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Evaluating Domestic Wastewater Treatment Efficiency of Field Scale Hybrid Flow Constructed Wetland in Series

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ABSTRACT

Constructed wetlands (CWs) are man-made systems designed to treat a range of residential, commercial, and industrial wastewaters. The objective of the study was to evaluate the efficiency of wastewater treatment systems using constructed wetlands. The effectiveness of removing chemical and physical pollutants was also evaluated. The setup consisted of a hybrid flow system composed of upflow constructed wetland and a horizontal flow constructed wetland connected in series that is used for primary treatment of the influent of domestic wastewater. Two systems were analyzed: one cultivated with the ornamental species Canna Indica, and one cultivated with the cattail Cymbopogon flexuosus. It consisted of two treatment sections consisting of two plant species Cymbopogon citratus (lemon grass – first CW) and Canna xalapensis Horan (Canna Indica – second CW). The water quality parameters i.e., BOD, COD, TSS were analyzed according to APHA (American Public Health Association) by daily sampling. The CW was monitored for the quality of wastewater inflows and outflows and nutrient accumulation in plants. Results showed that the maximum COD removal for Lemon Grass and Canna Indica beds were 75% and 70% respectively at 200mg/L COD loading in the CW setup over a six-month period respectively. The maximum BOD removal found in Lemon Grass and Canna Indica beds were 73% and 64% respectively at a feed concentration of 200mg/L COD. Both the CWs together as one unit showed similar rates of TSS removal irrespective of the type of wetland plant species and were more efficient in treating wastewater.

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INTRODUCTION

Constructed wetlands (CWs) have lately gained popularity as a treatment method due to their numerous benefits, which include low cost, ease of use and maintenance, adaptability to different climatic conditions, high water quality after treatment, and attractive look. Additionally, they are less vulnerable to changes in the pollution load. The quantity of wetland vegetation, substrate (soils, sand, aggregates), and kind of microbial assemblages all have a significant impact on the effectiveness with which CWs remove organic pollutants. To induce the removal behavior, on the other hand, a variety of chemical (precipitation, adsorption), physical (sedimentation, filtration), and biological (biodegradation, biosorption, and assimilation) interactions are employed (M Achak et al., 2023). The main components of a natural wetland are soil, plants, water, or sewage. Adopting sustainable technologies, or those that can effectively treat wastewater over the long term, is crucial for wastewater treatment. Since incorporating innovative wastewater treatment technology is technically and financially impossible, it appears pointless. While underdeveloped nations continue to struggle

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with the management of macro pollutants (organic matter, nutrients, and viruses), wealthy nations are working to reduce micropollutants. It has been demonstrated that constructed wetlands may effectively regulate organic matter, nutrients, and diseases (A Mustafa, 2013). Traditional wastewater treatment techniques include sand traps (grit chambers), septic tanks, Imhoff tanks, baffled reactors (such as the Anaerobic Baffled Reactor, ABR), anaerobic filters, green filters, constructed soil filters, aerobic stabilization ponds (maturation ponds/oxidation pond), rotating biological contactors (RBC), active sludge processes (ASP), and Up flow CWs are a man-made system that treats wastewater using a foundation material, plants, and organic matter. When compared to conventional power plants, CWs require less in the way of infrastructure, investments, raw materials, energy consumption, operation, staff, maintenance, odors, insects, flow fluctuations, harmful compounds, and byproducts. Flow direction, macro phytic development, and hydrology all affect how CWs are classified. The main components of a natural wetland are soil, plants, water, or sewage. The CWs treat mining water, industrial effluent, domestic wastewater, animal wastewater, urban stormwater, and field runoff. The main components of the CWs are aggregate, soil, and gravel that are utilised as filter media, together with macrophytes (vegetation) as Typha, Canna indica, Flax Lily, Banksias, Bottlebrush, Phragmites australis, common reed, Club-rush, Cattail, Reed canary grass, yellow flag, and Compact rush (A.K. Swarnakar et al.,2022). Assessments of the water quality were carried out in accordance with the procedures outlined in Standard Methods (APHA, 1995). The averaged influent and effluent concentrations of the aforementioned key parameters for water quality were used to calculate the treatment efficiency. Following the steps outlined in the American Society of Testing and Materials (ASTM) standard (D4820-96a), specific surface area was measured (T.Y. Chen et al., 2006). By replicating the characteristics of natural wetlands, constructed wetlands (CWs) provide an ecosystem with substrate, microorganisms, and vegetation that together enable the removal of pollutants from residual water. CWs have received a lot of attention for treating wastewater from home effluent, agricultural runoff, and livestock drainage due to their attractiveness, functionality, affordability, and sustainability. The quantity and composition of inflows, hydraulic stress, temperatures, and rainfall intensity are just a few examples of the many different variables that CWs are subjected to because to their natural and open-engineered nature (X Jhao et al., 2022). The main use of constructed wetlands (CWs) is the decentralised treatment of domestic sewage, while they have also been used to treat a range of wastewaters, including swine wastewater, industrial wastewater, and runoff from stormwater (N.M. Kulshreshtha et al.,2022). Additionally, CWs may produce environmental circumstances that might result in a considerable decline in the effectiveness of treatment or even a deterioration of water quality (F.J. Diaz et al., 2012).

Solid/liquid separations and biogeochemical transformations are two main treatment processes used in CWMs. Reduction, oxidation, acid/base reactions, biological processes, flocculation, and precipitation are all aspects of transformation. Adsorption, absorption, gravity separation, stripping, leaching, filtering, and ion exchange are examples of separation processes (Kumar & Dutta, 2019). Plants and media are vital elements of artificial wetlands used for sewage treatment. Using medium means filler, major contaminants in sewage may be trapped by the processes i.e., adsorption, filtration, and sedimentation. Additionally, it is the material that allows the other living components in constructed wetlands due to which plants and microorganisms to thrive (S Lu et al., 2016).

Constructed Wetlands (CW) are widely recognized as a sustainable, environmentally friendly technique with a demonstrated capability for treatment. A variety of industrial effluents have been treated using CW systems, including generated water from oilfields, tanneries, agro-industries including dairy farms, water contaminated with fuel additives and petroleum derivatives, and acid mine drainage. The primary advantage of CW is its environmental accessibility, which is further enhanced by its low operation and maintenance costs, low energy requirements, lack of chemical usage, and lack of extensive mechanical infrastructure and equipment. Therefore, CW technology may also be an appropriate option for treating the effluent (A Gholipour et al.,2020). The objective of the study was to evaluate the efficiency of wastewater treatment system of field scale hybrid flow constructed wetland in series. With the application of CWs, a variety of contaminants, including metals, total coliforms, BOD, COD, TSS, total keljdahl nitrogen (TKN), total phosphorus (TP), and plant uptake, can be removed from wastewater by microbial decomposition, substrate adsorption, filtration by packed substrates, and biological predation. For BOD and TSS, several artificial wetlands have high removal efficiency of >80% (Abou-Elela et al.,2013). Ye and Li (2009) investigated the effects of adopting two small-scale HFCW and VFCW systems with three distinct plant species to remove contaminants. Apart from TSS, NO_3, and TKN, they achieved excellent pollutant removal. They suggested that

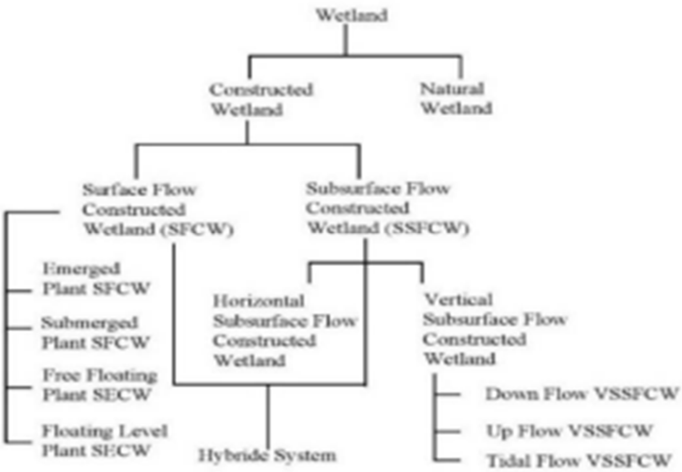

Fig. 1 . Types of Wetlands [2]

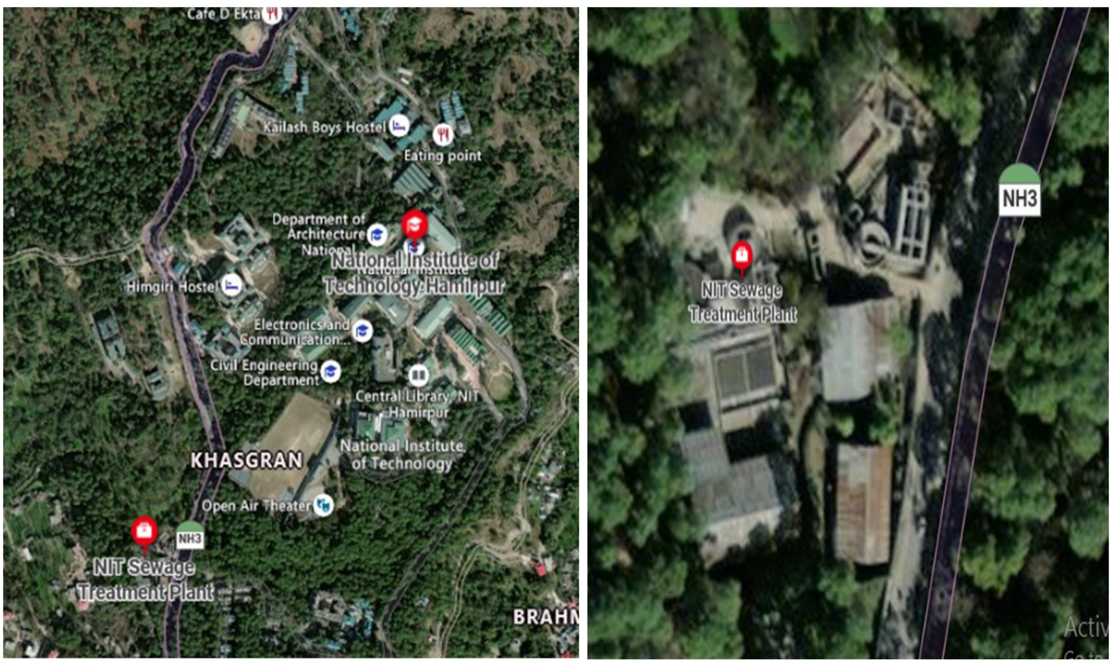

Fig. 2. Location of the study area

underdeveloped nations implement wetlands treatment (Ye &Li ,2009). The effectiveness of removing chemical and physical pollutants was also evaluated. The current work focuses on the field-scale demonstration of subsurface flow CWs with a unique combination of canna indica and lemongrass plant species. The specific objectives of this six-month (January–June 2023) field scale study was (i) to analyze the water quality parameters i.e., pH, BOD, COD, TSS (ii) quality of wastewater inflows and outflows and nutrient accumulation in plants.

MATERIALS AND METHODS

The two-field scale hybrid flow subsurface Constructed Wetlands (CWs) connected in series were setup. The pilot scale model has been made in open air at site of Sewage Treatment Plant (STP) of the National Institute of Technology, Hamirpur, Himachal Pradesh, India. A Hybrid Constructed wetland was designed for the treatment of Domestic Wastewater which consisted of Vertical Sub- surface flow (Upflow and horizontal flow). The study area is in the rain-fed agroclimatic zone. There are two units of CWs which receives domestic wastewater from a residential colony, canteens, departments, and hostels in the immediate vicinity of National Institute of Technology campus. The raw sewage wastewater was used. In order to avoid clogging or choking in the Vertical SSF-CW, a sedimentation/settling pond was built that absorbed untreated domestic wastewater and allowed the sedimentation of settleable solids/ coarse materials under gravity before passing it on to VSSF-CW. The variables which have been discussed in the study are pH, HRT, HLR, BOD, COD, and removal efficiency. The variation of BOD i.e. biochemical oxygen demand has been studied at different feed concentrations and reduction in COD concentration at different HRT has also been studied. The HRT was varied from 15days, 12days, 9days, 6days, 3 days and 1 day. Variation of COD at different feed concentration was also analyzed.

Field Scale CWs were designed. A 200 L tank with dimensions 66 x 66 x 73 cm was filled with raw wastewater and regularly stirred using a stirrer making sure the sludge does not get settled into the tank. After this it was fed to the Imhoff tank shaped chamber which had the capacity of 20L, Height: 43cm, Diameter: 24 cm and Thickness: 3-4mm. The inlet Flow rate is 4.44 L/day. The wastewater was then allowed to rest in the settling/ sedimentation tank (Imhoff tank). After the sedimentation/settling pond, the two chambers received uniformly directed wastewater but was controlled using flow regulator at the beginning of VSSF-CW through a PVC (Polyvinyl chloride) pipe. A PVC (polyvinyl chloride) pipe carried influent wastewater from the sedimentation tank to the VSSF-CW with even distribution. The VSSF-CW was filled with the indigenous mineral substrates having size i.e. first chamber with naturally available soil (8cm), brick waste of size (10mm+ 12.5mm) (15cm) and aggregates layer (15cm) of size (4.75 mm+ 10mm+ 12.5mm) and the other chamber with naturally available soil (8cm), demolished concrete waste (4.75 mm+ 10mm+ 12.5mm) (15cm) layer and aggregates layer (15cm) of size (4.75 mm+ 10mm+ 12.5mm). The vertical pipe was placed above in each of the for equal flow of wastewater. The design parameters i.e hydraulic design, aspect ratio, slope and media type, Collection/Growth of Wetland Vegetation prior to Treatment and detention time were taken care off. The representation of pilot constructed wetland is shown in figure 3.

Both the CWs received the same inlet wastewater during the six-month period (January 2023- June 2023). The wastewater used in this study was taken (pumped) from the WWTP plant inlet.

Experimental procedure and sample collection

Collection and analysis of raw sewage and the treated wastewater was carried out since January 2023 to June 2023. Determination of pH, electrical conductivity (EC), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), nitrate and total

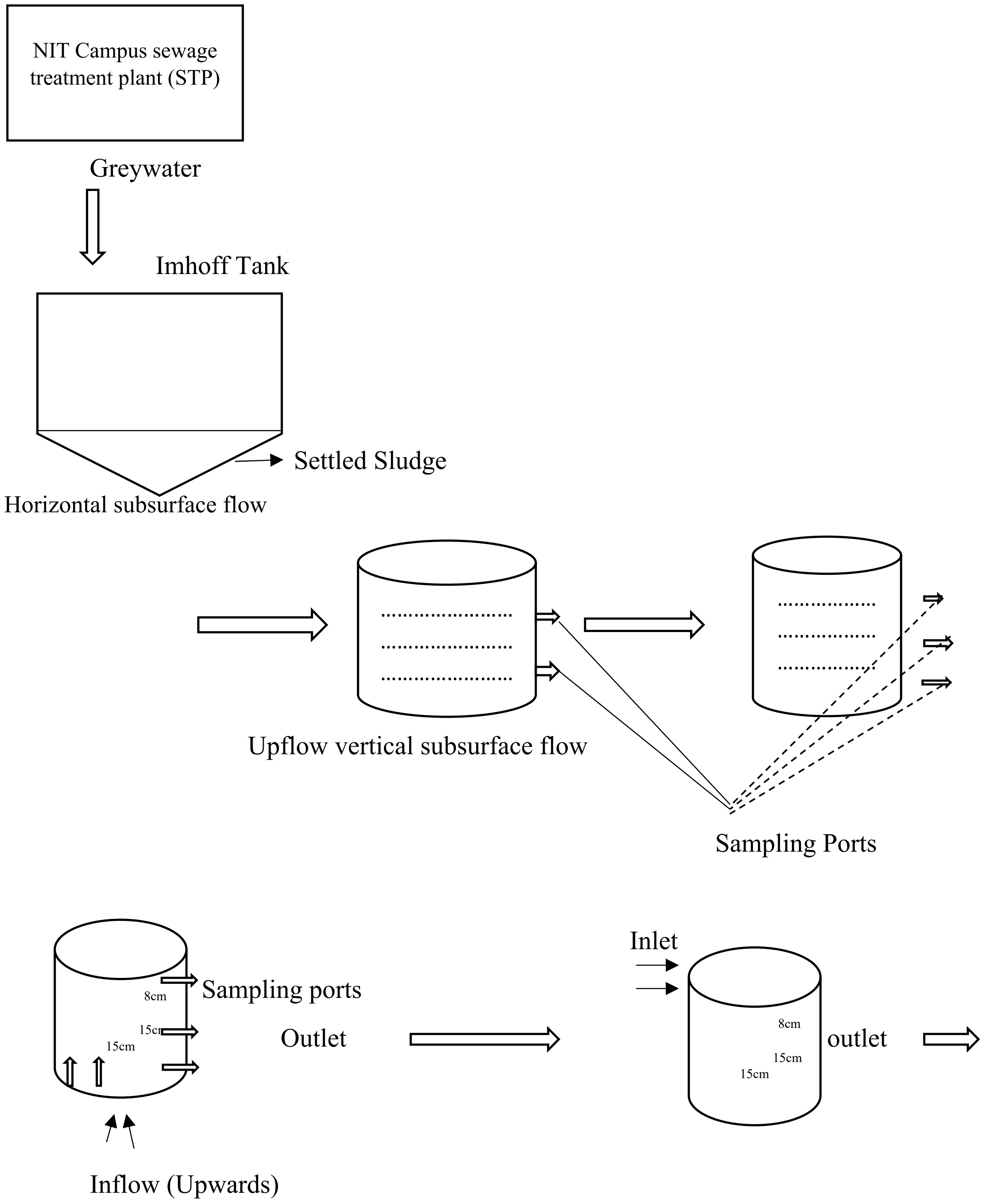

Fig. 3. a representation of pilot scale constructed wetland

phosphate was carried out both for untreated and treated wastewater.

During sample collection, the following actions were taken:

• Careful wastewater sampling, including both treated and untreated samples, was carried out in order to achieve accurate and trustworthy findings, as the correctness of the results depends on the accuracy of the sample that was collected.

• For a reliable analysis, adequate sample methods were used, along with the right instruments.

• Wastewater samples were collected at regular every day after 12 hours.
• Sampling procedures were consistently and carefully followed to ensure that results are comparable over time and between outlets.
• Analysis of the parameters was done.
[S Vishwakarma et al., 2023].

Computing HLR and HRT for CWs

For computing HLR and HRT, the following equations are used [A.S. Tilak et al., 2016]:

$$\text{HLR} = \frac{Average\ flow\ (Q)\ entering\ CW}{Surface\ area\ (As)\ of\ CW} \quad 1$$

$$\text{HRT} = \frac{n * L * W * D}{Average\ flow(Q)\ passing\ through\ CW} \quad 2$$

where L, W, and D stand for the length, breadth, and depth of the CW, respectively, and n is the media porosity.

The calculation formula of pollutant removal rate or efficiency of the system is shown below:

$$Removal\ Rate\ \% = \frac{c_0 - c_1}{c_0} \times 100\% \quad 3$$

where C_0 is the initial concentration of pollution in the raw wastewater, and C_1 is the concentration of pollution in effluent water (H Wu et al., 2020)

Wastewater quality monitoring

The wastewater samples were collected twice every month and analysed from January 2023 to June 2023 in Civil Department of NIT Hamirpur, Environment engineering Laboratory. Determination of pH, electrical conductivity (EC), chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS) was carried out both for untreated and treated wastewater using the APHA standard methods. The treatment efficiency of each parameter for both CWs is compared with the literature values. For the determination of COD model COD digester Hach DRB 200 was used. The closed reflux method was used to determine the initial COD of the wastewater. The pH was measured by dipping the probe into the wastewater sample and measuring the stable reading. For the determination of total suspended solids and total dissolved solids, a 100 ml sample of wastewater was taken and then dried in an oven. The dried weight of the sample (W1) gave the total solids present in the wastewater. Another 100 ml wastewater sample (W2) was taken and passed through a filter paper and collected in a beaker. The sample collected over the filter paper (W3) gave the total suspended solids, whereas the sample that passed through it gave the total dissolved solids (W4). An analytical balance with a precision of 0.0001 g (Model: A&D GR-200 (max 210 g, min 10 mg, e = 1 mg, d = 0.1 mg) was used to weigh the materials. An electric oven was used to dry the items (Model: SECOR INDIA). A COD digester (Modal: DRB 200, Hach, India) was used to calculate COD, while a pH meter was used to determine pH. (Model: LMPH-10 Labman scientific instruments Pvt. Ltd., India). An EC meter was used to calculate the electrical conductivity (Model: LMCM-20 Labman scientific instruments Pvt. Ltd., India). An aeration pump was used to provide oxygen to the cathode chamber (Model: SOBO aquarium pumps, India). The basic characteristics of the raw wastewater for influent are shown in table 1 below:

Inlet and outlet flow control

A Tap/Flow Regulator was used to control the influent and effluent flow rates (Figure 4). The suspended particles were allowed to settle in the Imhoff tank before to entering the CWs.

Table 1. Characterization of Influent wastewater [C Ramprasad & L Philip, 2018]

Parameters	Units	Minimum	Maximum	USEPA standard limits for reuse
pH	-	7.24	8.34	5.5 to 9.0
COD	mg/L	216	320	10
BOD	mg/L	72	120	<5
TSS	mg/L	224	320	10
TOC	mg/L	23	36.48	NA
TN	mg/L	17	28.82	10
NH4-N	mg/L	12.32	17.84	10
Nitrate nitrogen (NO3-N)	mg/L	10.28	14.56	<5
Total P	mg/L	2.934	3.84	1
Faecal Coliform (FC)	CFU/100ml	50	120	Nil
Total chromium (Cr)	µg/L	212.2	268.4	50
Nickel (Ni)	µg/L	38.4	57.2	30
Copper (Cu)	µg/L	41.2	50.6	50
Zinc (Zn)	µg/L	1616.7	2125.7	2000
Arsenic (As)	µg/L	33.3	43.2	10
Cadmium (Cd)	µg/L	32.7	51.2	10
Lead (Pb)	µg/L	146.6	228.5	100

Fig. 4. a tap/flow regulator

Plants Uptake and plant Growth

Emergent plants, submerged plants, floating leaved plants, and free-floating plants are all common macrophytes utilized in CW treatments. Although more than 150 macrophyte species have been employed in CWs worldwide, only a small number of these plant species are planted in CWs on a regular basis. The most common used emergent species are Phragmites spp. (Poaceae), Typha spp. (Typhaceae), Scirpus spp. (Cyperaceae), Iris spp. (Iridaceae), Juncus spp. (Juncaceae) and Eleocharis spp. (Spikerush). The most frequently used submerged plants are Hydrilla verticillata, Ceratophyllum demersum, Vallisneria natans, Myriophyllum verticillatum and Potamogeton crispus. The floating leaved plants are mainly Nymphaea tetragona, Nymphoides peltata, Trapa bispinosa and Marsilea quadrifolia. The free-floating plants are Eichhornia crassipes, Salvinia natans, Hydrocharis dubia and Lemna minor (H Wu et al., 2015). In the study the plant studies are shown in the figure 5 below.

Fig. 5. photograph of the plant a. Canna Indica b. Lemon grass

Table 2. The characteristics of raw wastewater

Parameters	Influent
BOD	230mg/L
COD	480mg/L
TSS	175mg/L
TP	4mg/L
TKN	25mg/L
NH^{4+}-N	15mg/L
NO_3-N	2mg/L
NO_2-N	0.6mg/L
Alkalinity	120mg/L

It was reported that during the cold winter months a translocation of nutrients from stems to rhizomes occurred which results in an increase of nutrient content in the wastewater. For that purpose, plant harvesting must be practiced in order to remove organic matters and nutrients from the system (Abou-Elela & Hellal,2012). The plants' growth was monitored from the start of the study until six months into the study's duration, and it was discovered that the average plant growth was 27 cm.- 36cm for Cymbopogon citratus (lemon grass) and 62-71 cm height for Canna xalapensis Horan (Canna indica) respectively.

RESULTS AND DISCUSSIONS

Overall evaluation and the effect of the presence of plants. Analysis is done on the raw wastewater and the characteristics found on the influent are listed below in Table 2:

pH and Temperature- The pH and temperature of inlet and outlet was recorded every day. It was observed that the pH range between 6.8 to 8.3 and the temperature between 29^o-33^{o}C.

BOD_5 Removal - The analysis of BOD_5 was carried out for both the samples from inlet and outlet. Table 3 below shows the values of BOD_5 at different loading.

At a feed dosage of 245 mg/L, the BOD_5 decrease was at its highest for the Canna Indica plant (73%), and the lemon grass plant (64%). It is also observed that at feed concentrations of 545 mg/L of COD, the BOD concentration after reduction is 67 mg/L for Canna indica plant and 72 mg/L for lemon grass, respectively, which is well within the CPCB-permissible limit.

Variations in BOD_5 at different feed concentrations (or influent concentrations) significantly

Table 3. Variation in BOD_5 at different feed concentrations

Variation in BOD_5 at different feed concentrations					
BOD_5 influent in mg/L	COD in mg/L	BOD_5 Effluent in mg/L		Removal efficiency of BOD_5 in %	
		Lemon grass in mg/L	Canna indica in mg/L	Lemon grass	Canna indica
89	200	32	24	64%	73%
160	500	72	67	55%	58%
272	750	152	125	44%	54%

Table 4. COD reduction in CW by varying HRT

COD reduction in constructed wetlands					
Conc (mg/L)	HRT (in days)	Canna indica in mg/L	Lemon Grass in mg/L	Removal Efficiency in %age	
200	15	55	60	72.5%	70%
200	12	47	55	76.50%	72.5%
200	9	38	65	81%	67.5%
200	6	34	55	83%	72.5%
200	3	32	50	84%	75%
200	1	27	40	86.5%	80%

impacts the efficiency and performance of the system. The influent concentrations represent the initial levels of pollutants entering the wetland system. It utilizes plants that aid in the treatment process by providing surface area for beneficial microorganisms to grow and aiding in oxygen transfer. High BOD_5 concentrations might affect the health and growth of these plants due to oxygen depletion or excessive pollutant loads. Variations in BOD_5 at different concentrations challenge the designed capacity of the wetland system. The system might function well within a certain range of BOD_5, but if the concentration exceeds this range, it might lead to reduced treatment efficiency and potential system failure.

Optimum HRT for Constructed Wetland Systems – HRT i.e hydraulic retention time is Hydraulic Retention Time (HRT) is a critical parameter in the field of environmental engineering, specifically in the design and operation of various water treatment systems, such as wastewater treatment plants and bioreactors.

HRT refers to the average amount of time that a substance, typically water or wastewater, spends in a particular system or reactor. It's calculated by dividing the volume of liquid within the system by the flow rate of liquid entering or leaving the system.

The ideal HRT for constructed wetland systems was determined by feeding wastewater containing 200 mg/L of COD. While maintaining the COD concentration constant at 200 mg/L, the HRT was changed for 15 days, 12 days, 9 days, 6 days, 3 days, and 1 day. Both wetlands systems' outlets were used to collect samples, which were then examined for COD removal effectiveness. It is shown in the table 4 below.

In conclusion, varying the Hydraulic Retention Time (HRT) in pilot constructed wetlands directly impacts the system's ability to treat and reduce COD levels in the influent water. It influences treatment efficiency, pollutant removal, oxygen demand, and the overall capacity of the wetland system. Optimizing the HRT based on the specific characteristics of the wetland and the influent water quality is crucial to ensure effective pollutant removal and efficient operation of the system.

COD Removal- The feed concentration was altered while maintaining the 4 days of HRT as a constant. A 200 mg/L COD increase was made to the feed concentration. Every COD loading

Table 5. COD variation at different feed concentrations

Variation in COD at different feed concentrations					
COD in mg/L	COD Influent in mg/L	COD Effluent in mg/L		Removal efficiency of COD in %	
		Canna indica in mg/L	Lemon Grass in mg/L	Canna indica	Lemon Grass
200	200	50	60	75%	70%
500	500	150	170	70%	66%
750	750	260	280	65%	62%

rate of 200 mg/L, 500 mg/L, and 750 mg/L resulted in the COD elimination in Lemon Grass and Canna indica bed being observed. The table 5 below provides the COD removal in both wetlands (Haydar S et al., 2020).

Variations in COD at different feed concentrations can significantly affect the pilot constructed wetlands by impacting treatment efficiency, oxygen demand, microbial activity, plant health, and overall system performance. Managing these variations and ensuring that the wetland is designed to handle fluctuations in pollutant loads is crucial for the efficient operation and success of the treatment system.

CONCLUSIONS

Most wastewater parameters are above the allowable discharge limits, according to the evaluation findings. Therefore, treatment is required prior to wastewater disposal. The optimum Hydraulic Retention time (HRT) for both the constructed wetlands units was found to be 15days. The pH range of effluent was observed between 6.9 to 8.4 and the temperature between 29^{o}-33^{o}C respectively. At 200 mg/L COD loading, the maximal COD removal for Lemon Grass and Canna Indica beds was 75% and 70%, respectively. Further increases in loading rate reduce the efficiency. At feed concentrations of 200 mg/L COD, the highest BOD_5 elimination in lemon grass and canna indica beds was determined to be 73% and 64%, respectively. The wetland as a whole consisting of two plants proved more efficient in treating campus wastewater compared to the wetland consisting of a single plant. The performance of constructed wetland pilots is intricately linked to the various parameters and variables within the system. Changes in these variables can directly affect treatment efficiency, microbial activity, oxygen demand, plant health, and the overall capacity of the system, potentially leading to variations in the system's performance and its ability to treat and remove pollutants effectively. Therefore, understanding these relationships is essential for optimizing and maintaining the efficiency of constructed wetland systems. It can be concluded briefly that:

- The presence of plants significantly improved the efficiency of the treatment process, especially in reducing BOD_5 and COD levels. It showcases the importance of vegetation in enhancing pollutant removal efficiency.
- Lowering the HRT positively influenced the removal of pollutants. Shorter HRT durations resulted in higher efficiency, indicating the potential for quicker treatment within the system.
- Despite varying influent concentrations, the constructed wetlands, coupled with plant presence, were effective in reducing pollutant levels, showcasing the system's resilience in managing different loads.

Overall, the presence of vegetation, optimal HRT, and the resilience of the system against variable pollutant concentrations significantly contributed to effective pollutant removal, thereby demonstrating the potential for constructed wetlands as efficient wastewater treatment systems.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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