The Scientific Temper (2024) Vol. 15 (3): 2954-2960
Doi: 10.58414/SCIENTIFICTEMPER.2024.15.3.68

E-ISSN: 2231-6396, ISSN: 0976-8653
https://scientifictemper.com/

RESEARCH ARTICLE

Horizontal flow biochar amended constructed wetlands as a sustainable approach for rural wastewater treatment

Vishal Panghal[1], Asha Singh[1], Dinesh Arora[1], Nidhi Ahlawat[1], Sunder S. Arya[2], Sunil Kumar[1*]

Abstract

Constructed wetlands (CWs) have provided an alternative technology to conventional wastewater treatment technologies for more than fifty years. Biochar is a carbon-rich porous material made in the absence of oxygen at higher temperatures that has recently been used as a substrate in constructed wetlands. The objective of this study was to measure the efficiency of horizontal flow (HF) biochar amended constructed wetlands planted with *Eclipta alba* (L) in treating rural wastewater in batch mode. A total of seven experimental sets were prepared. Two controls, one without plantation (C1) and one with plantation (C2), were used in the study. In five sets, various soil and biochar ratios ranging from 5 to 25% were used as a substrate, with a 5% biochar interval. Physio-chemical parameters like biological oxygen demand (BOD), chemical oxygen demand (COD), nitrate (NO_3^-), total kjeldhal nitrogen (TKN), sulfate (SO_4^{2-}) and phosphates (PO_4^{3-}) were analyzed at various hydraulic retention time (HRT) of 24, 48, and 72 hours to check the performance of HFCWs. The maximum removal efficiency of BOD, COD, NO_3^-, TKN and SO_4^{2-} were found to be 75, 70, 80, 71, and 46%, respectively, at HRT 72 hours and in B25 variation. Removal efficiency increased with an increase in HRT and biochar concentration. However, the removal of phosphates was highest at B25 at HRT 48 hours. The results reveal the critical role of wetland vegetation and biochar concentration as substrates. The biochar additions effectively removed organic contaminants and nitrates. Biochar-enhanced CWs can provide a long-term solution for treating rural home wastewater.

Keywords: Constructed wetlands, Rural wastewater treatment, Wetland vegetation, Biochar, Organic pollution.

Introduction

Water is becoming an increasingly limited resource on a worldwide scale. According to the International Water Management Institute, by 2025, one out of every three people in India will face acute water shortages (Boopathi and Kadarkarai, 2022). Within the decentralized wastewater treatment systems under investigation, constructed wetlands (CWs) have emerged as one of the most viable choices. CWs are commonly used as a low-cost wastewater treatment method that treats wastewater using physical, chemical, and biological processes (Villasenor *et al*., 2013). Constructed wetlands have effectively treated a wide range of wastewater types, including industrial effluents, landfill leachates, aquaculture wastewater, discharges from pulp and paper mills, and wastes from petroleum products, slaughterhouses, and seafood processing facilities (Fahim *et al*., 2023).

CWs are an environmentally friendly technique that is acknowledged as a sustainable, natural wastewater treatment option in which both the substrate and vegetation play important roles in the removal of pollutants (Younas *et al*., 2022; Addo-Bankas *et al*., 2021; Ohore *et al*., 2022). Over time, constructed wetlands have changed, and regular experiments have increased their efficiency. Hydraulic retention time (HRT), patterns of water flow, the presence of macrophytes, and the kind of substrates utilized are some of the aspects that have a significant impact on the performance of CWs.

The substrate is a critical component of CWs because it facilitates and enhances the operation of mechanical, physical, and biological processes that reduce pollutant concentrations in CW effluents. It plays a key role in the

---

[1]Department of Environmental Sciences, Maharshi Dayanand University, Rohtak, Haryana, India.

[2]Department of Botany, Maharshi Dayanand University, Rohtak, Haryana, India.

***Corresponding Author:** Sunil Kumar, Department of Environmental Sciences, Maharshi Dayanand University, Rohtak, Haryana, India., E-Mail: sunilevs@yahoo.com

How to cite this article: Panghal, V., Singh, A., Arora, D., Ahlawat, N., Arya, S. S., Kumar, S. (2024). Horizontal flow biochar amended constructed wetlands as a sustainable approach for rural wastewater treatment. The Scientific Temper, **15**(3):2954-2960.

Doi: 10.58414/SCIENTIFICTEMPER.2024.15.3.68

Source of support: Nil

Conflict of interest: None.

Received: 27/07/2024 **Accepted:** 28/08/2024 **Published** : 20/09/2024

direct removal of contaminants, provides reactive agents for pollutant transformation, supports plant growth, and ensures biofilm adhesion (Deng *et al.*, 2021; Barakoui *et al.*, 2023). Previous research has shown that different substrates have varying capacities for wastewater treatment, which has led to the widespread usage of different kinds of substrates like zeolite, gravel, limestone, coal ash, and different industrial wastes in constructed wetlands (Lu *et al.*, 2016). Biochar is becoming increasingly popular as an innovative wastewater treatment component. This carbon-rich substance is formed through the pyrolysis process, which involves heating biomass to high temperatures in an environment devoid of oxygen, resulting in a stable form of carbon that can improve the treatment process (Manyà, 2012).

Biochar is a potent tool for improving water purification procedures because of its large specific surface area and porous design, which have been demonstrated to effectively adsorb and immobilize a variety of contaminants found in contaminated water (Beesley *et al.*, 2011; Mohan *et al.*, 2014). Since biochar is rich in carbon, it has the potential to serve as a carbon source that enhances denitrification in wastewater with a low carbon-to-nitrogen ratio (Liang *et al.*, 2006; Liu and Zhang, 2009).

Numerous research conducted in several countries has investigated different substrate combinations in CWs to treat various forms of wastewater. Abedi and Mojiri (2019) used CWs enriched with charcoal and zeolite to efficiently remediate synthetic wastewater, demonstrating the potential of these materials in improving the treatment efficiency of constructed wetlands. Xu *et al.*, (2020) used a substrate made of iron, microorganisms, and biochar in their CW for synthetic wastewater treatment. Assad *et al.* (2022) used biochar-amended CWs to treat drainage wastewater, and Zhou *et al.*, (2018) used biochar-amended CWs to treat synthetic wastewater. In India, several researchers have looked into the use of CWs to cleanse various forms of wastewater. Sonu *et al.* (2021) addressed textile wastewater treatment by incorporating microbial fuel cells and charcoal as a substrate within CWs, while Nema *et al.* (2020) explored the treatment of greywater in CWs using a variety of plant species to enhance the process. Barya *et al.* (2020) treated home sewage with vertical subsurface flow CWs, while Kumar and Singh (2019) investigated municipal wastewater treatment with CWs. Rural domestic wastewater is primarily generated by activities such as laundry, dishwashing, home cleaning, bathing, tooth brushing, and face washing. These mechanisms transport nutrients, organic materials, and inorganic contaminants into rural ponds via village routes. As a result, cost-effective treatment measures at the village level should be adopted before releasing this wastewater into ponds. In this study, biochar-amended subsurface CWs were created to treat rural domestic wastewater, utilizing *Eclipta alba* as the wetland plant. To date, there are no reports in the literature regarding the application of *E. alba* in CWs. Additionally, research specifically addressing rural wastewater treatment through constructed wetland systems has been notably overlooked. The current study aims to solve the problems caused by home wastewater from rural areas, which deteriorates pond water quality and fuels eutrophication.

The objectives of the current study were: (1) To collect and analyze rural wastewater from the village of Dighal in the Jhajjar district, Haryana, India; (2) To develop biochar-modified subsurface CWs and acclimatize *E. alba;* and (3) To assess the performance of horizontal subsurface flow CWs operated in batch mode using *E. alba*, at varying HRTs of 24, 48, and 72 hours. This strategy seeks to provide a long-term solution for treating wastewater in rural areas, a field that has received little attention from previous studies.

Material and Methods

Experimental set-up

Horizontal flow biochar amended constructed wetlands were set up in the screen house of Maharshi Dayanand University, Rohtak, Haryana, India. A total of 7 set-ups were used to treat the rural domestic wastewater. The seven set-ups include two controls, one unplanted (C1) and one planted (C2). The rest of the five set-ups consist of different concentrations of biochar mixed with soil in different ratios starting from B5 (5% biochar), B10 (10% biochar), B15 (15% biochar), B20 (20% biochar) and B25 (25% biochar). The bottom layer comprised the pebbles while the middle layer consisted of river sand. The top layer was made of soil only in controls and in the biochar mixed with soil in the biochar-amended constructed wetlands. Plants were collected from the local canal area and transferred to CWs. In the present study, an equal number of *E. alba* plants were transferred to the CWs and provided with adequate time to acclimatize. Rural domestic wastewater was collected from the village and transferred to CW set-ups. Wastewater was fed in batch mode from the top and effluent was collected from the bottom of CWs.

The substrate

Pebbles, river sand, soil, and biochar were used as substrates. The total thickness of the substrate was 0.20 m (20 cm). The bottom layer consisted of pebbles having a mean size of 14 mm. The thickness of the lower layer was 12 cm. The middle layer was made up of river sand of size (1-3 mm) with a thickness of 4cm. The top layer was made of a mixture of soil and biochar and had a thickness of 4 cm. Biochar, produced from rice husks at a temperature of 550°C, was acquired from GNG Agritech and Waste Management Pvt. Ltd., a company based in Gurugram, Haryana. Each set-up exhibited varying levels of porosity, with B25 demonstrating the highest porosity and the control set-up showing the lowest. The porosity of biochar-amended constructed wetlands was more than control CWs and porosity increased with increasing concentration of biochar. The porosity of the media was assessed using the saturation method, where the volume of the soil's voids was quantified based on the amount of water required to achieve saturation (Raphael *et al.*, 2020).

Sampling of wastewater

Domestic wastewater flowing into the pond through wastewater channels from the village of Dighal in Jhajjar district, Haryana, India, was collected over an 8-hour period at 30-minute intervals. The samples collected at these periods were combined in equal parts in a sterile container to form a composite sample. The collection took place from 6 a.m. to 2 p.m. The samples were kept in a refrigerator at 4°C to maintain their originality and were examined within a span of 48 hours. Rural domestic wastewater was introduced into the various constructed wetlands (CWs) for treatment, and effluent samples were systematically collected from the outlets at 24, 48, and 72-hour intervals. These samples were gathered in sufficient volumes to allow for a comprehensive assessment of the relevant parameters.

Water quality monitoring

The HLR was maintained at 0.060 m^3/h until the CW was filled. Effluent samples were taken from the outlet at 24-hour intervals, specifically at 24, 48, and 72 hours of hydraulic retention time (HRT), and were subsequently analyzed in the laboratory.

The study assessed key parameters, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrate (NO_3^-), sulfate (SO_4^{2-}), total Kjeldahl nitrogen (TKN), and phosphate (PO_4^{3-}), with influent and effluent concentrations from CWs were estimated following the procedures outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005). BOD was assessed using a 5-day incubation at 25°C, with three different dilutions of wastewater prepared with deionized water prior to incubation. Dissolved oxygen (DO) levels were measured initially and after incubation using Winkler's method. COD was determined through a 2-hour reflux process, utilizing $K_2Cr_2O_7$ and H_2SO_4 as digestion reagents, followed by titration with ferrous ammonium sulfate. TKN was measured using the Kjeldahl apparatus, with boric acid as the medium for ammonia collection. Phosphate, sulfate, and nitrate concentrations were determined spectrophotometrically using the $SnCl_2$, $BaSO_4$, and phenol-sulfonic acid methods, respectively. All measurements were performed in triplicate to ensure precision and to calculate average removal rates.

Pollutant removal efficiency calculation

The removal efficiency (RE%) was determined using the formula presented below (Abdelhakeem *et al.*, 2016):

$$RE = \frac{Cin - Cout}{Cin} * 100$$

Where,

C_{in} = Inlet concentrations

C_{out} = Outlet concentrations of measured parameters respectively (mg/L).

Data Analysis

All descriptive data and removal efficiencies were calculated using MS Excel.

Result and Discussion

Rural raw wastewater was analyzed for its various physico-chemical parameters and results were compiled in Table 1. A total of seven set-ups of CWs comprising two controls (C1 and C2) and 5 different amendments of biochar and soil (B5, B10, B15, B20, B25) were used to treat rural wastewater at HRT of 24, 48, 72 hours. The results of effluents from CWs are presented in Table 2.

BOD Removal

Influent raw wastewater from villages has a BOD of 65mg/L. The biochar-amended CW B25 had the maximum BOD elimination of 75% after 72 hours of HRT. Throughout the experiment, control C1 (without plants) removed 38% BOD, while control C2 (with plants) removed 44% BOD at the same 72-hour HRT, indicating the positive response of plants in the removal of BOD. BOD removal efficiency in CWs improved with increasing biochar concentration. At a HRT of 24 hours, the efficiency rose from 10% in set-up B5 to 32% in set-up B25. Similarly, at 72 hours, BOD removal increased significantly from 47% in B5 to 75% in B25, demonstrating the positive influence of higher biochar concentrations on treatment performance. BOD removal effectiveness in biochar-amended CWs increased with an increase in HRT. This trend of enhanced BOD elimination was constant across all CW set-ups, indicating that increasing the HRT from 24 to 72 hours improved treatment efficiency. Batch-mode feeding has been shown to produce better aeration conditions in artificial wetlands than continuous feeding (Abdelhakeem *et al.*, 2016). Biochar reduces suspended and dissolved organic compounds in water, most likely through electrostatic attraction on its many surfaces. Additionally, it may increase microbial activity, which aids in the breakdown of organic pollutants in water (Zhou *et al.*, 2019; Wu *et al.*, 2019). Plants in horizontal flow-built wetlands (HFCWs) serve

Table 1: Analytical results of rural raw wastewater

S. No.	*Parameter*	*Concentration (mg/L)*
1	BOD	65
2	COD	130
3	Nitrate	16.5
4	Sulphate	53
5	Phosphate	15.7
6	TKN	52

Table 2: Remaining concentration (RC) and removal efficiency (RE) of effluents at various HRT during CW treatments

Wetland Type	*Effluent time (hours)*	*BOD*		*COD*		*Nitrate*		*Suphate*		*TKN*		*Phosphate*	
		RC	RE	RC	RE	RC	RE	RC	RE	RC	RE	RC	RE
C1	24	60	7	118	9.2	15	9.0	46	13	50	3.8	14	10
	48	48	26	98	24	12.8	22	41	22	49	5.7	12	23
	72	40	38	72	44	12	27	33	37	46	11	11	29
C2	24	60	7	116	10	15	9.	46	13	50	3.8	14	10
	48	46	29	97	25	12	27	39	26	47	9.6	11	29
	72	35	46	67	48	10.6	35	33	37	46	11	08	49
B5	24	58	10	102	21	14	15	40	24	49	5.7	10	36
	48	46	29	96	26	12	27	36	32	47	9.6	8	49
	72	34	47	63	51	9.6	41	32	39	45	13.	9	42
B10	24	58	10	99	23	13.4	18	38	28	44	15	8	49
	48	46	29	91	30	12	27	34	35	41	21	9	42
	72	32	50	61	53	9	45	28	47	40	23	9	42
B15	24	52	20	90	30	11	33	34	35	42	19	8	49
	48	41	36	87	33	8.3	49	30	43	40	23	6	61
	72	28	56	51	60	8.4	49	27	49	37	28	10	36
B20	24	46	29	81	37	8.4	49	29	45	39	25	4	74
	48	38	41	83	36	6.8	58	24	54	35	32	7	55
	72	21	67	45	65	5.6	66	22	58	33	36	7	55
B25	24	44	32	76	41	5	69	27	49	34	34	4	74
	48	30	53	67	48	4.4	73	21	60	32	38	2	87
	72	16	75	38	70	3.2	80	15	71	28	46	8	49

RC is the remaining concentration in mg/L and RE is removal efficiency in percentage (%)

several important services, including providing surfaces for bacteria to adhere to, releasing oxygen from roots into the rhizosphere, absorbing nutrients, and insulating the bed surface in colder climates (Langergraber *et al.*, 2009). Assad *et al.* (2022) investigated the use of biochar as a substrate in CWs for BOD removal and reported an efficiency of 82% in T4 with a biochar concentration of 2 kg/m^3. In separate studies, Nema *et al.* (2020) and Haydar *et al.* (2020) examined BOD removal in batch mode within CWs, achieving removal rates of 43 and 84%, respectively. This highlights the varying effectiveness of biochar across different studies and methodologies. The drop in BOD levels could be due to organic matter decomposition by microbial communities associated with macrophyte roots (Maina *et al.*, 2011; Stefanakis *et al.*, 2014). Batch mode feeding has been shown to produce more favorable aeration conditions in artificial wetlands than continuous feeding (Abdelhakeem *et al.*, 2016).

COD removal

The influent wastewater had a COD concentration of 130 mg/L. COD removal efficiency improved with increasing hydraulic retention time (HRT) from 24 to 72 hours, rising from 10 to 48% in control C2 (with vegetation) and from 9 to 44% in control C1 (without plants), while in the biochar-amended CW B25, it increased from 51 to 70%. COD removal efficiency in constructed wetlands (CWs) improved with increasing biochar concentration. At a hydraulic retention time (HRT) of 24 hours, the efficiency rose from 21% in set-up B5 to 41% in set-up B25. Similarly, at 72 hours, COD removal increased significantly from 51% in B5 to 70% in B25, demonstrating the positive influence of higher biochar concentrations on the treatment performance of CWs. The functional groups on the surface of the biochar may have contributed to the enhanced COD removal efficiency in CWs by strengthening the electrostatic interactions between organic matter and microorganisms (Zhou *et al.*, 2020; Zheng *et al.*, 2022). The mechanisms for COD removal are suggested to involve both π-π interaction dynamics between biochar and the molecules, as well as intermolecular hydrogen bonding (Deng *et al.*, 2021). In addition to adsorption, actions like precipitation, oxidation, and anaerobic digestion help to reduce COD (Kadlec, 2008). Batch mode feeding has been shown to produce more favorable aeration conditions in artificial wetlands than continuous feeding, which helps in more degradation of COD (Abdelhakeem *et al.*, 2016).

Nitrate removal

The nitrate concentration in untreated rural domestic wastewater was 16.5 mg/L. Nitrate removal efficiency improved as hydraulic retention time (HRT) increased from 24 to 72 hours, rising from 9 to 27% in the control set-up C1 (without plants), 9 to 35% in control C2 (with plants), and from 69% to 80% in the biochar-amended set-up B25. Nitrate removal efficiency in constructed wetlands (CWs) showed significant improvement with higher biochar concentrations. At a hydraulic retention time (HRT) of 24 hours, nitrate removal increased from 15% in set-up B5 to 69% in set-up B25. Likewise, at HRT 72 hours, the efficiency rose notably from 41% in B5 to 80% in B25, highlighting the beneficial effect of increased biochar concentrations on treatment efficacy. Numerous studies have found that biochar promotes denitrification and increases microbial activity in soil (Cayuela *et al*., 2013). According to studies, nitrogen removal requires a longer HRT than organic matter removal (Lee *et al*., 2009). The results were inclined with the studies conducted by Gupta *et al*. (2016) who used biochar as substrate in CWs and reported RE of 92% in their study. Xu *et al*., 2020 also used iron biochar coupled with microbes and reported a very high RE of 97% at an HRT of 24 hours.

Phosphate removal

Rural residential wastewater contains 15.7 mg/L phosphate. Unlike other measures, $PO4^{2-}$ elimination does not have a steady trend. Phosphate removal was most efficient at 48 hours (87% RE in B25); however, the concentration rose from 2 to 8 mg/L at 72 hours in B25, indicating that all adsorption sites were saturated by 48 hours, resulting in phosphate leaching from the biochar. Phosphate removal was most effective in treatment B25 at 48 hours, but the findings varied when compared to other hydraulic retention times (HRTs). These findings are inclined with those of De Rozari *et al*. (2016), who found that biochar-amended soil is not a very effective substrate for phosphate removal. The removal efficiency of phosphates for CWs, C1 and C2 was 29 and 49%, respectively. Traditional wetlands, on the other hand, showed a more consistent rate of phosphate removal than biochar-amended built wetlands (CWs). Several studies have found significant variations in phosphate removal between planted and unplanted wetlands, emphasizing the importance of plants in removing inorganic phosphorus (Gray *et al*., 2000; Wu *et al*., 2008).

TKN removal

Raw wastewater contains 52 mg/l of TKN and the RE of both controls (C1 and C2) were found to be the same 11%. This could be due to the higher time required for the removal of TKN in CWs. The removal efficiency of TKN increased with the increase in biochar concentration in the constructed wetlands from 13 to 46% in B5 to B25 CWs. In addition, the processes of ammonification, nitrification-denitrification, and sedimentation help to remove total kjeldahl nitrogen. Nitrification requires oxic circumstances, whereas denitrification necessitates anoxic conditions. Because of the difficulties of maintaining these conditions, TKN removal is typically less efficient than BOD, COD, and TSS removal (Abdelhakeem *et al*., 2016). The higher reduction in total nitrogen (TN) in biochar-packed CWs compared to gravel-packed CWs could be ascribed to anoxic conditions and biochar's wide surface area, which promotes the proliferation of denitrifying bacteria in microbial biofilms (Kizito *et al*., 2017). Furthermore, multiple studies have demonstrated that biochar can retain nitrogen (Ding *et al*., 2010; Gupta *et al*., 2016).

Conclusion

The present study gives valuable insights into rural wastewater treatment using biochar-amended constructed wetlands as a sustainable and economical approach. Horizontal subsurface flow biochar amended-constructed wetlands planted with *E. alba* worked efficiently to remove organics, nutrients and TKN from the rural wastewater. The results indicated that the longer the HRT more the removal of pollutants and results were also inclined with the increasing percentage of biochar in the CWs. The difference in the removal efficiency (RE) of the two controls (C1 and C2) indicated that *E. alba* played a positive role in the removal of pollutants. The removal efficiency of BOD and COD were 70 and 75% at HRT 72 hours in B25 amendment of CWs, indicating a positive response of biochar and macrophytes in constructed wetlands. RE of TKN (46%) at HRT 72 hours in the B25 amendment was less than other parameters, indicating the requirement of longer HRTs for denitrification. Phosphate removal was not promising as after achieving higher RE at 48 hours the amount of phosphates in effluents from CWs increased at 72 hours. The results of the present study indicated that biochar proved to be an effective substrate in the removal of pollutants. The results of the study show a promising approach to the sustainable treatment of rural wastewater *via* biochar-amended constructed wetlands. This treated wastewater can be used for irrigation, gardening or non-potable purposes.

Acknowledgment

The authors gratefully acknowledge the university for providing us with the opportunity to conduct experiments.

References

Abdelhakeem, S. G., Aboulroos, S. A. & Kamel, M. M. 2016 Performance of a vertical subsurface flow constructed wetland under different operational conditions. Journal of Advanced Research 7(5), 803–814.

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

Addo-Bankas, O., Zhao, Y., Vymazal, J., Yuan, Y., Fu, J., & Wei, T.

(2021). Green walls: A form of constructed wetland in green buildings. *Ecological Engineering*, *169*, 106321.

APHA 2005 Standard Methods for the Examinations of Water and Wastewater. 21st ed. APHA and AWWA and WEF DC, Washington.

Asaad, A. A., El-Hawary, A. M., Abbas, M. H., Mohamed, I., Abdelhafez, A. A., & Bassouny, M. A. (2022). Reclamation of wastewater in wetlands using reed plants and biochar. *Scientific Reports*, *12*(1), 19516.

Barya, M. P., Gupta, D., Thakur, T. K., Shukla, R., Singh, G., & Mishra, V. K. (2020). Phytoremediation performance of Acorus calamus and Canna indica for the treatment of primary treated domestic sewage through vertical subsurface flow constructed wetlands: a field-scale study. *Water Practice & Technology*, *15*(2), 528-539.

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental pollution*, *159*(12), 3269-3282.

Boopathi, N., & Kadarkarai, R. (2022). A laboratory-scale study of residential greywater treatment with sugarcane in a constructed wetland. *Environmental Science and Pollution Research*, *29*(40), 61178-61186.

Cayuela, M. L., Sánchez-Monedero, M. A., Roig, A., Hanley, K., Enders, A., & Lehmann, J. (2013). Biochar and denitrification in soils: when, how much and why does biochar reduce N2O emissions?. *Scientific reports*, *3*(1), 1732.

De Rozari, P., Greenway, M., & El Hanandeh, A. (2016). Phosphorus removal from secondary sewage and septage using sand media amended with biochar in constructed wetland mesocosms. *Science of the Total Environment*, *569*, 123-133.

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.

Ding, Y., Liu, Y. X., Wu, W. X., Shi, D. Z., Yang, M., & Zhong, Z. K. (2010). Evaluation of biochar effects on nitrogen retention and leaching in multi-layered soil columns. *Water, Air, & Soil Pollution*, *213*, 47-55.

El Barkaoui, S., Mandi, L., Aziz, F., Del Bubba, M., & Ouazzani, N. (2023). A critical review on using biochar as constructed wetland substrate: characteristics, feedstock, design and pollutants removal mechanisms. *Ecological Engineering*, *190*, 106927.

Fahim, R., Cheng, L., & Mishra, S. (2023). Structural and functional perspectives of carbon filter media in constructed wetlands for pollutants abatement from wastewater. *Chemosphere*, *345*, 140514.

Gray, S., Kinross, J., Read, P., & Marland, A. (2000). The nutrient assimilative capacity of maerl as a substrate in constructed wetland systems for waste treatment. *Water Research*, *34*(8), 2183-2190.

Gupta, P., Ann, T. W., & Lee, S. M. (2016). Use of biochar to enhance constructed wetland performance in wastewater reclamation. *Environmental Engineering Research*, *21*(1), 36-44.

Kadlec RH, Wallace S (2008) *Treatment wetlands*. CRC press

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.

Kumar, M., & Singh, R. (2019). Assessment of pollutant removal processes and kinetic modelling in vertical flow constructed wetlands at elevated pollutant loading. *Environmental Science and Pollution Research*, *26*, 18421-18433.

Langergraber, G., Giraldi, D., Mena, J., Meyer, D., Peña, M., Toscano, A., ... & Korkusuz, E. A. (2009). Recent developments in numerical modelling of subsurface flow constructed wetlands. *Science of the total environment*, *407*(13), 3931-3943. Lee, C., Fletcher, T. and Sun, G. 2009. Nitrogen removal in constructed wetland systems. *Engg. Life Sci*. 9: 11-22.

Lee, C. G., Fletcher, T. D., & Sun, G. (2009). Nitrogen removal in constructed wetland systems. *Engineering in life sciences*, *9*(1), 11-22.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B. J. O. J. F. J. J. E. G., ... & Neves, E. G. (2006). Black carbon increases cation exchange capacity in soils. *Soil science society of America journal*, *70*(5), 1719-1730.

Liu, Z., & Zhang, F. S. (2009). Removal of lead from water using biochars prepared from hydrothermal liquefaction of biomass. *Journal of hazardous materials*, *167*(1-3), 933-939.

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.

Maina, C. W., Mutua, B. M. & Oduor, S. O. 2011 Evaluating performance of vertical flow constructed wetland under various hydraulic loading rates in effluent polishing. Journal of Water, Sanitation and Hygiene for Development 1(2), 144–151.

Manyà, J. J. (2012). Pyrolysis for biochar purposes: a review to establish current knowledge gaps and research needs. *Environmental science & technology*, *46*(15), 7939-7954.

Mohan, D., Sarswat, A., Ok, Y. S., & Pittman Jr, C. U. (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.

Nema, A., Yadav, K. D., & Christian, R. A. (2020). Sustainability and performance analysis of constructed wetland for treatment of greywater in batch process. *International Journal of Phytoremediation*, *22*(6), 644-652.

Ohore, O. E., Qin, Z., Sanganyado, E., Wang, Y., Jiao, X., Liu, W., & Wang, Z. (2022). Ecological impact of antibiotics on bioremediation performance of constructed wetlands: microbial and plant dynamics, and potential antibiotic resistance genes hotspots. *Journal of Hazardous Materials*, *424*, 127495.

Raphael, D. O., Okunade, D. A., Ogedengbe, K., & Adekunle, O. A. (2020). Assessment of a batch-flow free water surface constructed wetland planted with Rhynchospora corymbosa (L.) Britton for campus greywater treatment. *Environmental Science and Pollution Research*, *27*, 4275-4283.

Sonu, K., Sogani, M., & Syed, Z. (2021). Integrated Constructed Wetland-Microbial Fuel Cell using Biochar as Wetland Matrix: Influence on Power Generation and Textile Wastewater Treatment. *ChemistrySelect*, *6*(32), 8323-8328.

Stefanakis, A., Akratos, C. S., & Tsihrintzis, V. A. (2014). *Vertical flow constructed wetlands: eco-engineering systems for wastewater and sludge treatment*. Newnes.

Villasenor, J., Capilla, P., Rodrigo, M. A., Cañizares, P., & Fernández, F. J. (2013). Operation of a horizontal subsurface flow constructed wetland–microbial fuel cell treating wastewater under different organic loading rates. *Water research*, *47*(17), 6731-6738.

Wu, Y., Chung, A., Tam, N. F. Y., Pi, N., & Wong, M. H. (2008). Constructed mangrove wetland as secondary treatment system for municipal wastewater. *Ecological Engineering*, *34*(2), 137-146.

Wu, Z., Xu, F., Yang, C., Su, X., Guo, F., Xu, Q., ... & Chen, Y. (2019). Highly efficient nitrate removal in a heterotrophic denitrification system amended with redox-active biochar: a molecular and electrochemical mechanism. *Bioresource Technology*, *275*, 297-306.

Xu, J., Liu, X., Huang, J., Huang, M., Wang, T., Bao, S., ... & 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*(39), 23212-23220.

Younas, F., Niazi, N. K., Bibi, I., Afzal, M., Hussain, K., Shahid, M., ... & Bundschuh, J. (2022). Constructed wetlands as a sustainable technology for wastewater treatment with emphasis on chromium-rich tannery wastewater. *Journal of Hazardous Materials*, *422*, 126926.

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

Zhou Xu, Z. Chen, Z. Li, H. Wu, 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, Chem. Eng. J. 396 (2020) 125349, https://doi.org/10.1016/j.cej.2020.125349.

Zhou, X., Liang, C., Jia, L., Feng, L., Wang, R., & Wu, H. (2018). 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., Wu, S., Wang, R., & Wu, H. (2019). Nitrogen removal in response to the varying C/N ratios in subsurface flow constructed wetland microcosms with biochar addition. *Environmental Science and Pollution Research*, *26*, 3382-3391.