

Biochar-Amended Vertical Flow Constructed Wetlands: A Green Technology for Dairy Wastewater Treatment

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ABSTRACT

Constructed wetlands (CWs) have gained prominence as a sustainable treatment technology due to their low operational costs and environmental compatibility. The incorporation of biochar, a high-surface-area carbon-rich material generated under restricted oxygen conditions, offers new opportunities to improve pollutant removal in CWs. This study evaluated the performance of vertical flow constructed wetlands (VFCWs) planted with *Canna indica* and amended with varying proportions of biochar (10–30%) for the treatment of dairy wastewater under continuous flow. Five experimental setups were established, comprising two controls (C1: unplanted and C2: planted) and three biochar-amended wetlands (B10, B20, B30) containing 10%, 20%, and 30% biochar, respectively. Key physico-chemical parameters—biochemical oxygen demand (BOD), Chemical oxygen demand (COD), nitrate (NO_3^-), phosphate (PO_4^{3-}), sulphate (SO_4^{2-}), and oil & grease (O&G)—were monitored at hydraulic retention times (HRTs) ranging from 12 to 120 hours at a 12-hour interval. Results showed that pollutant removal efficiency improved with both increased HRT and higher biochar concentration. Maximum removal efficiencies at 120 hr. were recorded in B30, reaching 81% for BOD, 77.4% for COD, 58.9% for NO_3^- , 57.7% for PO_4^{3-} , 64.4% for SO_4^{2-} , and 80.8% for O&G. While organic contaminants and O&G were removed rapidly between 48–72 hr., nutrient removal was slower, becoming significant after 84 hr., reflecting the time needed for microbial community establishment. The findings highlight the synergistic role of biochar and vegetation in enhancing CW performance and confirm that biochar-amended VFCWs provide an efficient, economical, and scalable solution for dairy wastewater treatment.

Key words: Vertical flow CWs, Dairy wastewater treatment, Biochar amendment, Wetland vegetation, Sustainable approach

Introduction

The escalating global water crisis, exacerbated by population growth, industrial expansion, and climate change, necessitates the development of innovative and sustainable wastewater treatment solu-

tions. Conventional wastewater treatment plants, while effective, often entail high capital investments, significant energy consumption, and the generation of chemical by products (Rahmadyanti *et al.*, 2021 and Vymazal, 1998). Constructed wetlands have emerged as an appealing substitute for traditional

wastewater treatment technologies in specific environmental contexts, offering a synergistic integration of natural processes and engineered systems for the removal of pollutants (Wei *et al.*, 2025).

Constructed wetlands (CWs) have emerged as a promising alternative, offering a nature-based approach to wastewater treatment with lower costs, reduced energy demands, and enhanced environmental compatibility (Swarnakar *et al.*, 2022 and Supreeth *et al.*, 2022). CWs are engineered ecosystems meticulously designed to harness natural processes involving vegetation, soil, and microorganisms to remediate pollutants from wastewater (Lavrniæ *et al.*, 2020 and Barya, 2020 and Younas, 2022). Despite their widespread adoption, the performance of constructed wetlands is highly variable. In many instances, these systems fail to achieve the desired levels of pollutant removal, particularly when relying on conventional substrates, such as sand and gravel (Swarnakar *et al.*, 2022 and Boopathi and Kadarkarai, 2022). The effectiveness of conventional wetlands in removing phosphorus is often restricted by the use of substrates such as gravel, sand, rocks, and pebbles, which have a limited capacity for phosphorus retention (Jia *et al.*, 2010 and Mohan *et al.*, 2014 and Yang *et al.*, 2018).

The performance of constructed wetlands is intricately linked to the plant species, water flow mode (vertical, horizontal, and hybrid setups), substrate media (conventional type sand, gravels, and advanced types including biochar and zeolites), and structural design used. The study conducted by Panghal *et al.* (2024) concluded that the setup without vegetation showed low removal efficiency of BOD, COD, nitrate, and phosphates as 38, 44, 27, and 29% respectively, whereas 44, 48, 35, and 49% by using *Eclipta alba* as a hyper accumulating plant species. Selecting appropriate substrate materials is crucial for optimizing the efficiency and longevity of constructed wetlands. Substrates have various purposes in constructed wetlands (CWs), such as storing pollutants, supporting plant growth, offering reactive materials to process pollutants, and serving as a substrate that facilitates biofilm adhesion (Asaad *et al.*, 2022).

Biochar is a versatile carbon-rich material created through the pyrolysis of agricultural biomass waste in oxygen-limited environments. Its high surface area, porosity, and abundance of functional groups make it an increasingly popular substrate for environmental applications. Biochar supports biofilm

formation, enhances pollutant removal, and reduces greenhouse gas emissions (Panghal *et al.*, 2025 and Ji *et al.*, 2022). Compared to biochar-modified CWs, conventional sand-based CWs often exhibit limited nitrogen removal efficiency. Deng *et al.* (2019) indicated that adding biochar to CWs improved the removal efficiencies of both ammonium and total nitrogen compared to gravel-packed CWs. Biochar-amended systems removed 49.69–63.51% of ammonium and 81.83–86.36% of total nitrogen, while gravel-only systems removed 47.40% and 80.75%, respectively. For textile wastewater treatment, the CW system amended with corn cob biochar outperformed the CW system in comparison to without biochar. In terms of COD removal, decolorization efficiency, and TDS reduction, the removal efficiencies in the biochar-amended system were 83%, 90%, and 84%, respectively, compared to 66%, 65%, and 67% in the system without biochar (Sonu *et al.*, 2021).

Extensive research has been carried out on the treatment of various types of wastewater, including effluents from textile, pharmaceutical, dye, paper, and pulp industries, as well as rural and municipal sources (Haydar, 2020 and Nema *et al.*, 2020). However, dairy industry wastewater, characterized by its high organic load and fat content, has received comparatively less attention due to its tendency to cause clogging and the limited efficiency of conventional treatment methods. The present study aims to bridge this gap by focusing specifically on dairy wastewater treatment. To closely simulate practical field conditions, raw untreated dairy effluent was utilized in a continuous flow mode, thereby enabling the assessment of system performance under conditions that could be directly scaled and implemented beyond the laboratory environment. Therefore, the present study seeks to address the limitations of costly and energy-intensive wastewater treatment technologies by demonstrating the potential of a low-cost, nature-based, and sustainable approach tailored for the dairy industry, which represents one of the largest and most resource-demanding sectors worldwide.

The specific objectives of the present study were: 1) To collect and analyse the raw dairy wastewater procured from the local Dairy industry, Rohtak, Haryana, India. 2) To design and develop biochar-amended subsurface constructed wetlands (CWs) and establish *Canna indica* as the selected wetland vegetation. 3) To evaluate the treatment performance of vertical flow constructed wetlands

(VFCWs) operated in continuous mode under varying hydraulic retention times (12–120 hr.), analysing the effluent at 12-hour intervals. This approach aims to establish a sustainable and cost-effective strategy for dairy wastewater management, addressing a critical area that has been relatively underexplored in literature.

Materials and Methods

Experimental set-up

Vertical upflow biochar-based CWs were set up in a screen house at Maharshi Dayanand University, Rohtak, Haryana, India. Five setups were made in a cylindrical container of length 50 cm and diameter 30 cm, consisting of two controls, one unplanted (C1) and the other planted (C2). The remaining three set-ups included biochar in different ratios: B10 (10%biochar), B20 (20%biochar), and B30 (30%biochar). The bottom layer was composed of pebbles, and the middle layer was prepared using river sand. Again, a thin layer of pebbles was laid down. The top layer was made of soil only in the control and soil with biochar in the biochar-amended CWs. Plants were procured from a local nursery and transferred to the system. In the present study, an equal number of *Canna indica* were transferred to each CW and left undisturbed for an acclimatization period of 10 days. Untreated wastewater was procured from the local dairy industry and transferred to the CW setups. Wastewater was fed in continuous mode with an HRT set from 12 h to 120 hr. The effluent container was positioned at a slightly elevated level in comparison to the wetland system to ensure continuous operation through gravitational flow. A pipe was initially inserted during the setup, through which wastewater was fed in a continuous mode, and the wastewater level continued to rise inside the system in a vertical up-flow manner. The system was designed to replicate real-time conditions and sustain the entire system sustainably, requiring zero energy demand from outside.

The substrate

River sand, soil, pebbles, and agriculture-based biochar were used in this study. Starting from the bottom to the top layers, the bottom-most layer was 10 cm in length, consisting of gravels–5 mm in size, while the middle layer was made from river sand

(15 cm). Again, a 5 cm-thick layer of gravel was laid to avoid any clogging conditions. The top layer was composed of a mixture of soil and biochar and had a thickness of 15 cm. This mixture was prepared in fixed ratios of 10%, 20%, and 30% in biochar-amended CWs to study the efficiency of the amended systems over the standalone CWs made only from conventional substrates. The outlet pipe of the system was positioned 3 cm above the uppermost substrate layer to enable the collection of the treated effluent. Biochar, made from mustard husks at 650 °C, was acquired from GNG Agritech and Waste Management Private Limited, a company based in Gurugram, Haryana. Biochar is a porous carbon-rich multipurpose material used for environmental purposes, formed by the pyrolysis of agricultural biomass waste under oxygen-limited conditions (Lehmann, 2007 and Ansari and Golabi, 2019). All CWs had different porosities. The controls had the least porosity and could handle up to 13 l of water, whereas the biochar-amended wetlands could hold up to 17 l of water. The controls had the least porosity, while porosity increased with biochar application, being highest in the CW with 30% biochar concentration.

Wastewater Sampling

Untreated dairy wastewater was collected from the local dairy industry, Rohtak, Haryana, India. A total volume of 150 l was sampled and distributed into three sterile containers of 50 l capacity each. To preserve the physicochemical characteristics and minimize microbial alterations, the collected wastewater was immediately transported to the laboratory under cooled conditions and stored at 4 °C until further use. Prior to experimental applications, the wastewater was subjected to a simple pre treatment step involving decantation for a 2-hour period, which effectively removed greasy clots and coarse suspended solids, thereby minimizing the risk of clogging in the constructed wetland system, along with preserving the inherent characteristics of the wastewater.

Analysis of wastewater

The hydraulic loading rate (HLR) was optimized at 0.0012 m³ h⁻¹ under continuous flow conditions to maintain a stable and uniform influent supply throughout the system. A continuous mode of operation was preferred over the batch mode because

it more accurately simulates real-world wastewater treatment scenarios. Effluent samples were collected at 12-hour intervals up to 120 hr. and subsequently analyzed for various physicochemical parameters under controlled laboratory conditions.

Wastewater parameters were analyzed in both influent and effluent samples of the CWs as prescribed in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005). The study assessed the following key parameters, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}), nitrate (NO_3^-), and oil and grease content. For BOD analysis, the dissolved oxygen (DO) levels of the samples were determined at the beginning and end of incubation using Winkler's method. COD was estimated through a 2-hour reflux procedure, employing $K_2Cr_2O_7$ and H_2SO_4 as digestion reagents, followed by titration with ferrous ammonium sulfate. Phosphate, sulfate, and nitrate concentrations were analyzed spectrophotometrically using the $SnCl_2$, $BaSO_4$, and phenol-disulphonic acid methods, respectively. The oil and grease (O&G) content was determined using petroleum ether through the Solvent Extraction Method, also known as Liquid-Liquid Extraction (LLE). To ensure accuracy and determine the mean elimination rates, all measurements were performed in triplicate.

Pollutant removal efficiency

The removal efficiency (%) of pollutants in wastewater treatment was calculated using the concentrations of the pollutant before treatment (influent) and after treatment (effluent).

The general formula is:

$$\text{Removal efficiency (\%)} = \frac{C_{in} - C_{out}}{C_{in}} \times 100$$

Where:

- C_{in} = Influent concentration of the pollutant (mg/L)
- C_{out} = Effluent concentration of the pollutant (mg/L)

Results and Discussion

Various CWs without vegetation (C1), with vegetation (C2), and with biochar amendment (B10, B20, B30) were constructed for the treatment of dairy wastewater. Various effluent parameters such as BOD, COD, nitrate, phosphate, sulphate, and oil and

grease were analysed to determine removal efficiency at various HRTs. The dairy raw water analysis results are summarised in Table 1.

Table 1. Pre-analysis results of raw dairy industry wastewater

S. No.	Parameter	Concentration (mg/l)
1	BOD	210
2	COD	486
3	Nitrate	73
4	Phosphate	18.26
5	Sulphate	298
6	Oil & Grease	240

Removal of BOD

The initial BOD of raw dairy wastewater was 210 mg/l. Between the two controls, the planted system (C2) exhibited higher BOD removal efficiency (44.3%) compared to the unplanted control (C1), which achieved 36.2% efficiency. The presence of plants likely promoted rhizospheric microbial growth and oxygen release through root exudation, thereby enhancing the biodegradation process. Furthermore, the addition of biochar as a substrate improved the pollutant removal efficiency of the system. The CW with 10% (B10) biochar amendment showed an increase in pollutant removal of up to 57.6% at 120 HRT. B10 showed moderate improvement compared to the controls, demonstrating the positive influence of biochar, even at lower dosages. With an increase in biochar concentration up to 20%, a removal of 75.2% was recorded at 120 HRT. B20 exhibited enhanced removal owing to the increased microbial activity supported by the greater biochar content. The highest BOD removal efficiency, reaching up to 81%, was achieved in the B30 at 120 HRT as shown in (Fig.1). B30 achieved the most efficient degradation, indicating that higher biochar ratios substantially accelerate organic matter stabilization by combining adsorption and biodegradation mechanisms. A rapid removal of pollutants can be seen during HRT (48-72 hr.), which can be attributed to the efficient working of the system. Minor fluctuations or slower declines at later HRT (84-120 hr.) can be explained by the diminishing availability of readily biodegradable organics, leading to the stabilization of BOD values. Biochar amendment significantly improved pollutant removal, as reflected by the sharper decline in BOD. This can be attributed to the porous structure, high surface area, and adsorp-

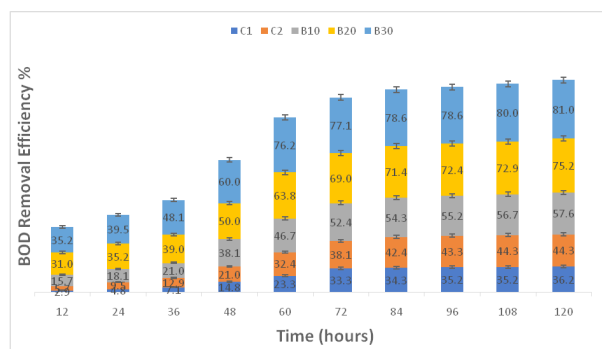


Fig. 1. BOD removal efficiency (%) in five different CW configurations (C1, C2, B10, B20, B30) operated under continuous flow.

tion capacity of biochar, which provide favorable niches for microbial colonization, rich surface functional groups, and facilitate organic matter entrapment (Barquilha and Braga, 2021 and Kadlec and Wallace, 2008).

Removal of COD

The influent raw wastewater had a COD concentration of 486 mg/l. In the planted control (C2), the COD removal efficiency after 120 hr. was 38.7% as compared to only 25.9% in the unplanted control (C1) at HRT 120. Vegetation plays a crucial role in the pollutant removal tendency of CWs. Plants contribute to CW treatment through physical effects of root structure, combined with aeration, which affect soil hydraulic qualities, filtering, flow velocity reduction, improved sedimentation, decreased resuspension, water distribution, and clogging prevention (Vymazal, 2011). In contrast, the biochar-amended systems demonstrated markedly higher efficiencies: B10 achieved 69.3%, B20 reached 74.1%, and B30 attained the maximum of 77.4% at the end of 120 hours, as shown in Fig. 2. The results clearly highlight the superior performance of biochar-based systems, with efficiency improving proportionally to the proportion of biochar in the substrate. Nonetheless, according to previous research studies, the use of biochar greatly accelerated COD elimination in CWs. Biochar's high adsorption capacity for organic molecules and its heterogeneous surface with numerous pores for oxygen filling and habitation by a variety of organic-degrading bacteria can be used to explain this outcome (Deng *et al.*, 2019 and Guo *et al.*, 2020). During the early 12-24-hour period, a sharp rise in removal efficiency reflects the rapid degradation and adsorption of readily biodegrad-

able organic matter. From 60-84 hr., the efficiency continues to increase but at a slower rate, as easily degradable fractions become depleted, leaving more resistant organics. The curve approaches a plateau during 96-120 hr., especially in controls, indicating that most biodegradable material has been removed and further reduction is limited by the presence of refractory compounds. Biochar systems, however, sustain efficiency gains longer due to their adsorption capacity and ability to support microbial communities even under nutrient-limited conditions.

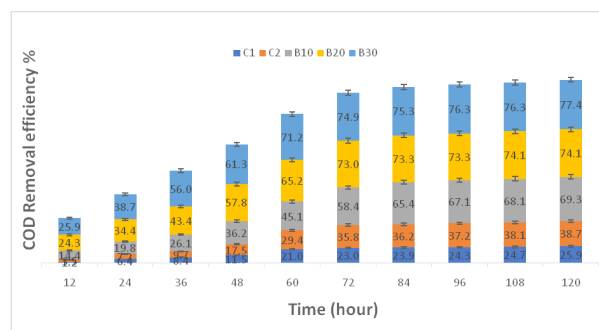


Fig. 2. COD removal efficiency (%) in five different CW configurations (C1, C2, B10, B20, B30) operated under continuous flow.

Removal of Nitrate (NO₃⁻)

The nitrate concentration in untreated dairy wastewater was 73 mg/l. The removal of NO₃⁻ in control C1 (Unplanted) was slow in initial HRT₃ from 12-72, varying from 1.4% to just 5.5% and exponentially increased from 84 HRT onwards from 12.3% to 15.1%. Nitrate removal in the planted control C2 was 11% till 72 HRT, and increased sharply from 21.9% to 28.8% from 84 HRT onwards, as shown in (Fig.3). Plants are a crucial component of CWs since they can absorb nitrogen as a nutrient and eliminate it (Vymazal, 2011 and Vymazal, 2010). According to a few studies, oxygen leaking from plant roots raises the redox potential of the soil and creates aerobic niches, which enhances nitrification, promotes heavy-metal sedimentation, and improves degradation. It has been shown that denitrification is accelerated by the carbon expelled by the roots (Shelef *et al.*, 2013). Aside from the benefits of vegetation, there are many studies that alter the substrate's composition to improve N removal in CWs. However, in traditional CW systems filled with gravel or sand, inadequate N removal efficiency is still a significant problem, in part because of the low adsorption ca-

capacities of gravel and sand (Kizito *et al.*, 2017 and Yang *et al.*, 2018).

According to the current study, the elimination efficiency in all B10, B20, and B30 was 24.7%, 26%, and 31.5%, respectively, until HRT 72. However, the efficiency of the system for NO₃⁻ removal increased 84 HRT onwards, giving the final removal rates as 41.1%, 50.7%, and 58.9% in systems B10, B20, and B30, respectively at HRT 120. The addition of biochar media can speed up nitrification and effectively improve NH₄⁺ and total nitrogen (TN) removal in CWs because biochar has a high cation exchange capacity, a large number of negatively charged functional groups for NH₄⁺ adsorption, and favorable porous structures for the growth of nitrifiers. Additionally, the high porosity of biochar substrates can facilitate atmospheric reaeration and oxygen filling within the CW matrix (Kizito *et al.*, 2017 and Wu *et al.*, 2019 and De Rozari *et al.*, 2018). Although the total removal efficiency is low, the current study shows that the NO₃⁻ removal capability increases as the concentration of biochar increases.

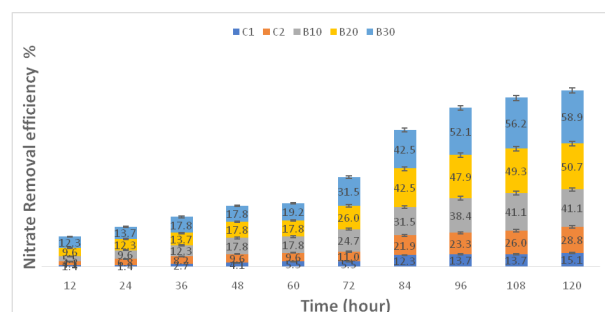


Fig. 3. Nitrate removal efficiency (%) in five different CW configurations (C1, C2, B10, B20, B30) operated under continuous flow.

Removal of Phosphates (PO₄³⁻)

Dairy wastewater contains 18.26 mg/l phosphate. The removal of PO₄³⁻ was at a very slow pace from HRT 12 to 72 hours. Thereafter, from HRT 84 to 120 hr., a relatively higher removal efficiency for PO₄³⁻ was noticed. The removal efficiency for unplanted control (C1) from 12 to 72 hr. rose from 0.9% to 8% and there onwards, from 84 to 120 hr., rose from 13% to 15.6%. In the case of planted control (C2), the removal rate was from 1.4% to 12.9% till 72 hours, and from 17.9% to 23.1% was observed from HRT 84 to 120 hours. This unique trend was confirmed when almost the same trend was noticed in the case

of biochar-amended CWs. In the case of B10, the removal efficiency from HRT 12-72 rose from 6.9% to 15.1%, and thereafter, from 24% to 31.9%, from 84 hr. onwards. With an increase in biochar concentration, the increased removal of PO₄³⁻ was observed in all the scenarios. Similarly, for B20 removal rate increased from 12.4% to 23.3% till HRT 72, and the rate increased from 31.2% to 42.7% from 84 HRT onwards as depicted in (Fig. 4.) The trend repeats in B30 as well, with the peak observed at 84 hr. with 43.6% and continued till 120 hr. with maximum removal of 57.7%, as opposed to 12-72 HRT, rising steadily from 12.4% to 36.5%. Therefore, a similar trend was observed in the case of PO₄³⁻ removal by using biochar-amended CWs as observed on NO₃⁻. The removal of TP was aided by the addition of biochar to CWs, which is explained by its high adsorption ability, high cation exchange capacity, and high concentration of metal ions (such as Al, Ca, and Mg) on the biochar's surface (Shakoor *et al.*, 2021 and De Rozari, 2016).

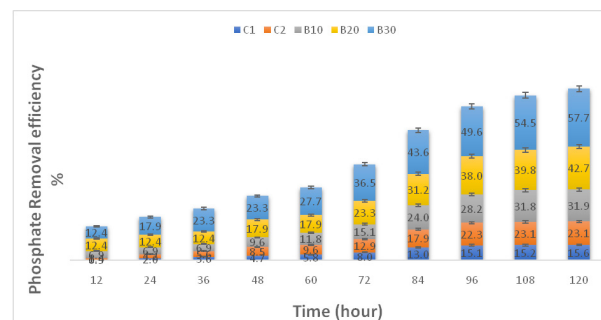


Fig. 4. Phosphate removal efficiency (%) in five different CW configurations (C1, C2, B10, B20, B30) operated under continuous flow.

Removal of Sulphates (SO₄²⁻)

The SO₄²⁻ in raw dairy wastewater was 298 mg/l. From HRT 12-120, the removal of SO₄²⁻ in unplanted control (C1) varies from 1% to 17.4%, and therein control C2 (Planted) varies from 2.7% to 25.5% as shown in (Fig. 5). Plants play a significant role in removing SO₄²⁻ from the wastewater. However, the conventional substrates still face an overall low removal efficiency of nutrients such as sulphur. With the addition of biochar as substrate, the removal efficiency rose by significant levels, as 40.6%, 59.1%, and 64.4% in B10, B20, and B30, respectively, from 12 to 120 hours. Therefore, the removal of SO₄²⁻ shows a positive correlation with the increasing concentration of biochar additions. Panghal *et al.*(2024)

observed 77% removal in the B25 (25%biochar) amendment, which is 38% higher than the control planted (C2), which somewhat aligns with the current study. Higher sulfate reduction might be linked to biochar-mediated adsorption (Panghal *et al.*, 2024). Biochar also serves as a reservoir for plant nutrients by adsorbing SO_4^{2-} , which can then be gradually taken up by plants during the subsequent treatment phases of the CW system (Chand *et al.*, 2021 and Drayer, 2016 and Vymazal, 2007).

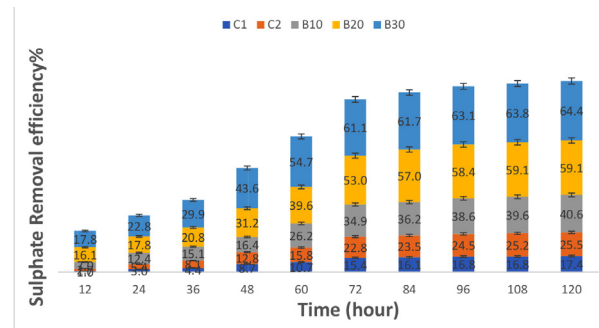


Fig. 5. Sulphate removal efficiency (%) in five different CW configurations (C1, C2, B10, B20, B30) operated under continuous flow.

Removal of Oil & Grease

The concentration of O&G in raw dairy wastewater was 240 mg/l. At the initial stage (12 hr. HRT), all systems exhibited relatively low O&G removal, ranging from 4.2% in C1 to 33.3% in B30. This gradual removal can be attributed to the limited contact time between wastewater and the treatment media, allowing only partial adsorption and sedimentation of greasy particles. A significant increase in removal efficiency was noted in all systems as the retention duration was extended to 24-48 hours, especially in setups that had been altered with biochar (B20: 48.8%, B30: 66.7% at 48 hours). The increased adsorption capacity of biochar, which offers a porous structure for capturing hydrophobic O&G chemicals, and the early microbial adaptation in both the planted and unplanted beds are linked to this increase. Beyond 48 hr., the O&G removal efficiency continued to increase, reaching 75.4% in B30 and 63.3% in B20 at 60 hr. HRT, while planted controls (C2) achieved only 25.8%, and unplanted controls (C1) remained comparatively low (17.1%) as shown in (Fig. 6).

The superior performance of biochar-amended wetlands during this period indicates the combined role of biochar's high surface area and microbial

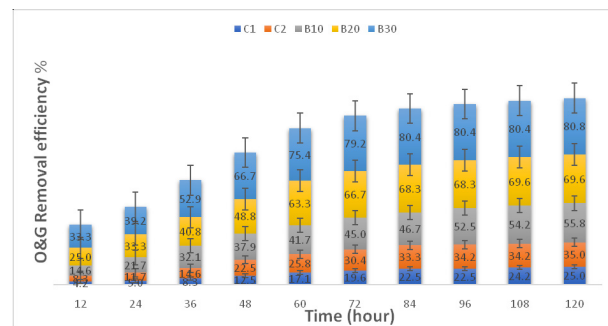


Fig. 6. Oil & Grease removal efficiency (%) in five different CW configurations (C1, C2, B10, B20, B30) operated under continuous flow.

colonization, which enhanced biodegradation of emulsified fats. From 72 hr. onwards, the removal efficiency approached stabilization in most systems. B30 consistently outperformed others, achieving 80.8% O&G removal between 72–120 hr., followed by B20 (69.6%) and B10 (55.8%). This plateau phase suggests that the most easily adsorbable and degradable O&G fractions were already removed, and the system approached a saturation state. The controls, particularly C1, showed only marginal improvement, reaching 25% removal at 120 hr., highlighting the limited capacity of conventional sand-gravel media without amendments. Very slight fluctuations observed in C2 and B10 between 84-120 hr. (e.g., 52.5% at 96 hr. & 55.8% at 120 hr. in B10) may be attributed to microbial dynamics and possible re-release of some trapped grease particles due to biomass sloughing or pore clogging. However, the overall trend confirmed that higher biochar dosage resulted in greater O&G removal efficiency, with B30 maintaining the highest and most stable performance throughout the experimental period (Kizito *et al.*, 2017; Wu *et al.*, 2019 and De Rozari *et al.*, 2018).

Conclusion

The present study provides significant insights into the treatment of dairy industry wastewater using biochar-amended constructed wetlands. Results clearly demonstrated that pollutant removal efficiency improved with increasing biochar dosage, highlighting the synergistic role of biochar and vegetation in enhancing system performance. Among the controls, the unplanted bed (C1) showed the lowest removal, whereas the planted control (C2) achieved comparatively higher efficiencies due to the presence of vegetation. Biochar-amended sys-

tems (B10, B20, B30) exhibited markedly better performance across all monitored parameters, with higher concentrations of biochar yielding superior results. Removal of organic pollutants such as BOD, COD, and oil & grease was more rapid, showing significant reduction between 48–72 hr., followed by stabilization at later retention times. Whereas, the nutrient removal was more evident only after 84 hr. and continued to improve up to 120 hr. This delayed response is consistent with previous studies and reflects the time required for microbial communities to establish and carry out nutrient transformations. The vertical, continuous-flow CW configuration used in this study successfully simulated realistic operating conditions and demonstrated reliable pollutant removal capacity. Overall, the findings establish biochar-amended constructed wetlands as a sustainable, cost-effective, and field-replicable solution for the treatment of dairy wastewater.

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Author contribution statement

Nidhi Ahlawat: Writing- original draft, conceptualization. Vishal Panghal: Review and editing. Pooja Choudhary: Review and editing. Vishwajit Hooda: Review and editing. Sunder Singh Arya – Review and editing. Sunil Kumar: Writing-review and editing, Validation, Supervision.

Conflict of interest

The authors have no relevant financial or non-financial interests to disclose.

Data availability

All data supporting the findings of this study are available within the paper.

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