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Testing the Effectiveness of Different Soil Media in Batch-Operated Lab-Scale Horizontal Subsurface Flow Constructed Wetlands for Wastewater treatment Using Twin-Hearth Furnace Slag

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ABSTRACT

This study evaluates the effectiveness of Twin-Hearth Furnace Slag (THFS) combined with local soils (Entisols, Inceptisols, Alfisols, and Vertisols) as substrates in horizontal subsurface flow constructed wetlands (HSFCWs) for domestic wastewater treatment. Both planted and unplanted CWs were tested, with *Canna indica* and *Typha latifolia* used as macrophytes. The experimental setup involved a hydraulic retention time (HRT) of 48 hours, with a 50:50 mixture of soil and THFS used in each CW. The results indicated significant removal efficiencies (RE) for various wastewater parameters, including BOD5 (78.7%), COD (85.3%), nitrate nitrogen (90.2%), and soluble reactive phosphorus (95.5%) in planted CWs. Unplanted CWs also showed notable treatment performance. The study concluded that the combination of THFS and soil in CWs effectively meets the effluent standards set by the central pollution control board (CPCB) and the world health organization (WHO). The findings suggest that slag-based CWs, with or without plants, offer a promising, low-cost solution for wastewater treatment, particularly in tropical regions.

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INTRODUCTION

Constructed wetlands (CWs) are a low-cost and low-manpower treatment system. CWs incorporate plants and substrates to aid in the treatment of various types of wastewater (WW). CWs are natural treatment technology that has been shown to be a superior alternative that can be incorporated with currently operational STPs to meet effluent discharge standards. The CW is a constructed structure that uses incredibly little energy, is simple to operate, and costs less money. As a result of the availability of land space, prolonged sunshine, and high temperatures in the Indian context, the usage of CWs makes this technique a workable option for treatment of sewage in India (Shukla et al., 2023). Various types of materials have been used as substrates, like gravel, aggregate, soil, charcoal, slag, crushed building materials, sugar bagasse, hair, compost, and mining waste (Swarnakar et al., 2021). Slag in steel industries is a byproduct formed during the production of steel, consisting mainly of impurities like silica, alumina, and lime. It is produced by separating these impurities from molten metal in the furnace. Global production of iron slag was projected to reach 340 million to 410 million tonnes in 2021

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(Tuck, 2022). Most people are aware that recycling and using industrial waste may conserve essential raw materials and energy sources and also help safeguard the environment. THFS is a byproduct of steelmaking processes. Some researchers have used the THFS for road pavement bases (Mishra and Guzzarlapudi, 2022). BFSS has been used in the cement industry, concrete, and road construction (Murmu et al., 2022). Very limited studies are available on the use of slag in CWs as a substrate. In a number of previous studies, the treatment performance of THFS demonstrated significant performance in terms of phosphorus and nitrogen removal due to CaO (Guo et al., 2017; Xu et al., 2010). The use of slags and gravels as substrates in large-scale CW systems has improved results in effluent. (Ge et al., 2015). A detailed review listed by researchers has found COD: 71.8%–80%, TN: 52%–82%, and TP: 77%–80% RE in the treatment of WW through slag substrates (Patyal at el., 2021). Slag based HSSF-CWs has also removed the landfill leachate with RE of COD;18.6%-61.25%, NH_3-N; 84%-99% and heavy metal by 90% (He et al., 2021). Soils are easy available natural economic substrates material for wetland. Although very little literature is available on soil-base CWs. Although relatively easy to build and inexpensive, systems using undisturbed soil for WW treatment entail a wide range of interrelated activities, which presents a challenge to researchers (Petitjean et al., 2015). Lateritic soil substrates in HSSF-CWs E have been observed in BOD_5; 36.0–80.6%, COD; 32.2–72.6%, TN; 89.0% and SRP; 69% (Jethwa et al., 2020). Substrates of garden soil have been used in HSSF-CWs and found RE in BOD_5; 86%, COD;77%, TSS;80%, NH_4^+-N;59%, TN;66%, and TP;64% (Aalam and Khalil, 2016). Some researchers have studied in lab-scale CWs the clogging in wetland by using very fine substrates. Few researches have used top layer of soil along with gravel media (Singh et al., 2019). Soil-based CWs have also reduced the fate of phosphorus from treated WW (Kumar et al., 2023 a, 2023b., Morvannou et al., 2022). Furthermore, soils have been used in to remediate the herbicide terbuthylazine (TER) by surface flow CWs (Papadopoulos and Zalidis et al., 2019). The cumulative problems related to void space clogging have drawn more attention globally during the past ten years (Wang et al., 2021). However, monitoring water quality and pollution removal effectiveness is frequently the extent of wetland performance evaluation. In addition, clogging difficulties or potential operating issues involving crucial design characteristics even in situations where indicators of congestion are apparent, they have not yet been appropriately identified or investigated (Ergaieg et al., 2021). Proper porous substrates base can remove the clogging problem in soil-base CWs.

In this paper, the pollutants were measured between November 2022 and February 2023, as well as the calculated RE of the above batch-operated lab-scale HSFCWs, and correlated to each other with relevant literature. *Canna Indica* and *Typha latifolia* are the most popular macrophytes for the HSFCWs used in this study. The WW was collected from staff quarters at the Institute campus. This research looks into the fact that, for the first time, both substrate materials (soil and steel slag) were used in the same amount (50:50) for CWs (pilot units). The main focus of the work is to evaluate the performance of planned and unplanned HSFCWs.

Table 1. Abbreviations for planted or unplanted CWs with varying soils and slag combinations

Abbreviation	CWeu	CWec	CWet	CWiu	CWic	CWit	CWsc
Name of Plant	Unplanted	*Canna Indica*	*Typha Latifolia*	Unplanted	*Canna Indica*	*Typha Latifolia*	*Canna Indica*
Substrates	Entisols	Entisols	Entisols	Inceptisols	Inceptisols	Inceptisols	Slag
Abbreviation	**CWau**	**CWac**	**CWat**	**CWvu**	**CWvc**	**CWvt**	**CWst**
Name of Plant	Unplanted	*Canna Indica*	*Typha Latifolia*	Unplanted	*Canna Indica*	*Typha Latifolia*	*Typha Latifolia*
Substrates	Alfisols	Alfisols	Alfisols	Vertisols	Vertisols	Vertisols	Slag

MATERIALS AND METHODS

Operational conditions, optimization and vegetation in wetland

The construction and operation of the CW followed the US Environmental Protection Act, with various operational conditions, such as flow rate and hydraulic retention time, applied to operate the CWs. Each lab-scale CW configuration was run and observed for three weeks before being flushed and adjusted once more to serve as the subsequent CW setup. Five sampling ports, two at the inlet and two at the outlet of the wetland (inside the CW), were supplied for the CWs. Samples were collected weekly at an HRT of 48 hours and analyzed for pH, alkalinity, TDS, EC, turbidity, DO, NN, COD, BOD_5, SRP, and TP following the APHA (2017) procedure in the Environment Engineering lab of the Department of Environmental Engineering, National Institute of Technology, Raipur, India, C.G.

The following parameters were measured on-site with a calibrated digital portable water meter (EUTECH Multi-parameter): temperature, pH, electrical conductivity (EC), and total soluble solids (TDS). For the five-day BOD_5, the BOD_5 was assessed using Winkler's azide modification method, and the amounts of SRP was calculated using UV spectrophotometric analysis (UV/ VIS, LABINDIA model UV 3000).

Collection and characterization of samples

On the campus of NIT Raipur, domestic WW was gathered from the employee housing. Table 2 lists the variables that were assessed, including pH, total alkalinity, TDS, turbidity, electrical conductivity (EC), dissolved oxygen (DO), biochemical oxygen demand (BOD_5), nitrate nitrogen (NN), chemical oxygen demand (COD), and soluble reactive phosphorus (SRP). THFS were collected from Bhilai steel plant, Durg, Chhattisgarh, India.

Meteorological conditions for study area

The study site was in Raipur, the Indian state of Chhattisgarh, at 21°15'00'N and 81°36'15'E. According to weather-and-climate.com, the site location has a tropical wet and dry climate with average daily temperatures of 35°C and total annual precipitation of 1260 mm. The rainiest months are June through October. The highest temperature recorded is 48°C (118°F) between April and May. The moderate winters, which stretch from November to January, can see lows as low as $14^{O}C$ to $17^{O}C$, which is relatively cool for a tropical climate.

Experimental set up

The experimental setup is shown in Figure 1, which is broken up into four sections: the distribution tank, the HSFCW with outflow, and the sedimentation tank. With mild steel sheets measuring 2 mm thick, fourteen laboratory-scale CWs with dimensions (LxWxH) of 1.0x0.35x0.30m and an outward slope of 0.01 (1.0%) were created. Each unit was created using the guidelines from the CPCB. Four of the 14 CWs were utilized as a blank, with the four distinct types of soil substrate but no plant species (table 1). Two sets of CWs (20 mm and 10 mm) using simply THFS as the substrate were also used for comparison. Four different types of locally accessible soils were gathered around the study area. After being air dried in the shade, the soil and THFS were filled in CW. An aggregate layer was placed at the inlet and outlet to prevent frequent clogging of the soil substrate in the constructed wetland (CW). In a lab-scale experimental examination, the HSFCW was employed to treat domestic WW, as shown in figure 2. After one hour of settling the raw WW in a 250L PVC tank, the supernatant was transported to two elevated PVC tanks for feeding the CWs. To maintain the head and give WW to the CWs, another tank was used. WW distribution in CW was done using gravity and a PVC pipe with a control valve. The Imhoff cone analysis was used to determine the hourly settling time. Two plants each of *Typha latifolia* and *Canna indica* (height 300 mm) were planted in the

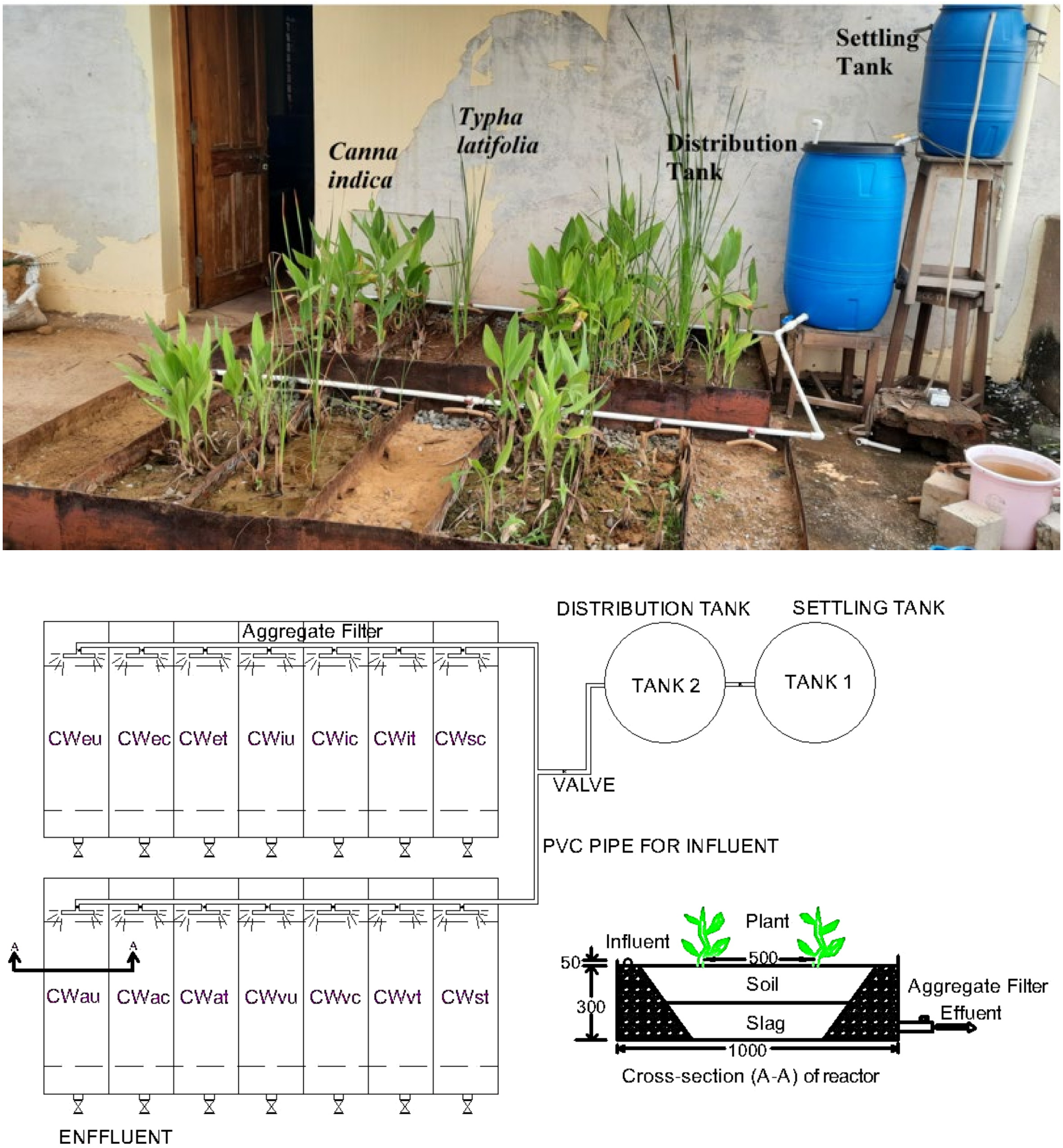

Fig. 1. Location view and plan, section of experimental setup

corresponding soil and aggregate base CW in HSFCW. Plant distances were restricted at 500 mm. Tap water was given into each unit for a month until fresh shoots started to appear. Table 1 shows the various combinations of soil and THFS with or without plants.

Throughout the study, stem height measurements and regular plant shoot counts were conducted, while WW was dosed at dilutions of 25%, 50%, 75%, and 100% for two months to acclimate the plants, following the USEPA (1988) guidelines. Input and effluent samples were taken for analysis after the plants had acclimated for two months.

Wetland removal efficiency (RE)

The removal efficiency (RE %) of various parameters in the used constructed wetlands (CWs) was calculated after a hydraulic retention time (HRT) of 48 hours, using the following equation.

$$\text{Removal efficiency (\%)} = ((C_{inlet} - C_{outlet})/C_{inlet}) * 100 \quad (1)$$

where,

C_{inlet} = Concentration of a parameter in the influent

C_{outlet} = Concentration of parameter in the effluent (samples were collected after 48 hours of retention time)

Characterization of slag

The slag under consideration has a pH value of 12.1, indicating that it is highly alkaline. This property is beneficial in constructed wetlands, particularly in treating acidic wastewater, as the high pH can help neutralize acidity and enhance the overall treatment process. The particle size of the slag, ranging between 8-20 mm, suggests that it is coarse and will provide adequate void space for water flow, allowing for good hydraulic conductivity. This size range is suitable for promoting microbial activity, which is essential for the removal of contaminants from wastewater (Singh et al., 2023). The specific gravity of 3.38 indicates that the slag is denser than many common soil materials, suggesting that it could be an effective medium for the stabilization of contaminants and offer long-term stability in wetland systems. Furthermore, the calcium oxide (CaO) content of 46.5% indicates that the slag has significant potential for chemical reactions, such as the precipitation of phosphates and heavy metals, thus contributing to the removal of pollutants (Park et al., 2016).

Data analysis

The data were analyzed for descriptive analysis, including mean, maximum and minimum, correlation analysis, one-way ANOVA and finding the data's significance using Microsoft Excel 2016 (Swarnakar et al., 2023).

RESULTS AND DISCUSSION

Physicochemical characteristics of influent

The measured pH values ranged from 7.4 to 7.8, while the measured EC values were between 1179 and 1365 µs/cm. These results demonstrated the presence of dissolved inorganic particles in the treated WW. TDS measurements ranged from 855 to 1121 mg/L. The ranges for the BOD_5 and COD, respectively, were 88 to 162 mg/L and 192 to 320 mg/L. NN and soil reactive phosphorus values ranged between 11.6 and 20.3 mg/L, and 2.3 to 17.5 mg/L, respectively. DO range from 2.6 to 3.8 mg/L. Turbidity ranged from 2.1 to 13.8 NTU.

Table 2 presents the analysis results for key parameters of the domestic wastewater. The analysis indicates that the wastewater quality ranged from weak to moderate, with most parameters falling within the acceptable limits set by the CPCB, WHO and USEPA (table 4).

Table 2. Characterization of influent, (n=10)

S. No.	Parameters	(min-max) (Average ± SD)
1.	pH	7.4-7.8 (7.7 ± 0.2)
2.	EC, (µs/cm)	1179-1365 (1285 ± 61.0)
3.	Turbidity, (NTU)	2.1-13.8 (7.4 ± 4.3)
4.	Total alkalinity, (as $CaCO_3$, mg/L)	290-362 (336 ± 23.0)
5.	TDS, (mg/L)	855-1121 (939 ± 86.9)
6	BOD_5, (mg/L)	88-162 (118 ± 27.6)
7	COD, (mg/L)	192-320 (264 ± 49.2)
8	NN, (mg/L)	11.6-20.3 (16.4 ± 2.9)
9	SRP, (mg/L)	2.3-17.5 (8.7 ± 5.7)

Table 3. RE(%) for WW treated through planted and unplanted CWs (DO-Increased*)

Types of CWs	pH	Alkalinity	Turbidity	TDS	BOD_5	COD	DO*	NN	SRP
CWeu	8.6	50.8	88.6	12.5	52.1	60.1	125.7	63.7	91.6
CWec	7.5	61.4	88.7	29.9	70.4	78.6	147.6	81.0	93.2
CWet	7.5	57.5	94.3	28.6	75.4	81.7	161.0	85.8	91.6
CWiu	8.5	47.4	89.1	15.5	77.1	59.0	130.5	64.7	91.8
CWic	7.7	50.0	94.4	31.8	61.8	85.3	162.9	85.3	93.8
CWit	7.5	52.9	96.0	33.2	78.7	81.5	159.5	64.6	95.5
CWsc	10.1	63.3	95.0	31.6	74.7	65.9	131.9	72.1	92.1
CWau	8.3	49.3	92.8	6.90	61.3	59.1	120.0	57.6	91.0
CWac	7.5	57.3	95.5	29.9	56.3	72.7	138.1	80.1	93.0
CWat	7.5	56.4	95.5	34.2	59.1	77.1	126.7	79.2	92.3
CWvu	8.5	42.3	91.0	13.0	65.9	60.1	116.2	57.3	90.8
CWvc	7.7	43.6	94.4	32.3	59.8	74.6	134.8	90.2	94.5
CWvt	7.6	38.5	94.3	23.3	62.8	77.8	131.9	90.2	95.4
CWst	9.4	57.1	96.1	43.0	61.1	61.4	154.8	68.7	92.9

Treatment of domestic WW through different set up of CWs

Table 3 shows the effluent pH for the various CWs. All types of CWs show consistently higher pH values than the influent 7.7 ± 0.2. The pH value of effluent from blank slag CW-THFS was the highest (>12). The effluent pH, although initially higher than the influent pH of 7.7 ± 0.2, decreased to 9.4 and 10.1 for the slag-based CWs planted with both plant varieties (CWst and CWsc). The elevated pH resulted in slower plant growth, and eventually, the plants wilted. Therefore, incorporating media such as soil is essential to support plant growth. In comparison with all unplanted slag and soil based CWs, planted CWs effluents have a lower pH value (<8). Table 3 is showing RE (%) of various parameters except DO. DO is increasing during the treatment.

Due to high pH (>12), measurement of alkalinity is an important factor for THFS. Before being used (for example, as aggregate) or while being disposed of in repositories and legacy sites, very alkaline leachate (>12) originating from the weathering of steel slag can be treated by CWs (Gomes et al., 2019).

Clay, which eventually separates into organic and inorganic matter and plankton, is a type of suspended and colloidal matter that causes turbidity in water (APHA, 2017). The presence of dissolved colour-causing substances is also a response to turbidity. For slag rust properties, the presence of water and air can change the colour of the effluent. Turbidity was higher in the WW sample (12.4 NTU) and averaged 7.4 ± 4.3 NTU. The turbidity varies from 1.6 to 0.6 NTU in all types of CWs, which is quite transparent and effluent. Turbidity was low in the effluent because the CWs effectively remove suspended solids through sedimentation, filtration, and absorption by the wetland media, particularly in the planted CWs. All planted soil and slag-based CWs have lower turbidity. After the treatment, the reduction in turbidity was maximum at 96% in planted, 92% in unplanted, and 96% in planted slag types of CWs.

Figure 2 depicts the levels of TDS in effluent at 48 hours of HRT in all distinct CW configurations. The TDS of influents is 1285 ± 61.0 µs/cm and the graph shows the effluent has a sufficient reduction. For each experimental configuration, unplanted CWs showed high RE. The surplus sludge and plant litter solids that are in the process of mineralization make up a portion of the non-trapping influent solids in the wetland. The sedimentation, filtration, bacterial decomposition, and absorption of the wetland medium are primarily responsible for

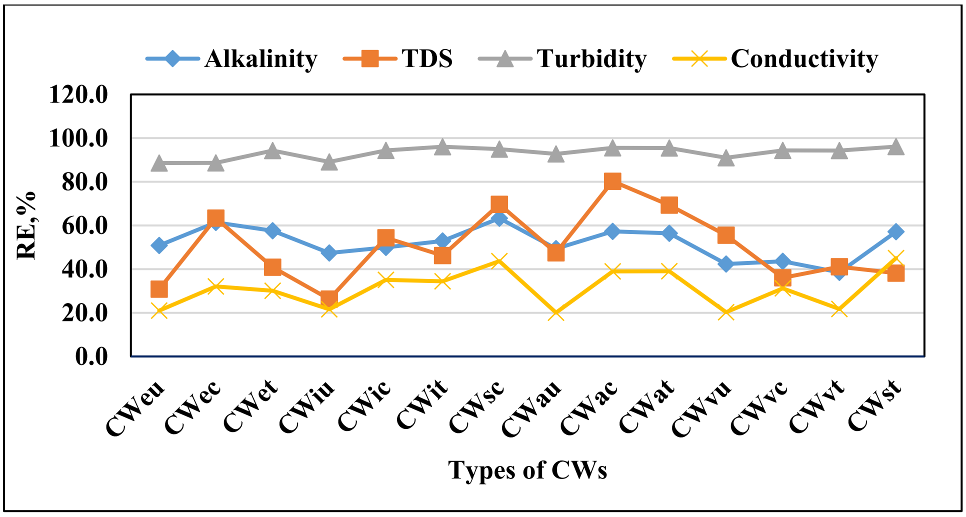

Fig. 2. RE (%) of soil and slag based CWs

the observed TDS, RE of the slag and soil system during operation.

In all experimental CWs setups, the BOD_5 value of the effluent significantly decreased, as indicated by the analysis of BOD_5 values across various CW configurations with a 48-hour HRT. The average influent BOD_5 concentration was 118 ± 27.6 mg/L. The RE of BOD_5 in planted CWs was 78.7%. The combination of THFS with Entisol and Inceptisol exhibited the highest BOD_5 RE, with a significant difference ($p < 0.05$). In comparison, unplanted CWs showed a 77% BOD_5 RE. Additionally, THFS with *Canna indica* achieved a 74.7% BOD_5 RE, outperforming THFS with *Typha latifolia*. Microbes that are present at media, plant roots and rhizomes region may breakdown and eliminate the soluble BOD_5 (Yadav et al., 2018). Because of the low depth of the water in CW, which produces an aerobic environment in the system, microbes follow aerobic routes (James, 2017). All planted CWs promote microbial activity and the breakdown of organic matter through aeration, root systems, and microbial interactions, which significantly reduce the BOD in the effluent. For vertical flow systems, the bottom of CWs has occasionally been discovered to be anaerobic (Korkusuz et al., 2015). As per the CBCB, the discharge limit for BOD_5 is 30 mg/L for inland surface water and 100 mg/L for land. After the treatment, all the effluent is within the CPCB limit for BOD_5. Therefore, at a HRT of around 48 hours the first-order mass flow relationship can be used to appropriately estimate the BOD_5 RE.

COD was likewise removed in the CWs setting throughout the study. The influent has avg. 264 ± 49.2 mg/L of COD concentration (table 2). The fourteen different setups were able to remove 59% to 85% of COD in 48 hours of HRT. Bacteria in the rhizosphere break down organic matter in effluent, which makes the environment perfect for microbial growth ($p < 0.05$). This is linked to higher COD removal in planted CW. All planted types CWs have above 74% RE have been achieved. Both plants have good RE with entisol and inceptisols type soil, THFS substrates. For unplanted CWs, 77% of RE has been achieved with inceptosols and THFS combinations. Only THFS with *Canna Indica* has 74.7% RE, which is higher than the *Typha latifolia*. A study shows slag- and gravel-based vertical flow CWs have achieved 47% and 44 % COD, RE for the treatment of domestic WW (Korkusuz et al., 2005).

All CWs have seen a 125% increase in DO. All planted types of CWs have higher DO (>5 mg/L) after treatment. Unplanted types of CWs also have excellent efficiency in decreasing DO (Fig. 3B). *Canna indica* and *Typha latifolia* have been shown to increase the DO. DO is an essential part of aquatic life and maintains the aerobic condition. The physical, chemical, and

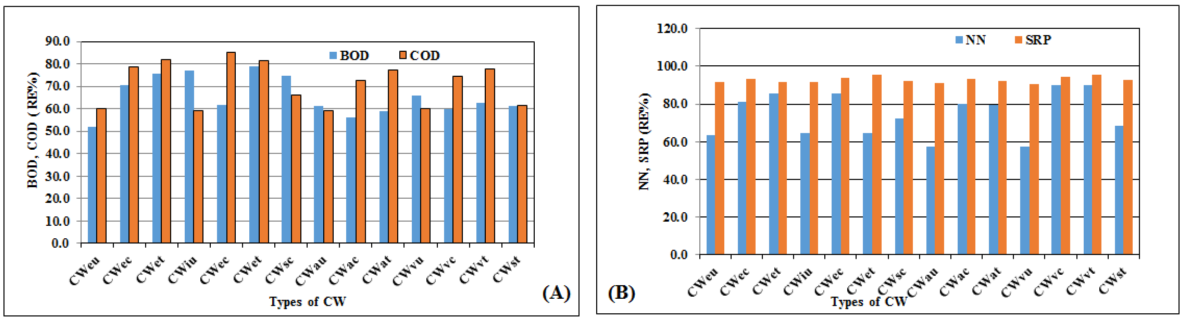

Fig. 3. Removal efficiency of THFS and soil-based CWs (A) BOD_5, (B) NN

biological activity occurring in water BOD_5 has an impact on the DO level in WW (Kumar et al., 2023).

Fresh home WW has a minor quantity of NN, whereas NN-containing biological treatment plant effluent is more abundant (APHA, 2017). NN is a required nutrient for many photosynthetic autotrophs. The average NN value in the influent was 16.4 ± 2.9 mg/L, which was removed from CW settings with a RE of 64.6%–90.2% in planted CWs and 57.6%–64.7% in unplanted CWs The low NN levels in the effluent from slag and soil-based CWs can be attributed to the combined effects of plant absorption and microbial activity. Both plants, , absorb nitrogen for their growth, while microorganisms in the rhizosphere also contribute to the denitrification process, converting nitrate nitrogen into nitrogen gas. The slag and soil media help facilitate these processes by providing suitable environments for microbial growth and plant nutrient uptake, leading to effective reduction of NN in the effluent.

Slag-based CWs (CWsc) have higher RE of NN as compare to CWst. In a WW treatment system, nitrogen is continuously involved in the conversion of organic to inorganic chemicals, and vice versa (Zhao et al., 2009). Two processes plant absorption and microbial activity along the rhizome can help emergent macrophytes like *Typha latifolia* and *Canna indica* obtain nutrients from the soil. Given that both plant species in this study exhibited a respectable growth (except CWst and CWst) pattern across the whole study bed, it can be inferred that the plant species could meet their nutritional requirements by fertilizer from WW, which helped reduce nitrogen levels by allowing for the intake of necessary nutrients.

For the development of flora and fauna, phosphorus is necessary. But when present in large quantities, it worsens the quality of the water and contributes to eutrophication. As a result, the design of CW allows for the extensive removal of phosphorus through the processes of adsorption, assimilation, and sedimentation (Kumar et al., 2023). SRP in domestic WW has been 8.7 ± 5.7 mg/L (table 2). The RE of SRP in planted and unplanted areas is very high (90.8%–95.5%)). More than 92.0% have found out in both slag-based CWs ($p<0.05$). A plant's ability to absorb phosphorus during growth and store it in the system of roots and shoots varies depending on the species (Khouja et al., 2020). Similar results have shown that HSSFCW treatment of phosphate from municipal WW was extremely effective, removing up to 90% of the SRP (Paruch et al., 2016). The calcium oxide available in slag (34%–44%) has a good absorbance of phosphorus (Murmu et al., 2023). Excellent results show the RE of SRP.

The montmorillonite nature of soil (CWic and CWit) aids in improving the quality of treatment in CWs due to its high cation exchange capacity (CEC) and ability to adsorb and retain nutrients, such as ammonium and phosphate. This property allows the soil to act as a buffer, enhancing the removal of nutrients and pollutants from wastewater, thereby improving the overall treatment efficiency (table 3). Additionally, montmorillonite-rich soils can help reduce clogging in CWs, promoting better water flow and filtration.

Table 4. Standard limits for reuse of effluent

Parameter	Unit	CPCB Standards	WHO Guidelines	USEPA Standards
pH	-	6.5 – 8.5	6.5 – 8.5	5.5-9.0
BOD_5	mg/L	≤ 30	≤ 20	≤ 30
COD	mg/L	≤ 250	≤ 125	≤ 125
NN	mg/L	≤ 10	≤ 10	≤ 10
TP	mg/L	≤ 2	≤ 1	≤ 1
Alkalinity	mg/L	200 – 500	Not specified	Not specified
Turbidity	NTU	≤ 10	≤ 5	≤ 5

Effluent discharge standards are essential for protecting environmental and public health by regulating the quality of treated wastewater released into the environment. Table 4 summarized the effluent disposal limits for various parameters as specified by the CPCB, WHO and USEPA.

As per table 4, the treated wastewater can be utilized for a variety of purposes, including irrigation of crops and lawns, industrial cleaning and process water, landscape maintenance, non-potable urban applications such as toilet flushing, public area washing, street cleaning, and firefighting.

Morphological study

A detailed morphological study was conducted on *Canna indica* and *Typha lati*folia, the two representative macrophytes used in the constructed wetlands (CWs). Both plant species exhibited initial growth, with new shoots emerging after two months of planting across all lab-scale CW reactors. By the end of the study, the number of plants increased from two to thirty. The growth and morphological parameters were more favorable for *Canna indica* than *Typha latifolia*, except in the CWs where plant density was low (CWst and CWsc). Root depth for both species was generally shallow, measuring less than 20 cm. Notably, *Canna indica* demonstrated superior survival and growth, thriving for up to two weeks without additional dosing. Plant height also showed significant growth, particularly in the CWs planted with *Canna indica* and *Typha latifolia*, reaching heights of up to 120 cm by the end of the study, compared to an initial height of 30 cm. The plants could not survive in CWsc and CWst due to the high pH values. After two weeks, they wilted.

CONCLUSIONS

The performance evolution of different soil media with THFS by batch-operated lab-scale HSFCWs for WW treatment shows significant performance. Under the current experiment, the residential WW was treated by different CWs configurations (both planted and unplanted). For the treatment of various parameters, all of CW's settings have worked to some extent. However, compared to unplanted CWs, a planted CWs configuration performed better. Planting CWs will, therefore, improve wetland functioning. The configuration with two macrophyte species (*Canna indica* and *Typha latifolia*) in the planted wetland had functioned better. Almost all of the parameters were treated uniformly by the various CW settings, bringing them all within the allowable limits of CPCB and WHO. The combination of 50:50 ratios of THFS and soil has functioned satisfactorily. THFS can be reused with soil, providing an economical option for substrates for CWs. The CWic, CWit, CWec, and CWet configurations demonstrated the highest RE results. Both laterite and black cotton soils, which are readily available in the region, contributed significantly to the improved performance of these CWs along with slag. More research is required to assess the connection between effectiveness and various loading rates for various types of influents.

FUTURE SCOPE

The future scope of this study lies in exploring the performance of CWs under varying HRTs to optimize treatment efficiency for different WW characteristics. Additionally, further research could focus on evaluating the RE of heavy metals in CWs, especially when using diverse substrates like slag and soil. This would help assess the ability of CWs to treat industrial WW containing heavy metals and their impact on the overall treatment process. Investigating the influence of different HRTs on the removal of heavy metals, along with assessing the long-term sustainability of CWs, will provide valuable insights for scaling up this technology in real-world applications.

ABBREAVATIONS

ANOVA	Analysis of Variance
APHA	American Public Health Association
BFSS	Blast Furnace Steel Slag
BOD_5	Five Days Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
CPCB	Central Pollution Control Board
CWs	Constructed Wetlands
DO	Dissolved Oxygen
EC	Electrical Conductivity
HRT	Hydraulic Retention Time
HSFCWs	Horizontal Subsurface Flow Constructed Wetlands
NN	Nitrate Nitrogen
NTU	Nephelometric Turbidity Units
RE	Removal Efficiency
STPs	Sewage Treatment Plants
SRP	Soil Reactive Phosphorus
TER	Terbuthylazine
TDS	Total Dissolved Solids
THFS	Twin-Hearth Furnace Slag
TP	Total Phosphorus
PVC	Polyvinyl Chloride
WHO	World Health Organization
WW	Wastewater

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CONFLICT OF INTEREST

The authors declare that none of the writers has any financial or other conflicts of interest with any other study team or individual. There are no conflicts of interest, either financial or otherwise.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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