosphorus removal (Bolton et al., 2019). The removal rate is directly related to the retention/contact time such as the removal rate of total nitrogen (TN) and total phosphorus (TP) increase by increasing the retention time from 2 to 3 days without NCB addition (Meng et al., 2019). In another case, water quality parameters like BOD_5, TSS, TVS, total coliform, and fecal were tested, and the results indicate that in the first 8 months, there was no difference in water quality parameters BOD_5, TSS, and TVS in sand and biochar in their outflow concentration, but the significant difference occurs in the last 3 months where the biochar showed better result than pure sand (De Rozari et al., 2015).

Feeding mode of influent

One of the most important parameters is the feeding mode of the influents (Zhang et al., 2012). The mode of feeding influents, whether it is in a batch, continuous, or intermittent manner, has a direct impact on the processes occurring in wetland systems. These processes include the diffusion and transfer of oxygen and the oxidation–reduction conditions, which ultimately affect the treatment efficiency. Several researchers have evaluated the effects of different influent feeding modes on the removal efficiency of CW treatments. Optimizing hydraulic retention time (HRT) conditions in a continuous biochar-augmented CW is crucial for effective wastewater treatment and ensuring sufficient contact time between biochar and the influent. This involves calculating the necessary minimum HRT based on treatment goals and wetland design parameters, taking into consideration both the flow rate and wetland volume. For batch systems, HRT is controlled by filling the wetland with wastewater and allowing it to stand for a specified period before draining and refilling. It is crucial to implement flow control mechanisms to regulate the influent flow rate into the wetland, which is accomplished by employing flow control structures like weirs, flumes, or flow meters (Qi et al., 2023). To maintain the desired HRT and prevent system overload in batch systems, manage the hydraulic loading rate (HLR) by adjusting it as needed. Additionally, incorporate buffer zones within the wetland to extend the HRT and improve treatment, especially for challenging-to-treat contaminants. A sequential treatment design within the wetland, where water passes through different sections or compartments with varying HRTs during batch cycles, optimizes the treatment for different contaminants and enhances the utilization of biochar. To prevent preferential flow paths in batch systems, design the wetland to minimize short-circuiting by ensuring an even distribution of flow. Properly placed baffles, distribution pipes, or other hydraulic control structures can effectively achieve this (Xing et al., 2021).

Generally, the batch feeding mode can attain better functioning as compared to continuous operations by elevating more oxidization conditions, on the elimination competencies in the tropical SSF-CWs (Deng et al., 2019). The study aimed to investigate the impact of biochar on nitrogen elimination in a CW using the intermittently aerated and batch mode. The performance of biochar, derived from decayed wetland plants (*Arundo donax*), was evaluated at different dosage levels. The dosage groups included group A with 0% biochar, group B with

10% biochar, and group C with 20% biochar (v/v). The objective was to assess the influence of biochar on the nitrogen removal efficiency of the CW system (Li et al., 2019b).

Removal of pollutant

Removal of inorganic material

Removal of nutrients, BOD$_5$, TSS,TVS

Biochar is used for nutrient elimination in CWs. Results have demonstrated that biochar could enhance phosphorus. Nitrogen retention has also been demonstrated; however, nitrogen reductions are generally processed by microbial activity (Feng et al., 2023). The elimination efficacy for PO_4–P was significantly larger than the control CWs, as compared to the biochar-containing system, proved by surface and elemental analyses. The biochar is also utilized as a soil fertilizer and has the latent to be reused and regenerated; nevertheless, further research is mandatory. Further inquiry is also necessitated about nutrient bioavailability on augmented biochar (Bolton et al., 2019). The biochar addition to the gravel substrate drastically improved the pollutant elimination performance in the SF-CWs. The VBF-CW along with NCB sludge fermentation (sewage sludge, rice straw, and food wastes) addition has significantly enhanced elimination efficiencies at a specific HRT of 3 days, while TP and TN removal rates at a reduced 2-day HRT were much higher as compared to HRT of 3 days without the NCB addition (Meng et al., 2019). Biochar lessened global warming potential values of CH_4 and N_2O to 24.0% and 18.5% (Guo et al., 2020a).

Biochar based on agricultural wastes/zeolite and gravel (biochar-amended CW) had established an ameliorate performance as compared to wetlands with only gravel substrate (Abedi & Mojiri, 2019). In another literature, three varieties of VF-CWs, crammed with the wood biochar (WB-CW), gravel (G-CW), and corn cob biochar (CB-CW), under tidal flow operations, were relatively assessed to explore the anaerobic digestion for treatment of effluent, mechanisms, and performance. It had established that the WB-CW and CB-CW impart suggestively elevated elimination efficiencies for the TN (37%), organic matter (59%), phosphorus (71%), and NH_4^+–N (76%), compared to G-CW (22–49%) (Kizito et al., 2017).

For the study of nutrient and organic removal, three hybrid (VF-HF) wetland systems were demonstrated. These CWs were full of unconventional and common media (biochar, sand, and gravel) with diverse water depth and saturation ratios (Saeed et al., 2019a). Adsorption characteristics and carbon content accessibility of the biochar were accompanied by improved nitrogen eliminations in the partly saturated VF-CWs; absenteeism of these specific factors shortens nitrogen exclusions in the gravel-based unsaturated VF-CWs. Amid the two variables, i.e., saturation depth and media type, the prior prejudiced nitrogen subtractions partly saturated VF-CWs. Another study documented that potential submission for the partially saturated shallow water depth–based hybrid wetland crammed with unconventional media attains significant organic and nutrient exclusion rates irrespective of improved input loadings (Fernandez-Fernandez et al., 2020).

Different water quality parameters are also affected by the presence of biochar in the wetlands. FWS-CWs removed PO_4^3–P, NH_3–N, and iron ions in the E-BHFCW effluent, which instantaneously enhanced DO absorption of the effluent, and elimination rates of TP and TN were also high as 52.99% and 62.62% (Gao et al., 2019). The TP and TN elimination efficiencies from wastewater were also highest in LBP (clay aggregates + biochar + plant filters) (20.0% and 22.5%, respectively), followed by LP (clay aggregates + plant) (13.7% and 16.2%, respectively) and LB (9.5% and 15.6%, respectively) filters. The study findings have confirmed that biochar has proved to be a beneficial supplement for the planted HSSF-CWs to improve the treatment competence of the systems (Kasak et al., 2018). Similarly, an experiment for TN removal was performed with a different substrate such as biochar and sand with different ratios. These outcomes confirmed that biochar can be a promising choice for sustainable maneuvering under seasonal temperature alternation (Li et al., 2019a).

Hybrid wetlands with specific media, such as biochar and CWs, have produced greater effluent potential for disposal. Biochar along with crushed mortar has been demonstrated to be an extremely efficient combination as a media for sub-surface flow CWs for wastewater treatment (Saeed et al., 2019b). TP was also reduced substantially from the wetland system effluent. The CW along with KS23 and biochar presented the highest TP elimination with the lowest value up to 15 mgL^{-1} (Saba et al., 2015).

Pollutant elimination with the help of woody biochar (from *Quercus* sp.) and gravel media has also been recorded in which CWs were planted with the *Canna* sp. The results showed that CWs along with biochar media showed better elimination efficiency as compared to the CWs with only gravel media (Gupta et al., 2015). Anaerobic digestion of effluents revealed that biochar media (from corn cob and wood biochar) had notably higher elimination efficiency (Kizito et al., 2015). Therefore, water quality parameters are easily affected by the presence of biochar which can bring water quality standards to health organizations. Table 3 illustrates the water properties, nutrient, and metal removal efficiency of biochar-amended CWs under various conditions.

Removal of heavy metal

Biochar filters offer an analogous performance to the sand filter despite having a lower bulk density which is coarsely one-tenth that of the sand filter. That is due to the elevated porosity and surface area of biochar. Wastewater remediation that is polluted with heavy metals entails numerous technologies, for example, reverse-osmosis, adsorption, electrodialysis, and ion exchange which are most common. Nearly all these technologies are costly, metal-specific, and energy-intensive. However, constructed wetland microcosm (CWM) macrophytes are recognized for their enormous potential toward the trace. CWMs for metal elimination involve chiefly sedimentation, cation exchange, filtration, complexation, adsorption, precipitation, microbial oxidation/reduction, and macrophyte uptake processes. Trace metal bioaccumulation has direct consequences on numerous abiotic, biotic, and environmental factors such as temperature and pH in the CWMs (Kumar & Dutta, 2019).

Hydric environments often experience prolonged saturation and/or flooding, leading to the alternation of oxic (oxygen-rich) and anoxic (oxygen-depleted) conditions in the soil. As a result, these soils frequently encounter variations in redox potential, pH levels, electron carriers in microbial activities, dissolved oxygen (DO), inorganic carbon concentrations, and more. These factors are particularly relevant in CWs hat serve as sinks for contaminated waters or sediments, which are subsequently discharged in response to changes in hydrodynamic conditions and physicochemical properties. The biogeochemical changes associated with discrepancies in flooding regimes and the presence of vegetation can potentially transform CWs into sources of metals. Therefore, amendments like calcium carbonates, typically effective in reducing metal mobility in upland sites, may not be sufficient in hydric soils (Álvarez-Rogel et al., 2018). In the remediation of arsenic and cadmium contamination in paddy soil, a study investigated the combined application of biochar and nZVI (nanoscale zero-valent iron). The results indicated that the co-application of biochar and nZVI effectively reduced the bioavailability and mobility of both cadmium and arsenic in the soil. The combined treatment demonstrated synergistic effects compared to using biochar or nZVI alone. The positive outcome can be attributed to several factors, including the enhanced formation of an iron plaque due to increased levels of amorphous iron oxides in the soil, the improved adsorption capacity of biochar, and the increased pH of the soil. These factors collectively contributed to the successful remediation of cadmium and arsenic contamination in the paddy soil (Qiao et al., 2018).

In another study, the elimination of nutrients and heavy metals from biogas slurry, the researchers explored the use of fillers (zeolite and biochar) and their mixtures with biosorbents (chlorella compound and a microbial agent) in CWs planted with water spinach (*Ipomoea aquatica*). The findings indicated that the CWs achieved a nutrient elimination rate above 60%. The efficiency of heavy metal removal from the biogas slurry in the CWs followed the order of copper < zinc < arsenic, with removal rates ranging from 0.32 to 0.88%, 8.15 to 23.69%, and 35.38 to 83.89% respectively. The combination of composite biochar and the microbial agent exhibited higher removal efficiency (Ouyang et al., 2023). The combination of two fillers and/or two biosorbents showed the most significant effect on reducing zinc and copper accumulation in the upper parts of water spinach. On the other hand, biochar alone demonstrated the best result in reducing arsenic accumulation in both the underground and aboveground parts of water spinach (Guo et al., 2020b).

Table 3 Contaminant removal efficiency of biochar-amended CWs under various conditions in treating various types of wastewater and removal efficiency

Type of CW	Filtration media with biochar	Plants	HLR	HRT	Removal efficiency		Reference
					Pollutant	Removal efficiency	
VF-CW	Biochar agricultural wastes/zeolite, and gravel	*P. australis* (common reed)	–	57.4 (h)	COD, ammonia Rem., Phenols Rem., Pb Rem., Mn Rem	99.9%, 99.9%, 99.9%, 99.9%, 99.9%	(Abedi & Mojiri, 2019)
MVFCWs	Bamboo at 500 ℃	*Oenanthe javanica*		72 h	Organic pollutants, NH_4^+–N, TN, N_2O emission	85%, 39%, 39%, 138–1008 Mg M^{-2} H^{-1}	(Zhou et al., 2018b)
HSSF-CWs	Chipped hemp fiber, based biochar	*Melaleuca quinquenervia* trees	0.023 M Per D	5.1 ds	PO_4–P, average P mass removal, pH	94.3%, 208.4 Mg L^{-1}, 7.3	(Bolton et al., 2019)
SF-CWs	Giant reed straw	*Acorus calamus*	0.05 $M^3 \cdot M^{-2} D^{-1}$	2 ds	Ammonium, total nitrogen	49.69–63.51%, 81.83–86.36%	(Deng et al., 2019)
VBF-CW system	Sludge fermentation	*Spartina anglica* Hubb	–	3 d or 2 d	Cod_{mn}, NH_4^+–N, TN, TP	83.3 ± 5.3%, 95.9 ± 3.4%, 28.0 ± 4.0%, 59.5 ± 11.8%	(Meng et al., 2019)
Batch mode CWS	Cattail harvested from the CW's	*Typha latifolia*	–	5 d	Synthetic wastewater, greenhouse gas (GHG), GWP values Of N_2O and CH_4, NH_4^+–N, COD/N ratios	18.5–24.0%, 53.9–43.1%	(Guo et al., 2020a)
VF-FWS-CWs	Bark of the *Acacia auriculiformis* plant	*Colocasia esculenta* and *Canna indica*	0.02–0.12 M/d	1–3 d	TSS, COD, BOD_5, NH_4–N, total coliform (Tcol)	71 ± 11%, 73 ± 13%, 79 ± 11%, 91 ± 3%, 70 ± 20%	(Nguyen et al., 2020)
HF-CW	Iron (Fe)-impregnated biochar	*Cyperus alternifolius*	–	3 d	Chlorpyrifos (pesticide)	95 ± 3 (99 ± 2)%	(Tang et al., 2016)
HSSF	95% charcoal alder/small proportions of charcoals from birch, oak, linden and willow	*Typha latifolia*	60	48 h	Phosphate removal, TN, TP	79.5%	(Kasak et al., 2018)

Table 3 (continued)

Type of CW	Filtration media with biochar	Plants	HLR	HRT	Removal efficiency		Reference
					Pollutant	Removal efficiency	
E-BHFCWs combined with FWS-CWs	Rice straw	E-BHFCW: *Hydrocotyle verticillata*, *Iris germanica* FWS-CW: *Potamogeton crispus*, *Myriophyllum verticillatum*, and *Hydrilla verticillate*		1 d	NO^{3-}–N, NH_3–N, PO_4^{3}–P	73.28%, 53.11%, 67.58%	(Gao et al., 2019)
SF-CWs	Decayed wetland plant, *Arundo donax*	*O. javanica*	0.13 M^3 M^{-2} $Batch^{-1}$	7 and 3 d	NO^{3-}–N removal, TN	91.27 ± 6.30% (20% Biochar) (phase I), 87.89 ± 3.78%, 92.72 ± 3.04% (phase II), 91.66%, 93.26% (phase I, II)	(Li et al., 2019a)
VF-CWs	Decayed wetland plant, *Arundo donax*	*Iris pseudacorus*	–	72 h	NH_4^+–N	98.30%	(Li et al., 2019b)
2 VF-CWs and 2 HF-CWs	Bamboo and wood	*Phragmites australis*	340–680 Mm/d	–	NH_4–N, TN, TP, COD, BOD_5, *E. coli*	$\geq 98, \geq 96, \geq 86, \geq 90, \geq 80, \geq 87\%$	(Saeed et al., 2019b)
Microcosm biofilters	Wood dust (300, 500, 700)	*Phragmites australis*	40 Cm/H	–	Bisphenol A (BPA) (BC700)	98.4%	(Lu & Chen, 2018)
CWs	Coconut shell/zeolite + biosorbents	Spinach (*Ipomoea aquatica*)	–	–	Heavy metals As > Zn > Cu	< 1%, 8.15–23.69%, 35.38–84%	(Guo et al., 2020b)
CWs	Coconut shell	*Typha latifolia*	–	–	Turbidity, TDS, BOD_5, COD	99.9%, 85%, 95%, 86%	(Vijay et al., 2017)
E-BHFCW	bamboo	*Cyperus alternifolius*	–	24 h	Nitrate, P	49.54%, 74.25%	(Gao et al., 2018)
CWEs	Sand media/woody BC	*Melaleuca quinquenervia*, *Cymbopogon citratus*	0.064 m/day	4 d	TSS, TVS, BOD_5	87–93%, 57–89%, 46–90%	(De Rozari et al., 2015)

Table 3 (continued)

Type of CW	Filtration media with biochar	Plants	HLR	HRT	Removal efficiency		Reference
					Pollutant	Removal efficiency	
IRCWs	Fe-BC	*Cyperus alternifolius*	–	–	Chlorpyrifos, 3,5,6-trichloro-2-pyridinol (Tcp)	$-1.03 \pm 0.09\%$ ($\varepsilon_{\text{bulk,c}}$ values)	(Tang et al., 2017b)
CWs	Coconut shell/dried neem seeds	*Typha latifolia*	–	120 h	Cr, turbidity, TDS, BOD, and COD	99.9%, 85%, 94%, 91%	(Vijay et al., 2019)
VF-CWs	Rice husk/strain	*Prescaria barbata*	–	20 min	Reactive black-5 dye, N removal	84%, 52–60%, 60% (BC), 78.7% BC plus KS23	(Saba et al., 2015)
CW-MFC reactor	Biochar-Mt-nZVI	*T. orientalis*	–	2 d	Phenanthrene anthracene	88.5 to 96.4%	(Wang et al., 2019)
VF-CWs	Maize husk, copper oxide/biochar, magnesium oxide/biochar, zinc oxide/biochar, manganese oxide/biochar	*Cymbopogon citratus*	–	24 h	Reactive Golden Yellow MERL (Yellow 145) dye	70–95%	(Munir et al., 2023)
CW	Green source activated carbon	*Phragmites australis*	–	24 h, 12 h, and 6 h	Nitrate from low carbon/nitrogen ratio wastewater	$97.07 \pm 1.76\%$, $85.91 \pm 3.02\%$, and $56.63 \pm 2.88\%$	(Xu et al., 2020)
Saturated and semi-saturated vertical flow constructed wetlands	Corn cob-derived biochar	*Phragmites australis*	–	3.5 days	Iodine and methylene blue	2.439 ± 0.120 mmol iodine g^{-1} and $5.86 \times 10^{-7} \pm 1.631 \times 10^{-8}$ mmol MB g^{-1}	(Gotore et al., 2022)
CW microcosms	Lanthanum-ammonia-modified hydrothermal biochar (La-A-HC) (*Phragmites australis* (PA) biochar)	*Acorus gramineus*	–	24 h	P removal	90.9%	(Shang et al., 2022)
CW-MFC	Rice husk	*Canna indica*	–	24 h	Methyl orange dye and COD	98% and 85.29%	(Sonu et al., 2022)

Constructed wetland-based removal of organic compounds

Organic pollutants encompass a wide range of compounds and molecules with varying sizes, all of which contain at least one carbon atom. Carbon serves as an energy source for various organisms, promoting the formation of biomass. However, excessive biomass growth, such as algae blooms, can occur as a result. The decomposition of organic compounds by bacteria consumes oxygen, leading to oxygen depletion and subsequent fish kills. Constructed floating wetlands (CFWs) are capable of reducing the concentration of organic pollutants through three main processes:

(i) Direct uptake of dissolved organic contaminants by the roots of vascular plants, bacteria, and algae cell walls or membranes
(ii) Microbial transformation of larger organic compounds into smaller compounds that can be readily absorbed by different parts of the plants
(iii) Adsorption of hydrophobic organic compounds onto particulate matter or directly onto the biofilm, eventually precipitating into the sediment

These processes contribute to the effective removal and mitigation of organic pollutants in CFWs, promoting improved water quality and ecosystem health (Bi et al., 2019). Figure 2 shows the mechanism of organic pollutant removal.

Polycyclic aromatic hydrocarbon (PAH)

With the addition of biochar to the soils, the PAH removal upsurges significantly to around twice as much as compared to fertilizer and CK treatments. The outcome is synergistic and improved by combining the fertilizer and biochar that are inserted into the soil; the exclusion rate upsurges up to 12.13% associated with that of the biochar addition only. This is perhaps because biochar endorses PAH absorption and decreases PAH levels. Consequently, biochar use is an auspicious way to remediate polluted soil. Bamboo-based biochar accumulation in the soil desorption and adsorption of diethyl phthalate (DEP) indicates that biochar highly improved the adsorption capacity of the soil, particularly for biochar based on high temperature (e.g., 600 °C) indicating that it depends on the soil organic carbon (SOC) level and aging of biochar processes. The improved phthalate acid ester (PAE) sorption in the soils by biochar may melodramatically decrease the leaching loss (Zhang et al., 2016).

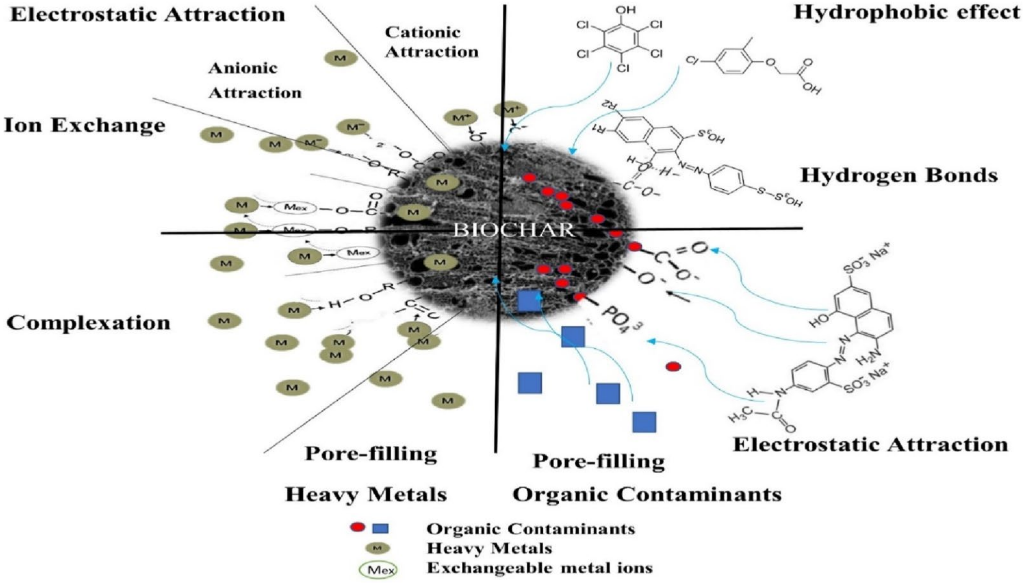

Fig. 2 Mechanism of inorganic and organic pollutant removal

Anthracene and phenanthrene

The frequent existence of PAHs in aquatic environments is of prodigious apprehension due to their carcinogenicity, mutagenicity, toxicity, and teratogenicity to human beings, plants, and animals. Constructed wetland microbial fuel cells (CW-MFC) were inspected along with an anode electrode modified without and with biochar nZVI. The average exclusion effectiveness for anthracene and phenanthrene ranged from 88.5 to 96.4%. The phenanthrene absorption in laminas roots and stems of *T. orientalis* was 2.3, 14.9, and 3.9 ng g^{-1} respectively, while that of the anthracene was 22.2, 1.3, and 3.1 ng g^{-1}, respectively (Wang et al., 2019).

Phenol

About 99% (50 mg L^{-1}) of the phenol was removed in all runs via zeolite, biochar, and gravel substrate coatings treatment. Biochar and zeolite substrate layers played a significant role in reducing phenols by about 99.9% abolition effectiveness (Abedi & Mojiri, 2019). Phenol eradicated about 60% of the wastewater of petrochemicals by the use of biochar (Razmi et al., 2019).

Bisphenol A (BPA)

Biochar derivatives from the wood dust (biochar 0) at diverse pyrolytic temperatures (300, 500, and 700 °C, referred to as biochar 300, biochar 500, and biochar 700, respectively) were categorized and inspected for their bisphenol A (BPA) adsorption. Compared with the other biochar, biochar 700 has shown a higher adsorption rate and capacity due to the high pore volume and specific surface area. Subsequently, fixed-bed columns amended with biochar 700 can eliminate BPA more efficiently than the columns with biochar 0, biochar 300, and biochar 500.

Organochlorine waste

Organochlorine from the papermaking industries has contaminated soils worldwide, and biochar addition has improved contaminated soils in several situations for wheat (*Triticum aestivum* L.). Straw-based biochar to the organic halogen polluted the saline-alkali soil. The addition of biochar has abridged the adsorbable organic halogen (AOX) concentrations in the extractable organic halogens (EOX) and soil in reeds (i.e., *Phragmites communis*) by 14 to 51% and 9 to 94%, respectively, and consequently improved the reed biomass by 1 to 25%; these vicissitudes were related to the variations in the diverse properties of soil. Soil properties, like the surface properties, pH, and organic functional groups, were enhanced followed by the biochar addition, and some variations were sustained at enhanced levels over time. The urease, enzyme activity, and sucrase and alkaline phosphatase in soil were amplified by 14–57%, 2–147%, and 1–75% as an escalating function of the amendment biochar, respectively, while the dehydrogenase was reduced by 13–60%, which may have assisted in the AOX decomposition acceleration. The assortment of the community of bacteria is also enhanced due to the biochar application and is prone to a key halogen degradation indicator.

The addition of biochar likely reduced organic halogens' bioavailability by enhancing the structure and function of the microbial community, reducing the transfer of reeds grown in the papermaking organochlorine-contaminated soils. So biochar plays a noteworthy part in the decrease of environmental pollution by organic halogens (Cui et al., 2019).

Mehlich-3 P

Biochar diminished Mehlich-3 P absorptions in the soils by 0.9 mg kg in the absenteeism of the phosphorus additions and improved Mehlich-3 P absorptions by 3.3 mg kg when attached to the phosphorus source (Nelson et al., 2011).

Pesticides (chlorpyrifos)

CWs have attracted attention because of their ability to eradicate pollutants such as pesticides and their low construction, maintenance, and operation costs. Recently, CWs have revealed an elevated capacity for the treatment of organic chemicals, chiefly pesticides, in wastewater. The primary mechanism elaborating CW elimination of the pesticides is unclear, because of the lack of comprehensive mass balance data, particularly for the trace organic pollutants. Pesticides are present in the water bodies either in the dissolved or particulate form. Particular pesticides, for instance, the extensively forbidden dichlorodiphenyltrichloroethane (DDT), are tenacious in the ecosystem, while newly industrialized pesticides usually have a shorter half-life. Microbial degradation and partially reversible adsorption have been recognized as the chief elimination processes for these pollutant groups. Direct removal by plants was extremely low to insignificant ($<0.6\%$). Pesticides with a high value of octanol–water partition coefficients (log K_{OW}) are probable for adsorption to the epidermal lipids in the roots without any additional uptake into plants. Though this eliminates these pesticides from the water bodies, it does not remove them from water bodies. Under evident circumstances, moderately sorbing pesticides, like metazachlor or isoproterenol, can be discharged back into the water (Bi et al., 2019).

Organophosphorus pesticide (OPP) removal can also take place in CWs, and the chief processes encompass phytoremediation (plant uptake, phytovolatilization, phytodegradation, and phytoaccumulation), substrate sedimentation or adsorption, or/and biodegradation. On quantitative analysis by mass balance, for water-soluble pesticides, the major elimination process was by microbiological degradation. This consequence was a divergence from verdicts obtained with the hydrophobic OPPs, in which the main processes were sorption and biodegradation by substrate (Liu et al., 2019). *Cyperus alternifolius* transpiration obtained by uptake of chlorpyrifos was 0.05 ± 0.01 and 0.06 ± 0.02 mg m^{-2} day^{-1} in the iron-amended biochar wetlands and plant cells, respectively, while the direct transpiration based on the uptake process was protuberant for about low to intermediate log K_{OW} values (0.5–3.0) (Tang et al., 2016). The compost addition can upsurge the organic matter contents and enhance soil biological activity, porosity, and nutrient availability. The iron-biochar presence would extensively upsurge the sorption capacity of chlorpyrifos, up to about 9.2–22.5% of the total elimination due to enhanced sorption and iron plaque in plant roots. However, it has been noted that the addition of biochar may have inverse effects on the pesticide transformation in soil (Liu et al., 2019; Tang et al., 2016). Four biochar amendments diminished the comprehensible content of 21 various organochlorine pesticides but amplified the Proteobacteria, Actinobacteria, Firmicutes, and Gemmatimonadetes abundances, (Ali et al., 2019). Sorption of pesticides on the biochar can increase its retention, thus reducing its bioavailability to microbes and plants in soil (Tang et al., 2017a).

The elimination of pesticides *tebuconazole* and *imazalil* at realistic concentration levels in the saturated CW mesocosms planted with the five varied plant species (*Iris pseudacorus*, *Typha latifolia*, *Phragmites australis*, *Juncus effusus*, and *Berula erecta*) was observed under varied hydraulic loading rates throughout the winter and summer. The elimination of imazalil and tebuconazole correlated with nutrient (P and nitrogen) removal, the evapotranspiration rate during summer and winter, and DO/oxygen saturation. This discloses two conceivable metabolization pathways: deprivation that took place inside the plant tissue after uptake and microbial degradation (plant-stimulated) in the bed substrate. Moreover, results indicated that nitrifying bacteria played an active role in pesticide biodegradation (Lv et al., 2016). The organic compound removal efficiency of CWs under various conditions and sizes is shown in Table 3 with different HRT and HLR.

Dye removal

CWs are a promising field, not only for detrimental chemical reduction but also for performing a noteworthy part in water recycling for agricultural functions. CW system–based treatment emphasizes the adsorption of dye by the soil substrate, microbial base degradation activity, and plant uptake base phytoaccumulation. Diverse forms of media have been utilized for the detoxification of wastewater, but little work has been done apropos agricultural waste, particularly for the biochar and rice husk; therefore, wastewater treatment in the CWs utilizing the agricultural waste and its biochar is a potential growth field and will offer a standard of the organic contaminant degradation kinetics for agricultural waste medium.

Reactive black dye adsorption on the rice husk has proven that dye adsorbs the biochar. It has been suggested that the presence of organic carbon in dried-out plant substances is hydrophobic and organophilic in nature, which has provided the sites for oxidizing strongly for the degradation of dye. In general, the obtained outcomes have indicated that half of the dye removal was achieved by CW substratum by the adsorption process (Saba et al., 2015). Efficiencies of color removal of about 99% obtained have demonstrated the azo bond cleavage and also established the

AO7 elimination and SO_4^{-2} discharge rates exposing adsorption onto the substrate constant (Davies et al., 2006).

Straw-based biochar (biochar) was produced as a profitable substitute for activated carbon (AC) that tested the adsorptive abilities of the rhodamine B (RB) and reactive brilliant blue (KNR). AC and biochar are similar in surface area but vary in the acidity of the surface, porosity, and surface charge. Both carbon-based compounds are greatly efficient as adsorbents for dyes at pH 3 and 6.5. Biochar was vaguely more efficient than AC in the adsorption of RB dye and low pH–based RB protonation. Their behavior was reversed in the effectiveness of the adsorption of reactive brilliant blue (KNR) for similar reasons (Qiu et al., 2009). Dyes are not degraded by wetlands themselves without any suitable substrate, and different studies have given us an indication of the use of biochar for this purpose.

Microbial communities in CWs

Biochar can also have an impact on microbial interaction and activity. The efficiency of purification of biochar-amended CW systems is closely correlated with changes in the microbial ecology and the number and activity of functional populations. The effect of adding biochar on the variety and richness of microorganisms in CWs has not regularly shown an influence, though (Yuan et al., 2020). Furthermore, the biochar-released elements, contaminants, and dissolved oxygen from wastewater may all move in the biofilm, forming a gradient-changing micro-environment along the depth direction of the biofilm (Gul et al., 2015). Aside from its potential as an organic carbon source, biochar also could act as just transferring electrons between donors, electric conductors, and acceptors for microbial nitrate reduction (Table 4), thus accelerating the biological pollutant removal rate (Sathishkumar et al., 2020). However, there were some opposing views expressed. Though biochar carbon may be utilized for denitrification, the amount was restricted. Given the nature of biochar, it may be difficult for microbes to assimilate the released carbon. Biochar absorbance extends the retention duration of some slow biodegradable substances and enhances the subsequent microbial pollutant interaction process (Zhuang et al., 2022). Another study aimed to enhance the nitrogen and phosphorus removal efficiency of surface flow constructed wetlands (SF-CWs) by incorporating biomass into the SF-CW matrix (Fan et al., 2021). Through simulation experiments, the researchers assessed the impact of varying biochar amounts on water purification, *Vallisneria natans* growth, and microbial mechanisms. It was found that the combined action of biochar and *Vallisneria natans* significantly reduced nitrogen and phosphorus concentrations in the effluent. However, excessive biochar (≥20%, v/v) hindered *Vallisneria natans* growth. Biochar addition (≥10%, v/v) increased carbon and nitrogen content but decreased phosphorus content in *Vallisneria natans*. Over time, nitrogen content in the matrices decreased, while phosphorus content increased. Microbial diversity and abundance in biochar-added SF-CW matrices decreased, but functional bacteria related to nitrogen and phosphorus removal increased. In conclusion, adding biochar improved water quality in SF-CWs, although excessive biochar limited *Vallisneria natans* growth, with potential benefits for denitrification and dephosphorization (Zheng et al., 2021). Biochar was employed to enhance the performance of CWs for the removal of organic matter and nitrogen from secondary wastewater (Guo et al., 2023). Four sets of non-aerated vertical flow CW (VF-CW) systems were established to investigate the combined effects of biochar and microorganisms on pollutant removal. The results demonstrated that VF-CWs, which included 1% w/w biochar alongside microorganisms and plants, achieved substantial removal efficiencies of 89.1% for chemical oxygen demand (COD) and 90.2% for nitrogen. In comparison to the control, VF-CWs also exhibited significantly higher removal rates for COD and total nitrogen (TN), with a 35% increase for COD and an impressive 52.3% increase for TN. The release of dissolved organic carbon from biochar within the VF-CWs indicated that water and acidic conditions were optimal for effective nitrogen removal. Analysis of the 16S RNA gene sequencing disclosed that the introduction of biochar in VF-CWs led to the enhanced prevalence of the bacterial phylum Proteobacteria, followed by *Chloroflexi*, *Planctomycetes*, and *Acidobacteria* (Ajibade et al., 2021).

Limitations

The environmental jeopardies of biochar during its utilization must be considered, and higher biochar in water or soil remediation limits its practical applications in the environment. Potential

Table 4 CWs' microbial communities regulated by biochar substrates and corresponding effects

Constructed wetlands	Biochar feedstock	Wastewater	Microbial communities	Effects of biochar	Reference
HSS-CWs	Tree branches	Domestic wastewater	OTUs, Chao 1, ACE, Shannon, Simpson	Enhancement of essential microbial metabolisms	(Ji et al., 2020)
Microcosm SF-CWs	Bamboo	Pollutant removal	Actinobacteria, Proteobacteria, Chloroflexi, Saccharibacteria, Bacteroidetes	Reduce N_2O emissions, ensure full denitrification and nitrification	(Liang et al., 2020)
CW	Bamboo	Swine wastewater	652 OUT, 597 OUT, Systems Shannon, Simpson, Chao1, Goods coverage, OTUs	Biochar addition supported rich and diverse microbial communities, combination with biochar and aeration could not improve diversity of microbe, demonstrating biochar addition would promote possession of richer bacterial community	(Feng et al., 2021)
VF-CWs	Bamboo	low C/N	Proteobacteria and Patescibacteria	Activity of enzymes and the proportion at the phylum level were appreciably enhanced with the addition of BC	(Zhang et al., 2021)
SSF-CWs	Bamboo	low C/N wastewater treatment	Shannon, Chao1, Goods coverage, OTUs	The abundance of bacterial community was promoted, especially for specific bacteria that related to the nitrogen removal	(Zhou et al., 2020)
intermittently aerated CW microcosms	walnut shells	Hg(II)-	*Arenimonas*, *Lysobacter*, *Micropruina*, and *Hydrogenophaga*	increased in the presence of Hg, implying their tolerance to Hg toxicity and potential roles in Hg detoxification in the CWs	(Chang et al., 2022)
CW microcosms		Microcystin (MC) pollution	*Burkholderiaceae*, *Nitrospiraceae*, *Micrococcaceae*, *Sphingomonadaceae*, and *Xanthomonadaceae* w	promoted by biochar addition regardless of addition ratios	(Cheng et al., 2022)

jeopardy of biochar encompasses the discharge of inherent pollutants from the biochar, adverse influences on organisms such as animals, microbes, and plants, and enables the pollutant's transformation and transport. Some researchers have found that the biochar or compost addition relatively in low concentrations stirred the microorganisms and enzyme activities and augmented microbial diversity, which improves the soil ecosystem's ability for organic pollutant degradation; on the other hand, research has also indicated that the high concentrations of biochar in an application can decrease the enzymatic activity, microbial diversity, and richness (Zhuang et al., 2022).

Another limitation in the use of biochar lies in the specific type of biochar employed, as not all biochars have a positive impact on the soil. This disconnection between the intended function of biochar and its actual performance can be attributed to structural limitations and a lack of comprehensive information on the thermochemical processes involved in specific biochar synthesis. Some researchers prioritize the production of biochar as an energy product, giving less attention to its intended purpose of returning the biochar to the soil. As a result, biochar researchers must consider each step systematically, from biochar preparation to its proper incorporation into the soil, in order to improve its effectiveness in soil enhancement (Tan et al., 2017). For instance, biochar derived from holm oak chip reduced lead and cadmium in the grain, with a slightly improved concentration in a field plot experiment (Moreno-Jiménez et al., 2016).

Waterlogging is another problem that directly affects on utilization of biochar in CWs because they affect the wetland species' growth response such as in cadmium-contaminated soil which is due to certain interactions between biochar and waterlogged environment (Zhang et al., 2013). Biochar use in soil may decrease pesticide bioavailability in soil which may reduce disease and pest control efficiency, which is an undesirable situation for agricultural production. (Ali et al., 2019). However, there is a lack of comprehensive data on the co-transport of pollutants and biochar in water or soil, which deserves more attention. It is crucial to thoroughly address the potential environmental risks associated with biochar before its application, considering factors such as the presence of inherent pollutants and the interactions between contaminants, biochar, and the biota in soil and water systems. Comprehensive studies are needed to better understand the dynamics and potential implications of these interactions to ensure the safe and responsible use of biochar in environmental applications.

Conclusions

A variety of biomass, mostly surplus biomass with slight to no worth and diverse thermal treatments, can be utilized for biochar production, which produces biochar with distinct characteristics in terms of phase structure, surface properties, and elemental composition. These multilevel structural properties of biochar have the auspicious potential for its application in wetlands for wastewater treatments by removing or immobilizing HMs and organic contaminants (e.g., pesticides and antibiotics). thus, the effect of biochar's performance in wetland-based remediation is always important. However, the applications of biochar in large-scale-based operations remain the main challenge for industrial wastewater. More field-scale research is required for the optimization of biochar's properties and performance in targeting contaminants. Another challenging point is the wetland maintenance along with biochar which can also cause a problem like waterlogging and affect the beneficial microorganism and pesticides which are beneficial against diseases. Thus, further research is required for the utilization of biochar in CWs.

Author contribution Ruba Munir: data curation, conceptualization, writing (original draft), and resources. Saima Noreen: supervision, conceptualization, and writing (reviewing and editing). Amna Muneer: data curation and writing (review and editing). Bushra Sadia: writing (reviewing and editing). Muhammad Zahid: writing (reviewing and editing). Muhammad Yaseen: writing (review and editing). Fazila Younas: investigation and writing (review and editing).

Data availability Not applicable.

Declarations

Ethical approval Research does not involve Human Participants or/and Animals.

Consent to participate Not applicable.

Consent for publication All authors have read, understood, and complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the instructions for authors.

Competing interests The authors declare no competing interests.

References

Abedi, T., & Mojiri, A. (2019). Constructed wetland modified by biochar/zeolite addition for enhanced wastewater treatment. *Environmental Technology & Innovation, 16*, 100472.

Ajibade, F. O., Wang, H.-C., Guadie, A., Ajibade, T. F., Fang, Y.-K., Sharif, H. M. A., Liu, W.-Z., & Wang, A.-J. (2021). Total nitrogen removal in biochar amended non-aerated vertical flow constructed wetlands for secondary wastewater effluent with low C/N ratio: Microbial community structure and dissolved organic carbon release conditions. *Bioresource Technology, 322*, 124430.

Ali, N., Khan, S., Li, Y., Zheng, N., & Yao, H. (2019). Influence of biochars on the accessibility of organochlorine pesticides and microbial community in contaminated soils. *Science of the Total Environment, 647*, 551–560.

Almuktar, S. A., Abed, S. N., & Scholz, M. (2018). Wetlands for wastewater treatment and subsequent recycling of treated effluent: A review. *Environmental Science and Pollution Research, 25*, 23595–23623.

Álvarez-Rogel, J., Gómez, M. d. C. T., Conesa, H. M., Párraga-Aguado, I., González-Alcaraz, M. N. (2018). Biochar from sewage sludge and pruning trees reduced porewater Cd, Pb and Zn concentrations in acidic, but not basic, mine soils under hydric conditions. *Journal of Environmental Management, 223*, 554-565

Bi, R., Zhou, C., Jia, Y., Wang, S., Li, P., Reichwaldt, E. S., & Liu, W. (2019). Giving waterbodies the treatment they need: A critical review of the application of constructed floating wetlands. *Journal of Environmental Management, 238*, 484–498.

Bolan, S., Hou, D., Wang, L., Hale, L., Egamberdieva, D., Tammeorg, P., Li, R., Wang, B., Xu, J., & Wang, T. (2023). The potential of biochar as a microbial carrier for agricultural and environmental applications. *Science of the Total Environment, 886*, 163968.

Bolton, L., Joseph, S., Greenway, M., Donne, S., Munroe, P., & Marjo, C. E. (2019). Phosphorus adsorption onto an enriched biochar substrate in constructed wetlands treating wastewater. *Ecological Engineering: X, 1*, 100005.

Chang, J., Peng, D., Deng, S., Chen, J., Duan, C. (2022). Efficient treatment of mercury (II).-containing wastewater in aerated constructed wetland microcosms packed with biochar. *Chemosphere,* 290, 133302

Cheng, R., Hou, S., Wang, J., Zhu, H., Shutes, B., Yan, B (2022) Biochar-amended constructed wetlands for eutrophication control and microcystin (MC-LR) removal. *Chemosphere*, 295, 133830

Cui, L., Yin, C., Chen, T., Quan, G., Ippolito, J. A., Liu, B., Yan, J., Ding, C., Hussain, Q., & Umer, M. (2019). Remediation of organic halogen-contaminated wetland soils using biochar. *Science of the Total Environment, 696*, 134087.

Davies, L., Pedro, I., Novais, J., & Martins-Dias, S. (2006). Aerobic degradation of acid orange 7 in a vertical-flow constructed wetland. *Water Research, 40*, 2055–2063.

De Rozari, P., Greenway, M., & El Hanandeh, A. (2015). An investigation into the effectiveness of sand media amended with biochar to remove BOD5, suspended solids and coliforms using wetland mesocosms. *Water Science and Technology, 71*, 1536–1544.

Deng, C., Huang, L., Liang, Y., Xiang, H., Jiang, J., Wang, Q., Hou, J., & Chen, Y. (2019). Response of microbes to biochar strengthen nitrogen removal in subsurface flow constructed wetlands: Microbial community structure and metabolite characteristics. *Science of the Total Environment, 694*, 133687.

Deng, S., Chen, J., & Chang, J. (2021). Application of biochar as an innovative substrate in constructed wetlands/biofilters for wastewater treatment: Performance and ecological benefits. *Journal of Cleaner Production, 293*, 126156.

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., Zimmerman, A. R., Ahmad, M., Shaheen, S. M., & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma, 337*, 536–554.

Fan, C., He, S., Wu, S., & Huang, J. (2021). Improved denitrification in surface flow constructed wetland planted with calamus. *Journal of Cleaner Production, 291*, 125944.

Feng, L., He, S., Wei, L., Zhang, J., & Wu, H. (2021). Impacts of aeration and biochar on physiological characteristics of plants and microbial communities and metabolites in constructed wetland microcosms for treating swine wastewater. *Environmental Research, 200*, 111415.

Feng, L., Gao, Z., Hu, T., He, S., Liu, Y., Jiang, J., Zhao, Q., & Wei, L. (2023). Performance and mechanisms of biochar-based materials additive in constructed wetlands for enhancing wastewater treatment efficiency: A review. *Chemical Engineering Journal, 471*, 144772.

Fernandez-Fernandez, M., de la Vega, P. M., Jaramillo-Morán, M., & Garrido, M. (2020). Hybrid constructed wetland to improve organic matter and nutrient removal. *Water, 12*, 2023.

Gao, Y., Zhang, W., Gao, B., Jia, W., Miao, A., Xiao, L., & Yang, L. (2018). Highly efficient removal of nitrogen and phosphorus in an electrolysis-integrated horizontal subsurface-flow constructed wetland amended with biochar. *Water Research, 139*, 301–310.

Gao, Y., Yan, C., Wei, R., Zhang, W., Shen, J., Wang, M., Gao, B., Yang, Y., & Yang, L. (2019). Photovoltaic electrolysis improves nitrogen and phosphorus removals of biochar-amended constructed wetlands. *Ecological Engineering, 138*, 71–78.

Ge, Y., Wang, X., Zheng, Y., Dzakpasu, M., Zhao, Y., & Xiong, J. (2015). Functions of slags and gravels as substrates in large-scale demonstration constructed wetland systems for polluted river water treatment. *Environmental Science and Pollution Research, 22*, 12982–12991.

Gotore, O., Rameshprabu, R., & Itayama, T. (2022). Adsorption performances of corn cob-derived biochar in saturated and semi-saturated vertical-flow constructed wetlands for nutrient removal under erratic oxygen supply. *Environmental Chemistry and Ecotoxicology, 4*, 155–163.

Gul, S., Whalen, J. K., Thomas, B. W., Sachdeva, V., & Deng, H. (2015). Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. *Agriculture, Ecosystems & Environment, 206*, 46–59.

Guo, F., Zhang, J., Yang, X., He, Q., Ao, L., & Chen, Y. (2020a). Impact of biochar on greenhouse gas emissions from constructed wetlands under various influent chemical oxygen demand to nitrogen ratios. *Bioresource Technology, 303*, 122908.

Guo, X., Cui, X., & Li, H. (2020b). Effects of fillers combined with biosorbents on nutrient and heavy metal removal from biogas slurry in constructed wetlands. *Science of the Total Environment, 703*, 134788.

Guo, F., Luo, Y., Nie, M., Zheng, F., Zhang, G., & Chen, Y. (2023). A comprehensive evaluation of biochar for enhancing nitrogen removal from secondary effluent in constructed wetlands. *Chemical Engineering Journal, 478*, 147469.

Gupta, P., Ann, T.-W., Lee, S.-M., Gupta, P., Ann, T.-W., & Lee, S.-M. (2015). Use of biochar to enhance constructed wetland performance in wastewater reclamation. *Environmental Engineering Research, 21*, 36–44.

Hoffman, A. (2019). *Water, energy, and environment: A primer*. IWA publishing

Hu, Z.-Y., Chen, X., & Jiang, H. (2022). A life cycle assessment of the combined utilization of biomass waste-derived hydrochar as a carbon source and soil remediation. *ACS ES&T Engineering, 3*, 165–173.

Ji, B., Chen, J., Mei, J., Chang, J., Li, X., Jia, W., & Qu, Y. (2020). Roles of biochar media and oxygen supply strategies in treatment performance, greenhouse gas emissions, and bacterial community features of subsurface-flow constructed wetlands. *Bioresource Technology, 302*, 122890.

Jia, W., & Yang, L. (2021). Community composition and spatial distribution of N-removing microorganisms optimized by Fe-modified biochar in a constructed wetland. *International Journal of Environmental Research and Public Health, 18*, 2938.

Ju, X., Wu, S., Huang, X., Zhang, Y., & Dong, R. (2014). How the novel integration of electrolysis in tidal flow constructed wetlands intensifies nutrient removal and odor control. *Bioresource Technology, 169*, 605–613.

Kasak, K., Truu, J., Ostonen, I., Sarjas, J., Oopkaup, K., Paiste, P., Kõiv-Vainik, M., Mander, Ü., & Truu, M. (2018). Biochar enhances plant growth and nutrient removal in horizontal subsurface flow constructed wetlands. *Science of the Total Environment, 639*, 67–74.

Kizito, S., Wu, S., Kirui, W. K., Lei, M., Lu, Q., Bah, H., & Dong, R. (2015). Evaluation of slow pyrolyzed wood and rice husks biochar for adsorption of ammonium nitrogen from piggery manure anaerobic digestate slurry. *Science of the Total Environment, 505*, 102–112.

Kizito, S., Lv, T., Wu, S., Ajmal, Z., Luo, H., & Dong, R. (2017). Treatment of anaerobic digested effluent in biochar-packed vertical flow constructed wetland columns: Role of media and tidal operation. *Science of the Total Environment, 592*, 197–205.

Knox, O. G., Weitz, H. J., Anderson, P., Borlinghaus, M., & Fountaine, J. (2018). Improved screening of biochar compounds for potential toxic activity with microbial biosensors. *Environmental Technology & Innovation, 9*, 254–264.

Kumar, S., & Dutta, V. (2019). Constructed wetland microcosms as sustainable technology for domestic wastewater treatment: An overview. *Environmental Science and Pollution Research, 26*, 11662–11673.

Li, J., Dai, J., Liu, G., Zhang, H., Gao, Z., Fu, J., He, Y., & Huang, Y. (2016). Biochar from microwave pyrolysis of biomass: A review. *Biomass and Bioenergy, 94*, 228–244.

Li, J., Fan, J., Liu, D., Hu, Z., & Zhang, J. (2019a). Enhanced nitrogen removal in biochar-added surface flow constructed wetlands: Dealing with seasonal variation in the north China. *Environmental Science and Pollution Research, 26*, 3675–3684.

Li, J., Hu, Z., Li, F., Fan, J., Zhang, J., Li, F., & Hu, H. (2019b). Effect of oxygen supply strategy on nitrogen removal of biochar-based vertical subsurface flow constructed wetland: Intermittent aeration and tidal flow. *Chemosphere, 223*, 366–374.

Liang, Y., Wang, Q., Huang, L., Liu, M., Wang, N., & Chen, Y. (2020). Insight into the mechanisms of biochar addition on pollutant removal enhancement and nitrous oxide emission reduction in subsurface flow constructed wetlands: Microbial community structure, functional genes and enzyme activity. *Bioresource Technology, 307*, 123249.

Liu, L., Tan, Z., Gong, H., & Huang, Q. (2018). Migration and transformation mechanisms of nutrient elements (N, P, K). within biochar in straw–biochar–soil–plant systems: A review. *ACS Sustainable Chemistry & Engineering, 7*, 22–32.

Liu, T., Xu, S., Lu, S., Qin, P., Bi, B., Ding, H., Liu, Y., Guo, X., & Liu, X. (2019). A review on removal of organophosphorus pesticides in constructed wetland: Performance, mechanism and influencing factors. *Science of the Total Environment, 651*, 2247–2268.

Lu, L., & Chen, B. (2018). Enhanced bisphenol A removal from stormwater in biochar-amended biofilters: Combined with batch sorption and fixed-bed column studies. *Environmental Pollution, 243*, 1539–1549.

Lu, S., Zhang, X., Wang, J., & Pei, L. (2016). Impacts of different media on constructed wetlands for rural household sewage treatment. *Journal of Cleaner Production, 127*, 325–330.

Lucke, T., Walker, C., & Beecham, S. (2019). Experimental designs of field-based constructed floating wetland studies: A review. *Science of the Total Environment, 660*, 199–208.

Lv, T., Zhang, Y., Zhang, L., Carvalho, P. N., Arias, C. A., & Brix, H. (2016). Removal of the pesticides imazalil and tebuconazole in saturated constructed wetland mesocosms. *Water Research, 91*, 126–136.

Meng, P., Pei, H., Hu, W., Shao, Y., & Li, Z. (2014). How to increase microbial degradation in constructed wetlands: Influencing factors and improvement measures. *Bioresource Technology, 157*, 316–326.

Meng, F., Feng, L., Yin, H., Chen, K., Hu, G., Yang, G., & Zhou, J. (2019). Assessment of nutrient removal and microbial population dynamics in a non-aerated vertical baffled flow constructed wetland for contaminated water treatment with composite biochar addition. *Journal of Environmental Management, 246*, 355–361.

Minakshi, D., Sharma, P. K., Rani, A., Malaviya, P., Srivastava, V., & Kumar, M. (2022). Performance evaluation of vertical constructed wetland units with hydraulic retention time as a variable operating factor. *Groundwater for Sustainable Development, 19*, 100834.

Mohan, D., Sarswat, A., Ok, Y. S., & Pittman, C. U., Jr. (2014). Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–A critical review. *Bioresource Technology, 160*, 191–202.

Moreno-Jiménez, E., Fernández, J. M., Puschenreiter, M., Williams, P. N., & Plaza, C. (2016). Availability and transfer to grain of As, Cd, Cu, Ni, Pb and Zn in a barley agri-system: Impact of biochar, organic and mineral fertilizers. *Agriculture, Ecosystems & Environment, 219*, 171–178.

Munir, R., Ali, K., Naqvi, S. A. Z., Muneer, A., Bashir, M. Z., Maqsood, M. A., & Noreen, S. (2023). Green metal oxides coated biochar nanocomposites preparation and its utilization in vertical flow constructed wetlands for reactive dye removal: Performance and kinetics studies. *Journal of Contaminant Hydrology, 256*, 104167.

Narayan, M., Srivastava, P. S. R. (2019). A review of constructed wetland coupled with microbial fuel cell: A recently emerged technology

Nelson, N. O., Agudelo, S. C., Yuan, W., & Gan, J. (2011). Nitrogen and phosphorus availability in biochar-amended soils. *Soil Science, 176*, 218–226.

Nguyen, X. C., Tran, T. P., Hoang, V. H., Nguyen, T. P., Chang, S. W., Nguyen, D. D., Guo, W., Kumar, A., La, D. D., & Bach, Q.-V. (2020). Combined biochar vertical flow and free-water surface constructed wetland system for dormitory sewage treatment and reuse. *Science of the Total Environment, 713*, 136404.

Novak, J., Sigua, G., Spokas, K., Busscher, W., Cantrell, K., Watts, D., Glaz, B., & Hunt, P. (2015). Plant macro-and micronutrient dynamics in a biochar-amended wetland muck. *Water, Air, & Soil Pollution, 226*, 2228.

Osman, A. I., Fawzy, S., Farghali, M., El-Azazy, M., Elgarahy, A. M., Fahim, R. A., Maksoud, M. A., Ajlan, A. A., Yousry, M., & Saleem, Y. (2022). Biochar for agronomy, animal farming, anaerobic digestion, composting, water treatment, soil remediation, construction, energy storage, and carbon sequestration: A review. *Environmental Chemistry Letters, 20*, 2385–2485.

Ouyang, P., Narayanan, M., Shi, X., Chen, X., Li, Z., Luo, Y., & Ma, Y. (2023). Integrating biochar and bacteria for sustainable remediation of metal-contaminated soils. *Biochar, 5*, 63.

Phiri, Z., Moja, N. T., Nkambule, T. T., de Kock, L.-A. (2024). Utilization of biochar for remediation of heavy metals in aqueous environments: A review and bibliometric analysis. *Heliyon*

Qi, Y., Zhong, Y., Luo, L., He, J., Feng, B., Wei, Q., Zhang, K., & Ren, H. (2024). Subsurface constructed wetlands with modified biochar added for advanced treatment of tailwater: Performance and microbial communities. *Science of the Total Environment, 906*, 167533.

Qi, Y., Zhong, Y., Luo, L., He, J., Feng, B., Wei, Q., Zhang, K., Ren, H. (2023). Subsurface constructed wetlands with modified biochar added for advanced treatment of tailwater: Performance and microbial communities. *Science of The Total Environment*, 167533

Qiao, J.-T., Liu, T.-X., Wang, X.-Q., Li, F.-B., Lv, Y.-H., Cui, J.-H., Zeng, X.-D., Yuan, Y.-Z., & Liu, C.-P. (2018). Simultaneous alleviation of cadmium and arsenic accumulation in rice by applying zero-valent iron and biochar to contaminated paddy soils. *Chemosphere, 195*, 260–271.

Qiu, Y., Zheng, Z., Zhou, Z., & Sheng, G. D. (2009). Effectiveness and mechanisms of dye adsorption on a straw-based biochar. *Bioresource Technology, 100*, 5348–5351.

Razmi, R., Ramavandi, B., Ardjmand, M., & Heydarinasab, A. (2019). Efficient phenol removal from petrochemical wastewater using biochar-La/ultrasonic/persulphate system: Characteristics, reusability, and kinetic study. *Environmental Technology, 40*, 822–834.

Saba, B., Jabeen, M., Khalid, A., Aziz, I., & Christy, A. D. (2015). Effectiveness of rice agricultural waste, microbes and wetland plants in the removal of reactive black-5 azo dye in microcosm constructed wetlands. *International Journal of Phytoremediation, 17*, 1060–1067.

Saeed, T., & Sun, G. (2012). A review on nitrogen and organics removal mechanisms in subsurface flow constructed wetlands: Dependency on environmental parameters, operating conditions and supporting media. *Journal of Environmental Management, 112*, 429–448.

Saeed, T., Haque, I., & Khan, T. (2019a). Organic matter and nutrients removal in hybrid constructed wetlands: Influence of saturation. *Chemical Engineering Journal, 371*, 154–165.

Saeed, T., Yasmin, N., Sun, G., & Hasnat, A. (2019b). The use of biochar and crushed mortar in treatment wetlands to enhance the removal of nutrients from sewage. *Environmental Science and Pollution Research, 26*, 586–599.

Sathishkumar, K., Li, Y., & Sanganyado, E. (2020). Electrochemical behavior of biochar and its effects on microbial nitrate reduction: Role of extracellular polymeric substances in extracellular electron transfer. *Chemical Engineering Journal, 395*, 125077.

Sehar, S., Nasser, H. (2019). Wastewater treatment of food industries through constructed wetland: A review. *International Journal of Environmental Science and Technology*, 1–20

Shang, Z., Wang, Y., Wang, S., Jin, F., & Hu, Z. (2022). Enhanced phosphorus removal of constructed wetland modified with novel lanthanum-ammonia-modified hydrothermal biochar: Performance and mechanism. *Chemical Engineering Journal, 449*, 137818.

Sharma, P. (2022). Role and significance of biofilm-forming microbes in phytoremediation-A review. *Environmental Technology & Innovation, 25*, 102182.

Sharma, S., & Bhattacharya, A. (2017). Drinking water contamination and treatment techniques. *Applied Water Science, 7*, 1043–1067.

Sonu, K., Sogani, M., Syed, Z., Rajvanshi, J., & Sengupta, N. (2022). Effectiveness of rice husk in the removal of methyl orange dye in constructed wetland-microbial fuel cell. *Bioresource Technology Reports, 20*, 101223.

Tan, Z., Lin, C. S., Ji, X., & Rainey, T. J. (2017). Returning biochar to fields: A review. *Applied Soil Ecology, 116*, 1–11.

Tang, X., Yang, Y., Tao, R., Chen, P., Dai, Y., Jin, C., & Feng, X. (2016). Fate of mixed pesticides in an integrated recirculating constructed wetland (IRCW). *Science of the Total Environment, 571*, 935–942.

Tang, X.-Y., Huang, W.-D., Guo, J.-J., Yang, Y., Tao, R., & Feng, X. (2017a). Use of Fe-impregnated biochar to efficiently sorb chlorpyrifos, reduce uptake by Allium fistulosum L., and enhance microbial community diversity. *Journal of Agricultural and Food Chemistry, 65*, 5238–5243.

Tang, X., Yang, Y., Huang, W., McBride, M. B., Guo, J., Tao, R., & Dai, Y. (2017b). Transformation of chlorpyrifos in integrated recirculating constructed wetlands (IRCWs). as revealed by compound-specific stable isotope (CSIA). and microbial community structure analysis. *Bioresource Technology, 233*, 264–270.

Vijay, M. V., Sudarsan, J., & Nithiyanantham, S. (2017). Sustainability of constructed wetlands in using biochar for treating wastewater. *Rasayan Journal of Chemistry, 10*, 1056–1061.

Vijay, M. V., Sudarsan, J., & Nithiyanantham, S. (2019). Sustainability of constructed wetlands using biochar as effective absorbent for treating wastewaters. *International Journal of Energy and Water Resources, 3*, 153–164.

Vymazal, J. (2013). Emergent plants used in free water surface constructed wetlands: A review. *Ecological Engineering, 61*, 582–592.

Vymazal, J. (2014). Constructed wetlands for treatment of industrial wastewaters: A review. *Ecological Engineering, 73*, 724–751.

Wang, J., Song, X., Li, Q., Bai, H., Zhu, C., Weng, B., Yan, D., & Bai, J. (2019). Bioenergy generation and degradation pathway of phenanthrene and anthracene in a constructed wetland-microbial fuel cell with an anode amended with nZVI. *Water Research, 150*, 340–348.

Wu, H., Zhang, J., Ngo, H. H., Guo, W., Hu, Z., Liang, S., Fan, J., & Liu, H. (2015). A review on the sustainability of constructed wetlands for wastewater treatment: Design and operation. *Bioresource Technology, 175*, 594–601.

Wu, S., Vymazal, J., & Brix, H. (2019). Critical review: Biogeochemical networking of iron in constructed wetlands for wastewater treatment. *Environmental Science & Technology, 53*, 7930–7944.

Xiang, L., Harindintwali, J. D., Wang, F., Redmile-Gordon, M., Chang, S. X., Fu, Y., He, C., Muhoza, B., Brahushi, F., & Bolan, N. (2022). Integrating biochar, bacteria, and plants for sustainable remediation of soils contaminated with organic pollutants. *Environmental Science & Technology, 56*, 16546–16566.

Xing, C., Xu, X., Xu, Z., Wang, R., & Xu, L. (2021). Study on the decontamination effect of biochar-constructed wetland under different hydraulic conditions. *Water, 13*, 893.

Xu, J., Liu, X., Huang, J., Huang, M., Wang, T., Bao, S., Tang, W., & Fang, T. (2020). The contributions and mechanisms of iron-microbes-biochar in constructed wetlands for nitrate removal from low carbon/nitrogen ratio wastewater. *RSC Advances, 10*, 23212–23220.

Yadav, G., Yadav, N., Sultana, M., Ahmaruzzaman, M. (2023). A comprehensive review on low-cost waste-derived catalysts for environmental remediation. *Materials Research Bulletin*, 112261

Yang, Y., Zhao, Y., Liu, R., & Morgan, D. (2018). Global development of various emerged substrates utilized in constructed wetlands. *Bioresource Technology, 261*, 441–452.

Ye, S., Zeng, G., Wu, H., Liang, J., Zhang, C., Dai, J., Xiong, W., Song, B., Wu, S., & Yu, J. (2019). The effects of activated biochar addition on remediation efficiency of co-composting with contaminated wetland soil. *Resources, Conservation and Recycling, 140*, 278–285.

Yu, P., Qin, K., Niu, G., Gu, M. (2023). Alleviate environmental concerns with biochar as a container substrate: A review. *Frontiers in Plant Science*, 14

Yuan, Y., Yang, B., Wang, H., Lai, X., Li, F., Salam, M. M. A., Pan, F., & Zhao, Y. (2020). The simultaneous antibiotics and nitrogen removal in vertical flow constructed wetlands: Effects of substrates and responses of microbial functions. *Bioresource Technology, 310*, 123419.

Zhang, D. Q., Tan, S. K., Gersberg, R. M., Zhu, J., Sadreddini, S., & Li, Y. (2012). Nutrient removal in tropical subsurface flow constructed wetlands under batch and continuous flow conditions. *Journal of Environmental Management, 96*, 1–6.

Zhang, Z., Solaiman, Z. M., Meney, K., Murphy, D. V., & Rengel, Z. (2013). Biochars immobilize soil cadmium, but do not improve growth of emergent wetland species Juncus subsecundus in cadmium-contaminated soil. *Journal of Soils and Sediments, 13*, 140–151.

Zhang, X., Sarmah, A. K., Bolan, N. S., He, L., Lin, X., Che, L., Tang, C., & Wang, H. (2016). Effect of aging process on adsorption of diethyl phthalate in soils amended with bamboo biochar. *Chemosphere, 142*, 28–34.

Zhang, Y., Li, M., Dong, L., Han, C., Li, M., & Wu, H. (2021). Effects of biochar dosage on treatment performance, enzyme activity and microbial community in aerated constructed wetlands for treating low C/N domestic sewage. *Environmental Technology & Innovation, 24*, 101919.

Zheng, C., Zhang, X., Gan, L., He, Z., Zhu, J., Zhang, W., Gao, Y., & Yang, L. (2021). Effects of biochar on the growth of Vallisneria natans in surface flow constructed wetland. *Environmental Science and Pollution Research, 28*, 66158–66170.

Zheng, F., Fang, J., Guo, F., Yang, X., Liu, T., Chen, M., Nie, M., & Chen, Y. (2022). Biochar based constructed wetland for secondary effluent treatment: Waste resource utilization. *Chemical Engineering Journal, 432*, 134377.

Zheng, H., Zhang, C., Liu, B., Liu, G., Zhao, M., Xu, G., Luo, X., Li, F., Xing, B. (2020). *Biochar for water and soil remediation: Production, characterization, and* *application, a new paradigm for environmental chemistry and toxicology*. Springer, pp. 153–196

Zhou, X., Jia, L., Liang, C., Feng, L., Wang, R., & Wu, H. (2018a). Simultaneous enhancement of nitrogen removal and nitrous oxide reduction by a saturated biochar-based intermittent aeration vertical flow constructed wetland: Effects of influent strength. *Chemical Engineering Journal, 334*, 1842–1850.

Zhou, X., Liang, C., Jia, L., Feng, L., Wang, R., & Wu, H. (2018b). An innovative biochar-amended substrate vertical flow constructed wetland for low C/N wastewater treatment: Impact of influent strengths. *Bioresource Technology, 247*, 844–850.

Zhou, X., Chen, Z., Li, Z., & Wu, H. (2020). Impacts of aeration and biochar addition on extracellular polymeric substances and microbial communities in constructed wetlands for low C/N wastewater treatment: Implications for clogging. *Chemical Engineering Journal, 396*, 125349.

Zhuang, L.-L., Li, M., Li, Y., Zhang, L., Xu, X., Wu, H., Liang, S., Su, C., & Zhang, J. (2022). The performance and mechanism of biochar-enhanced constructed wetland for wastewater treatment. *Journal of Water Process Engineering, 45*, 102522.