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COMPARATIVE STUDY OF PILOT-SCALE SOIL BASE HORIZONTAL SUBSURFACE FLOW CONSTRUCTED WETLAND UNDER DIFFERENT OPERATIONAL CONDITIONS FOR WASTEWATER TREATMENT

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ABSTRACT

The effectiveness of a horizontal subsurface flow constructed wetland (HSFCW) for treating domestic wastewater (DWW) effluent was investigated over a six-month period under a variety of operational conditions, including vegetation (planted or unplanted "*canna indica* and *Typha letifolia*," media type (various types of soil, sand, and aggregate), and mode of wastewater feeding (continuous and submerged). All contaminants, with the exception of phosphorus, were significantly affected by plants ($P< 0.05$) in terms of removal effectiveness and mass removal rate. The average maximum removal efficiencies for total suspended solids (TSS), biological oxygen demand (BOD_5), chemical oxygen demand (COD), soluble reactive phosphorus (SRP), and total Kjeldahl nitrogen (TKN) were 96.1%, 75.4%, 59.0%, 64.7%, and 49.4%, respectively, for planted beds versus 89.1%, 69.2%, 55.9%, 65.2%, and 42.4%, respectively, for unplanted beds under both conditions. On the removal efficiency of COD and BOD_5, neither the media type nor the feeding mode system had a significant impact. When compared to gravel, soil media considerably ($P <0.05$) improved the wetland's ability to remove SRP, especially in the planted beds. Comparing the continuous mode (HRT 0.5 days) to the submerged mode (HRT 02 days), the continuous mode was more efficient at removing SRP.

Keywords: Wastewater, Constructed wetland, Soil, Performance evaluation, Flow condition

INTRODUCTION

Freshwater shortages affect numerous nations across the world, including India (Baba Hamed, 2021; Remini et Amitouche, 2023). Based on a study conducted by the Central Pollution Control Board, India currently produces approximately 72,368 MLD of municipal wastewater nationwide, of which approximately 40,527 MLD is discharged directly into bodies of surface water (CPCB, 2021). Currently, rural communities lack access to regular, safe, and sufficient drinking water (Waikhom et al., 2015; Soro et al., 2020; Pandey et al., 2022). Due to inadequate finance and administration, there is a problem in India where there is a significant difference between municipal wastewater that has been treated and municipal wastewater that has not (CPCB, 2019; ENVIS n.d.). Water is a priceless gift from nature to humans, and by evaluating its physical, chemical, and biological properties, we can determine its quality (Achour et al., 2017; Tohouri et al, 2017; Chaudhari et al., 2021). Decentralized sewage treatment plants (STPs) are being replaced by CWs as a viable replacement for the simultaneous removal of organics and nutrients (Kulshreshtha et al., 2022). Aboulroos et al. (2010) found that constructed wetlands (CWs) can reduce the cost of treatment and the amount of work that needs to be done without lowering the level of pollution control. Small rural and urban communities without access to public wastewater systems can greatly benefit from CWs (Vymazal et al., 1998). A horizontal subsurface flow wetland system (HSFCW) has wastewater flowing through the rooting material (USPEA, 1988). It is possible to plant or leave the SSFCW unplanted. According to numerous studies, plants improve treatment effectiveness by oxygenating the system and creating an environment that is conducive to the growth of microbial communities (Taylor et al., 2010). As water moves through the wetland system, sediments and other pollutants, including emerging contaminants, might settle since wetland hydrology often involves slow flows with shallow waters or saturated substrates (Omondi and Navalia, 2020). The hydrology of a wetland depends on wastewater flow conditions. Subsurface flow-built wetlands (SSFCWs) have demonstrated the ability to consistently remove organic C and particle matter from wastewater, although N and P removal has been less successful (Mitchell and McNevin 2001). At influent and effluent discharges, design criteria have been based on concentration variations of a few factors, such as biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total nitrogen (TN), total phosphorus (TP), dissolved oxygen (DO), and total suspended solids (TSS). By selecting the right growing media, CWs can achieve a high level of filtration. Important variables in this regard include the growth medium's particle size, surface type, bulk porosity, and pore spaces (Amos and Younger, 2003). Formation media offer extra sites for biofilm growth and nutrient absorption in addition to providing physical support for plant growth and encouraging the filtering and sedimentation of contaminants (Priya and Brighu, 2013). A detailed literature review by Karungamye 2022 shows the potential of canna indica for heavy metals, organic matter, and nutrients. Laterite soil is the most commonly used media substrate in soil-based HSFCWs (Jethwa et al., 2020; Kadam et al., 2009; Madhukar et al., 2012). According to Suntud et al. (2006) and Bhagwat et al. (2018), CWs with media containing a soil and sand mixture have the highest contaminant removal efficiency.

Singh and Vaishya (2022) used a topsoil layer for a constructed wetland for municipal wastewater treatment. Submerged, continuous, and batch-feeding techniques can be used to operate CWs. The inconsistent treatment results for plant presence, media type, weather conditions, types of influents, and CW feeding mode point to the need for additional study to improve system performance. Canna indica and Typha latifolia have been used by most researchers in their studies (Calheiros et al., 2007; Jethwa et al., 2020; Rani et al., 2015; Taufikurahman et al., 2019). Often, the performance of wetlands is judged by how well the removal process works and how quickly pollutants are removed from wastewater. When making artificial wetlands, a first-order equation is used that says the concentrations of water coming in and going out will drop by an exponential amount if the amount of water coming in stays the same (Swarnakar et al., 2021). Two types of experiments are used to study the removal processes in soil-based CWs (SBCWs): continuous-flow conditions (CFCs) and submerged conditions (SCs) for DWW.

The authors of this study had the following objectives:

1. to compare the various operating conditions for wastewater treatment through the HSFCW.
2. Performance evaluation for the various types of soil media in the HSFCW
3. to compare planted and unplanted HSFCW for wastewater treatment.
4. to estimate the contributions of both plant species.
5. The removal efficiency in the HSFCW was compared using different types of fills.

The experiment was conducted in 14 HSFCWs.

MATERIAL AND METHODS

Description of the study site and source of wastewater

The pilot-scale CWs were set up at the National Institute of Technology Raipur (NITR), Chhattisgarh, India (21°15 ‘00' N and 81°36 '15' E). Raipur is the capital of Chhattisgarh. The city of Raipur is located in a region with a semiarid climate. Water is provided to NITR by a campus-based borewell. CWs were assembled with four different types of soil substrates and two types of plants. It was also assembled with two types of aggregate base substrates. The WW samples were collected manually from the inspection chamber before the septic tank in the campus staff house (Neelgiri apartment). The WW generated is from 24 families residing in apartments. An actual scale contains the following treatment steps: sample collection, settling tank, head loss tank, feeding, hydraulic retention time (HRT), effluent collection, and experiment in the laboratory.

Constructed wetland setup

Fourteen wetland units were fabricated with mild steel sheets (2 mm) and had effective volumes of 0.126 m^3 and dimensions of 1.0 x 0.35 x 0.35 m for length, width, and depth, respectively. The WW level was 5 cm below the surface of the growth medium, which was 0.30 m deep. The treated WW was collected from the bottom of the unit, and the raw WW influent was distributed horizontally from the top of the unit. SBCWs were made into three numbers in the same way. One for Canna indiaca, one for Typha latifolia, and one blank, while aggregate CWs are assigned to have two numbers for both plants. Fig. 1 shows the layout of the lab-scale constructed wetland.

Soil sampling and analysis

Chhattisgarh, India, is a land with diverse soils. There are four different types of main soil: 1. Entisol 2. Inceptisol 3. Alfisols 4. Vertisols were collected from different locations. For aggregate-based CWs, four types of aggregates—40 mm, 20 mm, 10 mm, and 6 mm—were collected from local quarries. The sand was collected from a local river.

Types of plant species used

It is important to choose a plant with a large root zone and the ability to grow in wet areas under local hydrological conditions. To conduct this study, beds were planted with Canna indica and Typha latifolia. In the summer of 2021, canna indica species were taken from the NIT Raipur campus, and Typha latifolia was taken from a nearby pond. In this experiment, two plants of each species were placed in each type of wetland and run simultaneously as a control unit to monitor the behavior of the plant in the treatment system. The control unit was designated as the one lacking a plant. Before being placed in the substrate, plant roots and leaves were meticulously cleansed with tap water and allowed to gradually accumulate in WW. Due to the abundance of sunshine needed for plant growth, the experimental setup was placed in a covered area with plenty of natural light within the old roof of the building.

Investigation start-up and operation system

WW from the NIT, Raipur, was used for this study. WW, such as kitchen waste and urinal effluent from toilets, was included in this mix of shower, basin, and laundry water. A homogenous sample was used for investigation. The WW was manually poured into 50-liter barrels and moved to the location of the experimental setup by hand cart.

During the first 60 days of the experiment, tap water was used to clean and start up the equipment. The experimental configuration was run using batch feeding. Several researchers have found that plants can filter and absorb nutrients from wastewater with a hydraulic retention time (HRT) of two days in batch mode. Accordingly, 50 L of wastewater was utilized in each segment of the batch mode, and after two days of retention time, the hydraulic loading rate (HLR) for the setup was 0.014–0.028 m^3/day/m^2. Sample effluents underwent various tests, and the effectiveness of every system was examined. Samples were promptly examined on the same day. For each parameter, triplicate tests were run, and the average reading was supplied for analysis.

Table 1: Abbreviations for planted or unplanted constructed wetlands with different soils

Abbreviation	**CWeu**	**CWec**	**CWet**	**CWiu**	**CWic**	**CWit**	**CWagc**
Name of Plant	Unplanted	Canna Indica	Typha Latifolia	Unplanted	Canna Indica	Typha Latifolia	Canna Indica
Substrates	Entisols	Entisols	Entisols	Inceptisols	Inceptisols	Inceptisols	Aggregates with sand cover
Abbreviation	CWau	CWac	CWat	CWvu	CWvc	CWvt	CWagt
Name of Plant	Unplanted	Canna Indica	Typha Latifolia	Unplanted	Canna Indica	Typha Latifolia	Typha Latifolia
Substrates	Alfisols	Alfisols	Alfisols	Vertisols	Vertisols	Vertisols	Aggregates with sand cover

Table 2: The characteristics of influence and the methods used in this study (average value standard deviation, n = 20)

S. No.	Parameters	Units	Value	Method	References
1	pH @ 27°C	pH units	7.7±0.2	Potentiometric	APHA
2	Total suspended solids (TSS)	mg/L	68 ± 11	Gravimetric method	APHA
3	Dissolved Oxygen (DO)	mg/L	2.1 ± 0.5	Titrimetric	APHA
4	Total Kjheldal Nitrogen (TKN)	mg/L	17.5±3.6	Macro-Kjeldahl method	APHA
5	Biological Oxygen Demand (BOD_5)	mg/L	109±30.0	5 days incubation at 20 °C	APHA
6	Chemical Oxygen Demand (COD)	mg/L	276 ± 3.0	Close reflux	APHA
7	Soluble Reactive Phosphorus (SRP)	mg/L as PO_4^{2-}	14.1 ± 5.0	UV spectrophotometer	APHA

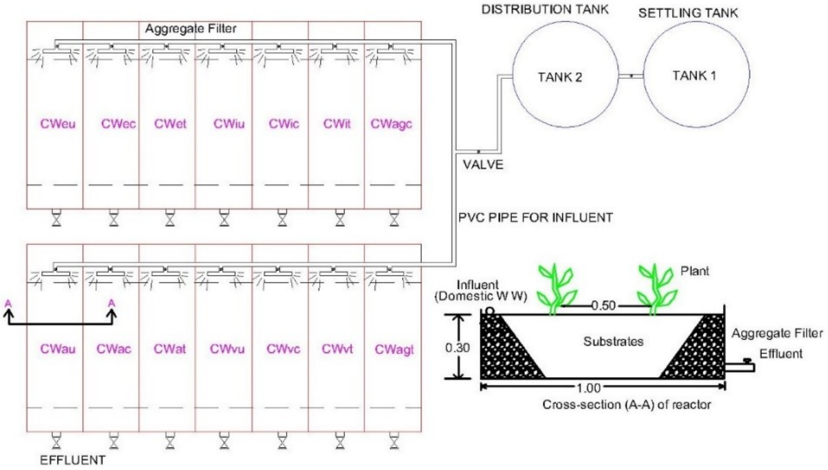

Figure 1: Lab-scale experimental setup of the soil-base horizontal subsurface flow constructed wetland

RESULTS AND DISCUSSION

BOD5, COD, and TSS removal

Figs. 2 and 3 show how much COD and BOD_5 are in the influents and how much is in the effluents from a pilot-scale soil-based HSFCW with and without plants. As per the influent physicochemical parameter, the wastewater was weak to medium in strength (Qteishat et al., 2011). According to Fig. 2, the wetlands were able to significantly reduce the COD levels in the raw wastewater influent. The operational parameters of the wetland affected how much the pollutant concentration decreased after treatment. For all studied conditions, the planted beds generally produced lower concentrations of COD, BOD_5, and TSS in the effluent compared to the unplanted beds. The maximum concentrations of TSS, BOD_5, and COD in the effluent treated by unplanted beds ranged from 85.5%. Throughout the course of the experiment, the average concentrations of each pollutant in the influent wastewater and the final effluent were calculated. The removal efficiency was determined to assess how varied operational conditions affected the wetland's performance, and the results are shown in Tables 1 and 2 for both flowing conditions. BOD_5 is typically measured between 100 and 400 mg/L for raw sewage and 200-700 mg/L for COD (Choksi et al., 2015a). As the percent removal and mass removal rates of COD were less than half and one-third of those removed by the planted beds, respectively, the unplanted beds were much less efficient at removing COD than the planted beds. The media impact on COD removal varied depending on vegetation conditions. While both aggregate and soil media in the planted beds were similarly successful at removing organic impurities, the soil was more effective than aggregate media in the unplanted beds.

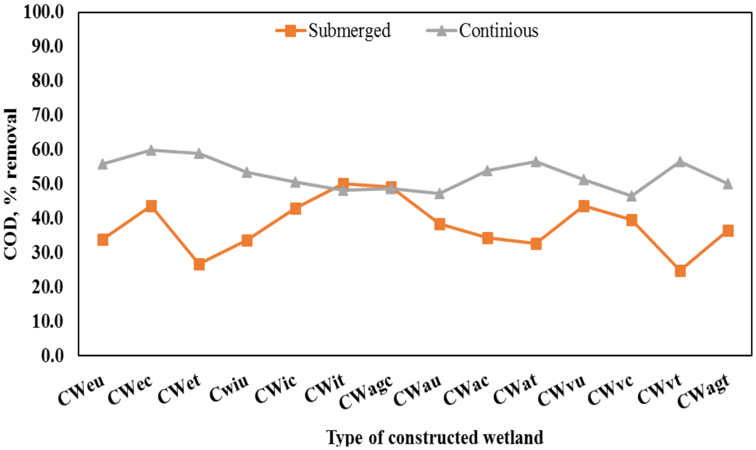

Figure 2: COD Removal Efficiency of Various SBCWs for DWW Treatment under Various Flow Conditions

In all of the operational conditions that were examined, Table 2 shows that BOD_5 was slightly better at removing COD than COD was. The average proportion of BOD_5 removed by the planted beds was 84%, compared to just 36% for the unplanted beds, indicating that vegetation plays a major and important ($P < 0.05$) role in BOD_5 removal. The prior finding from Fig. 3 that the BOD_5 level in the effluent from the planted beds was comparable to or lower than that advised by the guidelines may be explained by this disparity.

Under either vegetation conditions or the type of media utilized, that media type had no discernible impact on the elimination of BOD_5. Under all conditions of vegetation or media type, the feeding mechanism had no discernible impact on BOD_5 elimination. Batch feeding, as opposed to continuous flow feeding, generally encourages more oxidized conditions and, hence, better performance for the removal of organic pollutants (Cooper et al., 1997; Vymazal, 2010). The type of manmade wetland employed may be the reason for the study's findings that the feeding mode had no impact on the removal of organic pollutants. It is probable that the batch method of feeding, especially under the low HRT used in this work, did not further improve the existing redox conditions under HSFCS. The efficiency of BOD_5 removal is higher in the CFC than in the SC. The COD removal efficiency is higher in CWeu, CWiu, CWac, CWat, CWvu, and CWvt than in CFC. In both aggregate-based CWs, the COD removal efficiency was higher in SC.

The solid components of sewage can be divided into dissolved, suspended, and total suspended solids (Choksi et al., 2015b). Compared to the continuous feeding mode, the SC mode made it possible for more solids to get stuck in the pores of the media, which led to higher TSS removal efficiency values. Physical methods such as sedimentation and filtration were largely used to remove suspended particles. The vast root systems of Canna indica and Typha latifolia that were produced in wetland cells in the current study improved the TSS removal efficiency by increasing the surface area, lowering the water velocity, and bolstering settling and filtering in the root network.

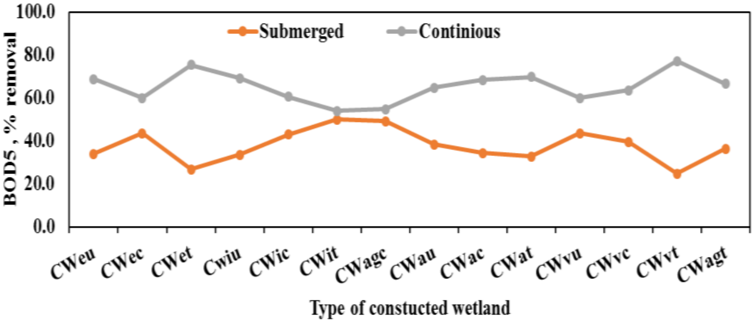

Figure 3: BOD Removal Efficiency of Various SBCWs for DWW Treatment under Various Flow Conditions

Nutrient removal

According to Table 3 (Appendix), the removal of SRP from the influent was higher in CWiu (65.2%) and almost the same in all types of CW for a continuous flow condition. The removal efficiency of TKN in submerged conditions was found to be at a maximum of 49.4% in CWec. The removal efficiency is lower in submerged conditions than in continuous conditions. The removal efficiency for the continuous flow condition is maximum TKN removal in CWet and minimum TKN removal in CWau. Typha latifolia has the highest aggregate base CW in continuous flow conditions when compared to canna indica. The treatment efficiency of TKN is better in entisol soil for continuous conditions, and an intisole soil base CW gives good results in submerged conditions. In Fig. 4, the graph shows the variation in TKN removal efficiency. The removal efficiency of TKN in both conditions increased in the following order: planted beds (64.2% for SC), unplanted beds (42.4% for CFC), and aggregate media (53.7% for CFC).

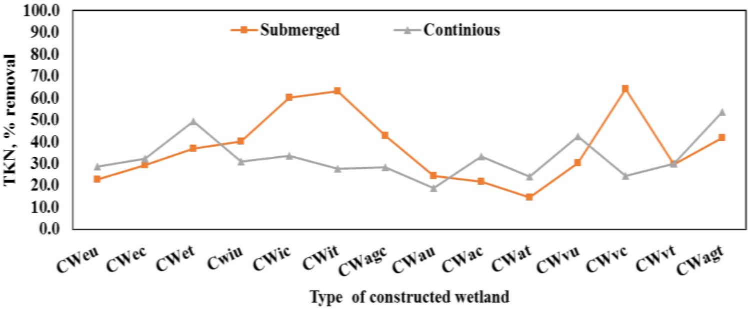

Figure 4: TKN Removal Efficiency of Various SBCWs for DWW Treatment under Various Flow Conditions

The difference between the rates at which TKN is formed by organic N mineralization and removed by nitrification results in the concentration of TKN in the effluent. It is possible that plants taking in TKN and a higher rate of nitrification in planted areas can explain why TKN is removed at a higher rate than in unplanted areas. Tables 2 and 3 show that the concentrations of TKN in the unplanted bed decreased, but in the effluent of the planted beds, they increased by 42.4% compared to the concentrations in the influent. This finding shows that plants do not do much to remove TKN compared to nitrification, which is thought to be the main way TKN is removed. The kind of media and feeding method used in planted beds had a significant impact on the elimination of TKN (up to a maximum of 64.2%), according to statistical analysis ($P < 0.05$). The bulk removal rate of TKN was typically relatively low (minimum of 14.5% in SC). The main challenge in many treatment wetlands for increasing nitrogen removal is the differing oxygen requirements for nitrification and denitrification. The feeding mode system or the vegetation conditions had little impact on how well wastewater was removed. Despite the fact that, when compared to the literature, the removal effectiveness of TKN in this investigation is shown to be quite poor, Prochaskan et al. (2007) found a lower nitrogen reduction removal rate of 11% for TKN in municipal wastewater. A similar result was reported by Nema et al. (2020).

Under continuous flow conditions, the SRP removal efficiency rate was above 60% in all types of CWs. Under SC conditions, the SRP removal efficiency is very low compared to that of CFC. Not only planted, unplanted, and aggregate-based CWs have good SRP removal in continuous flow conditions. The maximum removal efficiency of SRP in CWes is 64.7% in CFC, and for SC, it is 45%. In submerged flow conditions, Zachritz et al. (2008) reported a very low SRP removal efficiency (3.0% in submerged surface flow CWs).

The removal of much more SRP (above 60.0%) by the soil media and aggregates (max. 64.0%), however, was significant ($P < 0.05$), which may be related to P adsorption on soil surfaces. Unless particular substrates with high sorption capacities were chosen, P removal in all types of built wetlands was reported by Vymazal to be minimal.

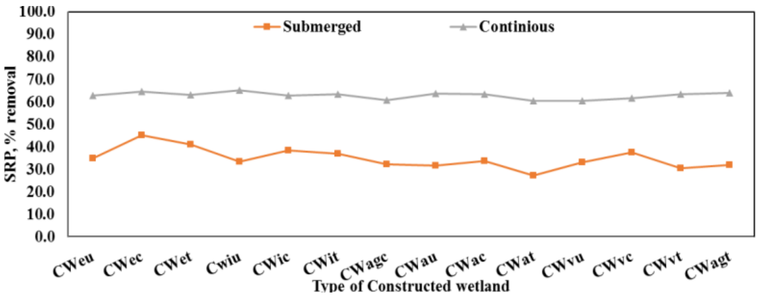

Figure 5: SRP Removal Efficiency of Various SBCWs for DWW Treatment under Various Flow Conditions.

In comparison to the aggregate, the CWec had an SRP removal effectiveness that was higher (Tables 3 and 4). The SRP average mass removal rate is a sign of the CW's ineffectiveness at removing nutrients from CFC. However, the low removal rate of SRP in this scenario is advantageous, similar to TKN, as nutrients will be available for plants watered with treated wastewater (Abdelhakeem et al., 2016). This is because the goal is to reuse the water for agricultural purposes. For phosphorus consumption, phosphorus removal involves two stages: (i) phosphorus adsorption from algal or plant surfaces and (ii) surface-adsorbed phosphate transfer inside soil media (EPA). In the current trials, the removal efficiency of SRP ranged from 27.2% to 64.7% in both conditions; this is primarily due to the soil medium, algae, and plant bodies' ability to absorb nutrients.

Table 3: Removal (%) for wastewater treated through planted and unplanted CW in continuous flow conditions

Parameter (in mg/L, unless specified)	CWeu	CWec	CWet	CWiu	CWic	CWit	CWagc
pH	7.3	7.2	7.4	7.4	7.4	7.4	7.2
TSS	82.3	93.6	96.1	84.5	93.6	94.4	90.2
DO (% increase)	167.6	123.8	115.2	141.9	172.3	165.7	110.4
BOD_5	68.8	60.0	75.4	69.2	60.6	54.1	54.9
COD	55.9	60.0	59.0	53.5	50.6	48.1	48.7
SRP	62.8	64.7	63.0	65.2	62.8	63.4	60.7
TKN	28.8	32.3	49.4	30.8	33.7	27.7	28.2
Parameter (in mg/L, unless specified)	**CWau**	**CWac**	**CWat**	**CWvu**	**CWvc**	**CWvt**	**CWagt**
pH	7.4	7.3	7.5	7.6	7.2	7.2	7.2
TSS	81.4	93.2	92.1	84.4	92.1	93.3	91.5
DO (% increase)	169.5	134.2	133.3	166.6	148.5	92.3	109.5
BOD_5	64.8	68.4	69.9	60.0	63.7	77.2	66.6
COD	47.2	53.9	56.7	51.3	46.5	56.5	50.1
SRP	63.7	63.4	60.6	60.6	61.6	63.3	64.0
TKN	18.6	33.1	24.2	42.4	24.4	29.8	53.7

Table 4: Removal (%) for wastewater treated through planted and unplanted CW in submerged conditions

Parameter (in mg/L, unless specified)	CWeu	CWec	CWet	CWiu	CWic	CWit	CWagc
pH	7.0	6.8	7.2	7.1	7.1	7.1	6.9
TSS	84.3	94.2	95.8	85.3	94.5	95.4	91.2
DO (% increase)	135.4	112.5	139.6	164.6	124.0	179.2	116.7
BOD_5	29.6	43.2	40.1	22.3	30.3	30.3	29.3
COD	42.7	61.4	64.3	48.6	60.5	59.7	66.9
SRP	34.9	45.1	41.2	33.3	38.3	37.1	32.2
TKN	22.8	29.3	36.9	40.3	60.3	63.3	42.9

Parameter (in mg/L, unless specified)	**CWau**	**CWac**	**CWat**	**CWvu**	**CWvc**	**CWvt**	**CWagt**
pH	7.1	7.1	7.1	7.1	7.1	7.1	6.9
TSS	88.1	94.4	93.8	89.1	94.7	94.9	93.4
DO (% increase)	159.4	144.8	109.4	156.3	124.0	137.5	142.7
BOD_5	13.8	23.0	18.3	11.0	28.6	29.6	25.6
COD	34.7	52.0	53.4	40.1	56.5	52.9	56.0
SRP	31.7	33.7	27.2	33.2	37.5	30.4	32.1
TKN	24.4	21.9	14.5	30.2	64.2	29.5	41.7

Dissolved oxygen (DO)

Dissolved oxygen (DO) is a key physicochemical indicator that many aquatic organisms need to live (Atazadeh et al., 2020). There may be less oxygen exchange between the air and water in wetlands because the water in these lentic systems does not move very much. DWW had a consistently low DO. Because horizontal subsurface flow systems are deemed anoxic or anaerobic if they operate continuously, this lack of free oxygen can be used to explain why the DO at the CWU output is so low (Kadlec et al., 2000; Vymazal and Kropfelova, 2006). Additionally, microbial respiration and chemical oxidation will quickly deplete the oxygen present when the substrate is inundated (Kadlec et al, 2000). By diffusing into vegetated beds and releasing oxygen from the roots of macrophytes, the atmosphere provides the oxygen needed for aerobic decomposition (Kadlec et al., 2000; Vymazal, 2001; Stein and Hook, 2005; Vymazal and Kropfelova, 2006). According to Bendix et al. (1994), T. latifolia has an efficient internal gas transport system that is based on pressurized convection through the flow of gases.

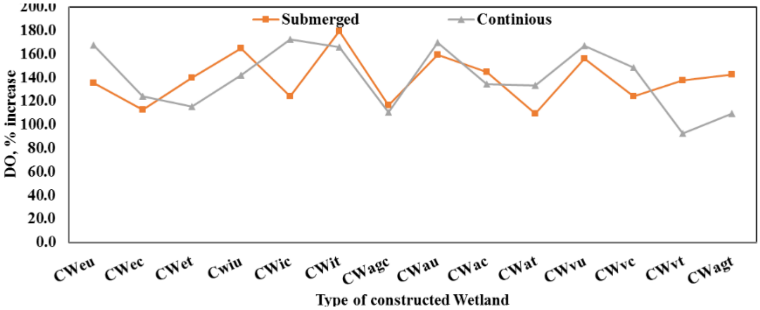

Figure 6: DO Level During the Experiments

In fluent water, dissolved oxygen was satisfactory at 139% on average. Under aerobic conditions, CWs with a high level of dissolved oxygen exhibit good microbial activity. There was no foul odor detected in the effluent. Soil- and aggregate-based CWs under both conditions increased the DO label. In Fig. 6, the graph shows the variation in DO in both conditions for wastewater treatment. A high level of DO is also beneficial to plant yield.

CONCLUSIONS

This study will help determine how well WW removes waste in ponds, lakes, rivers, and natural wetland areas based on local hydrology. The six-month study determined the removal efficiency of the plant, unplanted, and aggregate base CWs and their performance. The technology of CWs for the treatment of wastewater under both conditions is quite satisfactory for total suspended solids and DO prospects. The continuous flow condition is quite satisfactory for BOD_5 removal efficiency. For COD removal efficiency, both conditions are almost the same for planted, unplanted, and gravel-based CWs. The soil base CW had low efficiency in the removal of SRP and TKN under both conditions. Planting is an essential element for increasing the performance of CWs. The results indicate that the performance efficiencies of various SBCWs are high. Compared to unplanted CWs, planted CWs performed better for wastewater treatment. The interaction of the substrate, soil layers, aggregate, and vegetation affected the entire treatment procedure. Furthermore, the two locally accessible plants utilized in the lab-scale CW model, Canna Indica and Typha latifolia, showed quick growth and survival in the treatment wetland bed (even at a higher atmospheric temperature). The removal effectiveness of TSS, BOD, COD, TKN, and SRP was promising and steady during the treatment process, so it can be employed in small-scale applications and locations with few people. Locally available soil is the cheapest substitute for substrate materials for CW. In this study, the authors conclude that the CFC is a time-saving process for WW treatment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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