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Performance of horizontal flow constructed wetland for secondary treatment of domestic wastewater in a remote tribal area of Central India

Reetika Shukla[1,2], Deepak Gupta[1,2], Gurudatta Singh[1] and Virendra Kumar Mishra[1,2*]

Abstract

The purification of the primary treated domestic sewage was performed in the present study through the horizontal sub-surface flow constructed wetland (CW) of 10 × 3.5 m dimension. The study was performed using three setups of CW 1 (Unplanted CW), CW 2 (CW planted with macrophyte *Typha latifolia*), and CW 3 (CW planted with two species of macrophyte *T. latifolia* and *Commelina benghalensis*). The purification experiments were performed by converting one type of CW into the other form sequentially, i.e., CW 1 was built first and after the experiments, it was converted into CW 2 and then CW 3. The CW was filled with a layer of coarse and fine gravel of 70 cm depth as filter media in 1:2 ratio. Each set of wetland was operated for 3 months (12 wk) during which the treatment performance of wetlands for basic physicochemical parameters was evaluated. The CW was operated in continuous mode at an average hydraulic loading rate of 250 L h^{-1} and the treated effluent was analysed twice every week at four different sampling points having hydraulic retention times (HRT) of 12, 24, 36 and 48 h for important sewage quality parameters All the three setups of CW were able to clean the primary treated sewage significantly. Among the three sets of wetlands used, CW 3 was the best performer removing 79, 77, 79, 79, and 78% of biochemical oxygen demand, chemical oxygen demand, nitrate, ammonia, and phosphate respectively in 48 h HRT. Among the three sets of wetlands, the CW 3 removed the highest percent of total coliforms, fecal coliforms, and *E. coli* as 64, 61 and 52% respectively.

Keywords: Constructed wetland, Macrophytes, Hydraulic retention times, Domestic wastewater, *Typha*, *Comelina benghalensis*

Introduction

Water resources in India are facing a serious threat of contamination due to the continuous discharge of wastewater from various sources such as domestic wastewater, industrial effluent, and agricultural run-off, etc. [1]. Lack of proper wastewater treatment facilities with consequent disposal of untreated or partially treated wastewater in the aquatic ecosystems leads to the deterioration of the water quality in receiving water bodies [2]. According to one estimate, about 70% of the total water consumed ends in wastewater which is finally disposed-off in lakes, rivers, or freshwater, thus polluting the water resources [3]. Domestic wastewater in India is one of the most important sources contributing to the contamination of water resources [4]. According to the report published by the Indian central agency, Central Pollution Control Board (CPCB) of India, there is a huge difference between the amount of total wastewater generated, i.e., 61,754 MLD (10^6 L d^{-1} and the amount of total wastewater treated (2, 2963 MLD) in India [4].

* Correspondence: virendra78@gmail.com
[1]Institute of Environment and Sustainable Development, Banaras Hindu University, Varanasi 221005, India
[2]Department of Environmental Science, Indira Gandhi National Tribal University, Amarkantak 484887, India

Thus, the substantial amount of sewage (38,791 MLD) is discharged into a water body in an untreated manner. It is predicted that by 2051 urban and rural India will generate 120,000 and 50,000 MLD of sewage, respectively, with very little probability of complete treatment of all the generated wastewater [5]. Since there are no sewage treatment facilities in rural areas in India and under the existing scenario it will be economically unbearable to develop a sewage treatment facility for all the rural populations in the country. Hence, the generated sewage may be directly discharged in an untreated manner, consequently creating water pollution and at the same time, freshwater availability would be declining [4].

Constructed wetlands (CWs) are man-made, engineered, integrated systems based on principles of the natural wetland; designed for the treatment of various types of wastewaters like grey water, municipal wastewater, industrial wastewater, and agricultural runoff [6–8]. CWs have been adopted as an ecologically sustainable and economically viable solution for the treatment of wastewater [9]. Selection of CWs for wastewater treatment has several advantages, i.e., low-cost setup with longer life, less maintenance requirement, needs no electricity, effective pollutant removal, a self-sustaining system with scenic beauty. The main disadvantage of CWs is its large surface area requirement for its installations, but this can be very useful in rural areas where land availability is not an issue [10].

Horizontal sub-surface flow CW (HSSFCW) is one of the most preferred types of wetland and has been successfully used during the past few decades for the treatment of various types of pollutants from the wastewater [11]. The use of macrophytes in such wetlands makes the system more efficient in comparison to the unplanted wetland [12]. Overall, the performance and efficiency of CWs concerning pollutant removal from the wastewater are governed by its components like growth media, plant, microbes, and pattern of water flow in the wetland system [13]. Coleman et al. [9] reported gravel as an effective filter media for the wastewater treatment and treatment efficiency was better when wetland set up was planted. But later on, research conducted by Priya et al. [14] demonstrated sand as more effective media than gravel in removing pollutants from the wastewater. However, in some studies, the higher removal efficiency was achieved with media having a mixture of both soil and sand [15]. Different types of media such as biochar, zeolite, vermiculite, lime, etc. are also used in CWs for enhancing its performance [16, 17]. CWs can be used in planted or unplanted state and both have been found successful in treating wastewater [9]. In planted CWs different macrophytes such as *Cyperus papyrus, Canna, Commelina benghalensis, Eichhornia crassipes, Populus trichocarpa, Phragmites australis, Typha angustifolia, Hydrilla verticillata,* and *Salvinia natans* were used to treat the municipal wastewater in a vertical flow CW [18]. In a study conducted by Calheiros et al. [19] five different species of macrophytes, i.e., *Canna indica, Typha latifolia, P. australis, Stenotaphrum secundatum,* and *Iris pseudacorus* were used for the treatment of tannery wastewater through CW.

Several studies dealing with the application of CWs for the treatments of municipal wastewater and subsequent reuse of treated effluents have been performed in India [3]. Briefly, Rana and Maiti [20], performed the treatment of municipal wastewater through CW planted with *Colocasia esculenta* and *T. latifolia,* in a mesocosm study with findings able to remove several important parameters like chemical oxygen demand (COD), by 71%; total Kjeldahl nitrogen by 64–72% and some of the heavy metals. In another study, Bhagwat et al. [21] used *Typha aungstifolia* and *Acorus calamus* in CW to treat the landfill leachates. Sudarsan and Srihari [22] setup lab-scale CW with biochar for the treatment of tannery wastewater and achieved 60 to 70% removal efficiency for the removal of colour, chromium, biochemical oxygen demand (BOD), and COD.

Considering the advantages of CWs for the treatment of wastewater over the existing technologies, the wetlands can be a preferred technology for the same [4]. However, studies regarding the treatment of wastewater through CWs in the Indian context are still very limited. Most of the studies have been conducted on a lab-scale or at a mesocosm scale; therefore, more studies are required at field scale to establish CW technology as a sustainable approach for wastewater treatment in India [3]. Moreover, the presence of BOD, nutrients, and pathogens in the treated sewage restricts its reuse, which can be restored by the polishing of primary treated wastewater through CW. Due to lack of attention and other priorities, there have been very limited researches on sustainable and natural sewage treatment methods in India. Therefore, the present study was performed to treat the primary treated sewage through CWs to produce treated wastewater which can be reused safely in various sectors.

Materials and methods

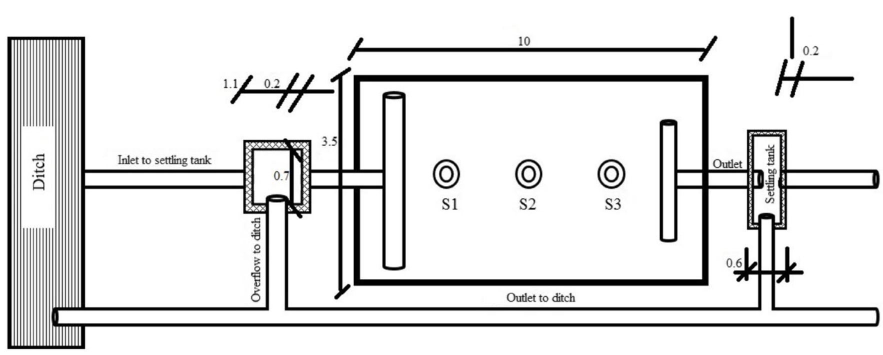
Experimental constructed wetland

The results of the present study are based on the findings of the operation of the CWs on the campus of Indira Gandhi National Tribal University (IGNTU), Amarkantak, MP, India [3]. The study site is located between 22°80′ N and 81°75′ E at an elevation of 1048 m in the central part of India. The climate of the region is characterized by an average annual rainfall of about 1235 mm and a normal annual mean maximum and minimum ambient temperature of 31.6 and 18.2 °C, respectively. To perform the treatment of primary treated sewage, a HSSFCW with the surface area of 35 m^2 (3.5 × 10 m) was filled with gravel media (Fig. 1), and a perforated PVC (polyvinylchloride) pipe was inserted vertically upward at a fixed interval for aeration and sample collection. To maintain a gravity flow, a slope of 1° was maintained from inlet to outlet of the wetland. The present study was conducted with three different settings of CWs. These settings were: (i). CW 1 (unplanted CW/gravel bed) (ii). CW 2 (CW planted with *T. latifolia* giving it 100% cover to grow) and (iii). CW 3 (CW planted with two different species of macrophyte, *T. latifolia* and *C. benghalensis*) in which both the species were given equal cover, i.e., 50% area of the wetland to grow. Each set of the wetland was operated for the 3 months, after this period the wetland was flushed and converted into next wetland set up by making appropriate changes. To begin with, CW 1 was built (Fig. 1) and filled with gravels of size 26 and 18 mm in the 1:2 ratio. The depth of gravel column in the CW was maintained up to 70 cm, while the water level within the CW during the operation was always maintained below the column of gravel bed, i.e., a sub-surface flow was always maintained. Perforated PVC interlocked pipes were used to feed the wetland and were inserted horizontally in the wetland from inlet to the rear end of the wetland. A second collection tank of approximately 1 m^3 was made to receive and store the treated water. The rear end of the wetland was connected with the collection tank through drainage pipe made up of PVC pipes of 10.2 cm diameter. Four sampling ports (S1, S2, S3, outlet) were made for the sampling of treated effluent at different hydraulic retention times (HRTs) (12, 24, 36, and 48 h).

Initially, just after the establishment, CW was optimized for various operational parameters such as hydraulic loading rate (HLR), HRT, till the wetland achieved a pseudo steady state. After the initial optimization period of 2 weeks the wetland was ready for further study and provided some promising results from preliminary study [3]. Further, the CW was investigated for the treatment of primary treated sewage through different settings. To achieve the further treatment, primary treated sewage from the sewage treatment plant (STP) of the IGNTU campus was passed through the experimental CWs in the continuous operation mode. A qualitative change in the different parameters of primary treated sewage at four different HRT, i.e., 12, 24, 36, and 48 h was observed for three different setups (CW1, CW2 and CW3).

Collection of wetland plants and its adaptability

Two macrophyte species namely *T. latifolia* and *C. benghalensis* were grown on CW to enhance the removal performance of wetland. Emerging plants of both the species were collected from the ponds located nearby village areas and within the university campus. After the collection, plants were washed properly for the removal of soil and debris attached to them, followed by this the macrophytes were planted in the gravel media, in a nursery established at IGNTU campus, after 1 month's adaptation period macrophytes were transferred to the experimental CW. About 14 plants were planted in area of CW and left for stabilization for about 1 month. During this period the plants were given intermittent irrigation with the pond water. When the macrophytes planted in the CWs were acclimatised to the wetland



S. No.	Sampling points	Distance, m	HRT, h
1	Inlet port (Inlet of CW)	0	0
2	Sampling port 1 (S1)	2.5	12
3	Sampling port 2 (S2)	5.0	24
4	Sampling port 3 (S3)	7.5	36
5	Outlet port (at the end of CW)	10	48

Fig. 1 Dimensions and sampling port for the experimental wetland

environment, experiments with regular monitoring were initiated.

Sampling and analysis of treated and untreated sewage

The primary treated sewage for the experiment was collected from the already existing 200 KLD moving bed biofilm reactor based STP on the IGNTU campus. The primary treated sewage was collected from the settling tank of the existing STP and stored in a 1 m^3 collection tank, just before the CW (Fig. 1). From the collection tank, the primary treated sewage was managed to feed the CW at an average HLR of 250 L h^{-1}. The primary treated sewage was analyzed with a frequency of two times a week for various physicochemical parameters listed in Table 1. Samples of primary treated sewage were collected in triplicates and analyzed according to the protocol prescribed in the Standard Methods [23]. All the reagents were prepared in the double-distilled water using AR grade chemicals. The wetland treated sewage samples were also collected twice per week at 12, 24, 36, and 48 h HRT from sampling points S1, S2, S3 and S4 (Fig. 1) and analyzed as per Standard Methods [23].

The physicochemical analysis of the influent and treated effluent collected from CW were conducted for temperature, pH, conductivity, acidity, alkalinity, total dissolved solids (TDS), phosphate, nitrate, BOD, and dissolved oxygen (DO). The analyses were conducted on the same day in the research laboratory of the Department of Environmental Science, IGNTU, Amarkantak. The basic parameters viz. temperature, pH, conductivity, and TDS were measured on-site using a calibrated digital pH meter of Hana (model 98,191). A five-day BOD was measured using the Winkler's azide modification method, nitrate (NO_3-N) was estimated by UV spectrophotometric method [24] using UV-Visible Spectrophotometers of Thermo Fisher (model evolution 201) and phosphate (PO_4^{3-}) was measured by using stannous chloride method.

Table 1 Average physico chemical quality of primary treated sewage used for the study

Parameter (in mg L^{-1} unless specified)	Primary treated sewage Mean ± standard deviation (minimum-maximum)
pH [no unit]	7.8–8.7
Temp [°C]	29.3 ± 1.1 (29.1–30.2)
Conductivity [μS cm^{-1}]	1133 ± 35 (1083–1193)
TDS	566 ± 17 (501–597)
Chloride	52 ± 0.59 (51–54)
BOD	370 ± 19 (358–387)
COD	473 ± 26 (453–498)
NO_3^{-}–N	43 ± 2.1 (32–45)
PO_4^{---}-P	13 ± 0.5 (12–15.9)
NH_4^+	42 ± 0.1 (34–40)
Total coliform [CFU 100 mL^{-1}]	3×10^6
Fecal coliform [CFU 100 mL^{-1}]	2×10^5
E. coli [CFU 100 mL^{-1}]	3×10^4

N = 24

Wetland removal efficiency

The removal efficiency of different CWs was calculated by the percent difference in values at 0 and 48 h denoted as the removal percentage (r %) for all the wetland settings and was calculated by using following equation (Eq. (1))

$$\text{Removal\%} = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad (1)$$

where, C_{in} = Concentration of a parameter in influent (at 0 h) and C_{out} = Concentration of parameter in effluent (at 48 h).

Results and discussion

Physicochemical characteristics of primary treated sewage

The primary treated domestic sewage was collected from the STP of IGNTU campus and that pH, temperature, conductivity, and TDS were analysed immediately after collection (Table 1). The pH values were ranged from 7.8 to 8.7. Conductivity values were ranged from 1083 to 1193 μS cm^{-1} in primary treated sewage, this high value indicates presences of highly dissolved inorganic matter. The amount of TDS and total suspended solids (TSS) varied from 501 to 597 mg L^{-1} and from 448 to 474 mg L^{-1} in primary treated sewage, respectively. Values of the DO, BOD, and COD were ranged from 1 to 2.1, 358 to 387, and 453 to 498 mg L^{-1} respectively in influent wastewater. The concentration of acidity, alkalinity, and hardness was ranged from 123 to 142, 93 to 106 mg L^{-1} $CaCO_3$, and 275 to 299 mg L^{-1} $CaCO_3$ respectively in primary treated sewage. Nutrients present in the primary treated sewage where NO_3-N, NH_4^+, and PO_4-P varied from 32 to 34, 34 to 40, and 12 to 13.3 mg L^{-1}, respectively.

Primary treated sewage also contained Total Coliform (TC), Fecal Coliform (FC) and *E. coli* were present in high quantity which was 3×10^6, 2×10^5, and 3×10^4 (CFU 100 mL^{-1}), respectively. The values of some important parameters of primary treated sewage collected from IGNTU STP are given in Table 1. Overall, the primary treated sewage was of medium to high strength as the influent to CWs [25].

The removal of pollutants by three different types of CWs (CW 1, CW 2 and CW 3) at different HRT (i.e., 0, 12, 24, 36, and 48 h) has been evaluated for this primary treated sewage. The average physicochemical properties of various pollutants at different stages of treatment in different CWs are given in Table 2.

Performance of the pilot unit to treat primary effluent under different setups

To perform the further treatment of primary treated sewage, it was allowed to flow into different CWs (CW 1, CW 2 and CW 3) with the HLR of 250 L h^{-1}. Substantial purification of primary treated sewage has resulted through three different types of CWs during different HRTs, and important results are given in coming section (Table 2).

During the experiment, the influent pH values in different wetland setups were ranged from 7.8 to 8.7; the result obtained from the experiment indicated that the pH suddenly decreased at 12 h HRT but there was a gradual increase in CW 1 and CW 3 wetland. In CW 2 pH value was consistent with increasing HRT. The influent conductivity values were ranged from 1083 to 1193 μS cm^{-1}, it was reduced to 490, 422, and 268 μS cm^{-1} respectively at 48 h HRT in three different wetlands (CW 1, CW 2 and CW 3). The reduction in conductivity followed the order of CW 3 > CW 2 > CW 1 with 76 > 63 > 56% removal efficiency, respectively (Fig. 2).

TDS values were ranged from 501 to 597 mg L^{-1} in CW influent it was treated through three different setups of wetland, i.e., CW 1, CW 2 and CW 3 and was reduced to 260, 269, and 270 mg L^{-1}, respectively at HRT 48 h. A maximum reduction in TDS was noted by CW 3 with a 54% removal efficiency (Fig. 2). Similarly, TSS values were ranged from 448 to 474 mg L^{-1} in influent and after the wetland treatment with three different settings it was reduced to 221, 310, and 322 mg L^{-1}, respectively at HRT 48 h. The maximum removal efficiency for TSS was shown by CW 3 at 53% (Fig. 2). TSS removal is generally credited to sedimentation and its interaction with microbes for its assimilation, filtration achieved by the media and retention time [26, 27]. The variations in TDS and TSS of wastewater through different setups and at different HRTs are shown in Fig. 3a.

During the present study, the DO values were ranged from 1.0 to 2.1 mg L^{-1} in influent wastewater, and it was found to be in increasing order in all the CWs with respect to a change in HRT. This could be because of aeration pipes that were installed at a fixed interval, tends to aerate the system, and supply oxygen from the atmosphere which facilitates the oxidation process within the wetland system. In the planted wetland, the effect of the root zone might have enhanced the concentration of DO [28]. BOD values were ranged from 358 to 387 mg L^{-1} in influent, whereas after 48 h HRT the BOD was reduced to 77 mg L^{-1} in CW 3, 147 mg L^{-1} in CW 2, and 153 mg L^{-1} in CW 1, with maximum BOD removal of 79% (Fig. 2) done by CW 3. Similarly, the COD values were ranged from 453 to 498 mg L^{-1} in influent wastewater, after 48 h HRT it was reduced to 223 mg L^{-1} in CW 1, 202 mg L^{-1} in CW 2, and 109 mg L^{-1} in CW 3, maximum COD removal with 78% was achieved in CW 3.

Removal of BOD and COD through CW was poor at lower HRTs, i.e., 12 or 24 h but it steadily increased with increasing HRT [29] (Fig. 3b). Nitrate values were ranged from 32 to 45 mg N L^{-1} in influent; after 48 h HRT it was reduced to 17, 16 and 7 mg N L^{-1} in CW 1, CW 2 and CW 3, respectively, with the maximum removal of 79% in CW 3 (Fig. 3c) which made the treated effluent almost comparable to secondary treated wastewater [3].

Table 2 Removal of physicochemical and biological parameters of primary treated sewage through constructed wetlands (CW 1, CW 2 and CW 3)

Parameters (in mg L^{-1} unless specified)	CW 1			CW 2			CW 3		
	0 h (influent)	48 h (effluent)	Removal (%)	0 h Influent)	48 h (effluent)	Removal (%)	0 h (influent)	48 h (effluent)	Removal (%)
TDS	547	270	50	566	268	52	565	260	54
TSS	458	321	30	460	309	32	467	220	53
BOD	376	152	59	375	147	61	368	76	79
COD	473	223	53	483	202	58	486	109	77
NO3--N	35.2	16.8	52.3	43.4	15.6	64.	33.0	6	79.3
NH_4^+	36.5	17.7	51.5	38.6	15.3	60.3	36.5	7.5	79.4
PO_4^{---}	15.8	5.6	64	12	4	61	13	2.9	78
Total coliform (CFU 100 mL^{-1})	3×10^6	1.8×10^6	39	2.9×10^6	1.7×10^6	41	3.1×10^6	1.1×10^6	64
Fecal coliform (CFU 100 mL^{-1})	2×10^5	1.4×10^5	30	1.8×10^5	0.9×10^5	50	1.6×10^5	0.6×10^5	61
E. coli (CFU 100 mL^{-1})	3×10^4	1.95×10^4	35	2.9×10^4	1.6×10^4	45	3.1×10^4	1.5×10^4	52

No. of samples (N) = 24

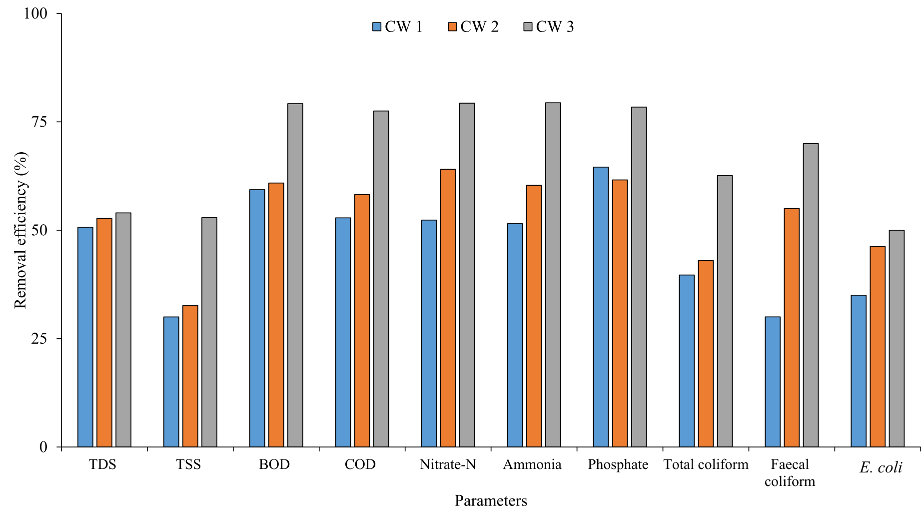


Fig. 2 Removal efficiency of various parameters of primary treated sewage through different setups of constructed wetland

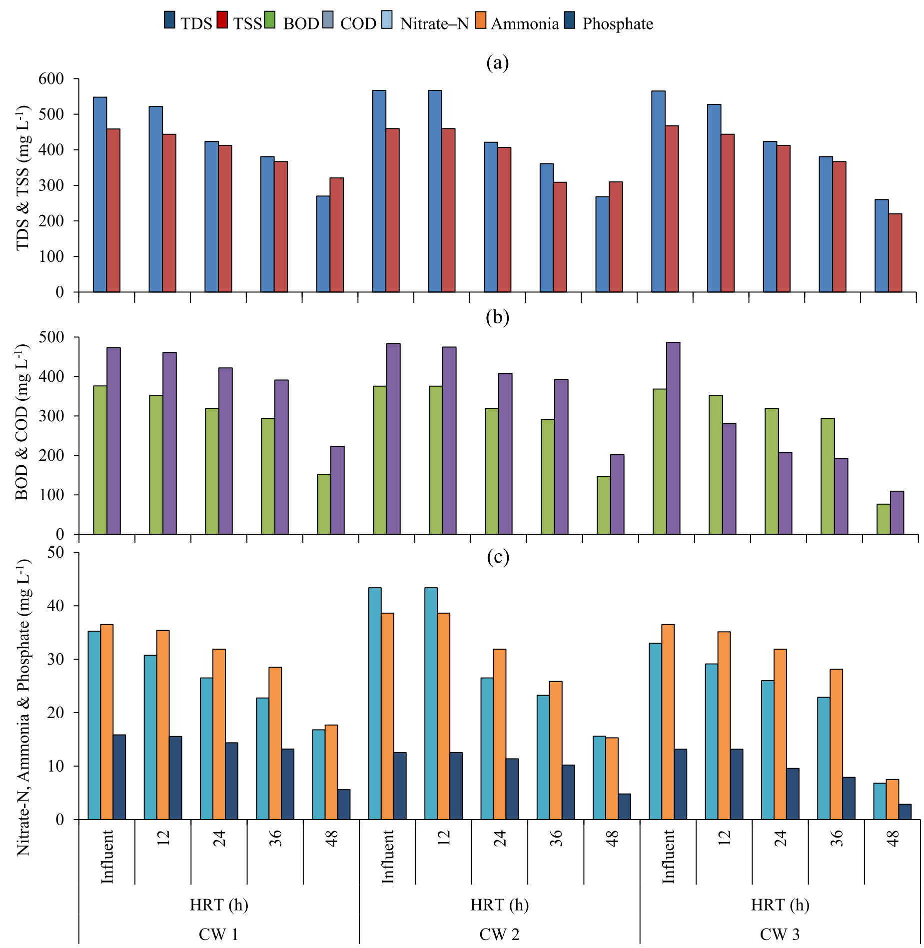


Fig. 3 Variation in physicochemical properties (TDS, TSS, BOD, COD, Nitrate-N, Ammonia, & Phosphate) of primary treated sewage through different set of constructed wetlands as a function of HRT

Microbial activity plays a vibrant role in CW to remove the nitrate through denitrification processes indulging in plant uptake and microbial catabolic action [30]. Ammonia, the other important parameter was ranged from 34 to 40 mg L^{-1} in influent and after 48 h HRT it was reduced to 18 mg L^{-1} in CW 1, 15 mg L^{-1} in CW 2, and 8 mg L^{-1} in CW 3, with a maximum of 80% by CW 3 (Fig. 3c). Phosphate values were ranged from 12 to 16 mg L^{-1} in influent and after 48 h HRT it was reduced to 5.6 mg L^{-1} in CW 1, 4.8 mg L^{-1} in CW 2, and 2.9 mg L^{-1} in CW 3, with maximum phosphate removal of 78% by CW 3 (Fig. 3). Paruch et al. [31] have reported phosphate removal from domestic wastewater up to 90% in HSSFCW. The gravel bed used in CW alone has the potential to remove about 20–30% phosphate concentration from wastewater [32]. The variations in the concentration of nitrate, ammonia, and phosphate of wastewater at different HRTs in different setups are shown in Fig. 3c.

Microbial treatment

The present study has demonstrated a substantial removal of TC, FC, and *E. coli* from primary treated sewage during 48 h HRT. Most probable number (MPN) of TC was reduced from 3×10^6 (CFU^{-1} 100 mL^{-1}), to 1.8×10^6 (CFU^{-1} 100 mL^{-1}) in CW 1, from 2.9×10^6 to 1.7×10^6 (CFU^{-1} 100 mL^{-1}) in CW 2 and from 3.1×10^6 to 1.1×10^6 (CFU^{-1} 100 mL^{-1}) in CW 3 as shown in Fig. 4; the removal efficiency of TC was achieved maximum by CW 3 (64% followed by CW 2 (41%) and then CW 1 (39%). FC initial concentration was found to be 2×10^5, 1.8×10^5, 1.55×10^5 (CFU/100 mL^{-1}) for influent (primary treated sewage at 0 h) entering in CW 1, CW 2 and CW 3 and when passed through CWs, it was reduced to 1.4×10^5; 0.9×10^5; and 0.6×10^5 (CFU^{-1} 100 mL^{-1}) respectively. Removal efficiency of different setups for FC removal were in the order of CW 3 (61%) > CW 2 (50%) > CW 1 (30%).

MPN of *E. coli* in influent was estimated to be 3×10^4, 2.9×10^4, and 3.1×10^4 (CFU 100 mL^{-1}) for CW 1, CW 2, CW 3 respectively and when it was passed through these three CWs its MPN was decreased to 2.0×10^4; 1.6×10^4 and 1.6×10^4 (CFU 100 mL^{-1}) respectively. Overall, the removal efficiency of *E. coli* was in the order of CW 3 (52%) > CW 2 (45%) > CW 1 (35%).

In CW 1 (unplanted system) microbial removal might be due to the natural die-off, sedimentation [33], mechanical filtration [34, 35], and bio-film treatment [36]; HRT also plays a role in the microbial reduction in the system [37]. In CW 2 and CW 3 (planted system) microbes were more efficiently removed than CW 1 (unplanted system). This might be achieved by the above processes and in addition to it, several processes such as oxidation, i.e., the release of oxygen from the rhizospheric zone of macrophytes in CW can be key driving factors [10]. Biocides, i.e., roots excretion by macrophytes and bactericidal excretion have the potential to destroy TC, FC, and pathogens [10, 37, 38] and variety of macrophytes [39] have played an important role in this. Overall, the result obtained from the experiments indicated that CW 3, i.e., wetland planted with *T. latifolia* and *C. benghalensis* has good removal efficiency to combat microbial population such as TC, FC and *E. coli* present in primary treated wastewater (Figs. 2 and 4).

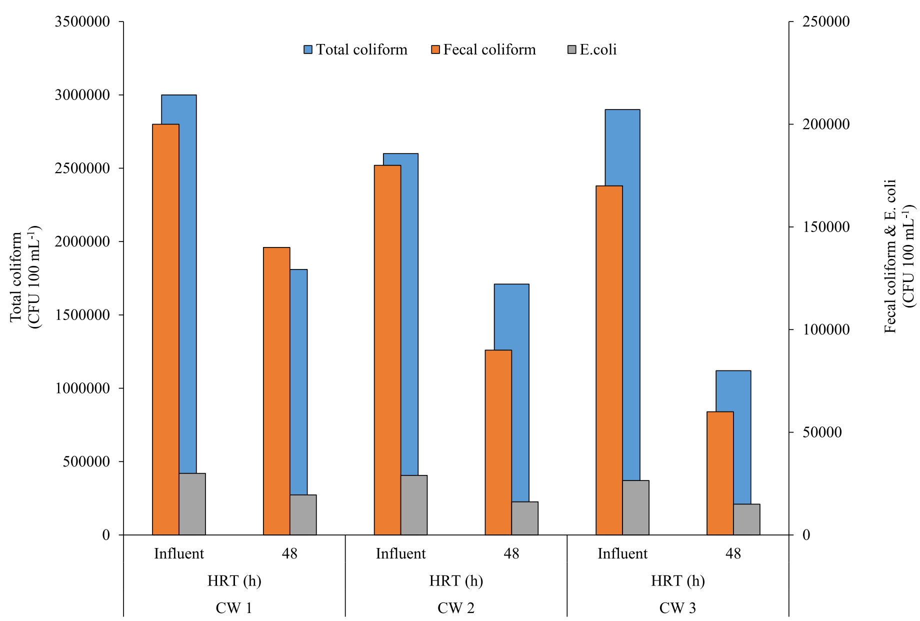


Fig. 4 Variation in coliform (Total, Fecal and *E. coli)* of primary treated sewage through the constructed wetland

General mechanisms involved in the wetland for the treatment of various contaminants

The results of experiments under the present investigation have shown a satisfactory treatment of various parameters by the CWs. The quality of the wetland treated effluent by CW 3 has fulfilled the established norms of secondary treated wastewater set by the CPCB [3]. The removal of these parameters was in line with some of the important studies conducted in other parts of the world [10, 17]. Treatment of various parameters of primary treated sewage such as BOD, COD, nitrogen, phosphate, and pathogens in a CW was facilitated by a combination of various natural processes including physical, chemical, and biological processes. Most of the organic matter contained in the wetland are stabilized by diverse microbial consortia [40–42]. The degree of treatment by CW depends upon the length of HRT, type of filter media, plant species used, and nature of microbial consortia. Longer retention time speeds up the treatment of contaminants, although, too-long retention times can have detrimental effects [43, 44]. Low water velocity coupled with gravel or sand media in HSSFCW promotes settling and adsorption of solid materials [45].

The principal physical mechanisms for the removal of TSS are sedimentation and interception. It is noteworthy that TSS production may occur in the wetland due to the death of microbes, fragmentation, detritus from plants, and formation of chemical precipitates [46]. Formation of biofilm over the filter media also supports the removal of TSS, as this biofilm adsorbs colloidal and soluble compounds where they may be metabolized and converted into soluble compounds [46, 47]. The HSSF CWs are highly efficient in removing organic loads such as BOD, COD, nitrogen (nitrate, ammonia), phosphate, and pathogens from the wastewater [48]. Organic contaminants in settleable forms are treated by deposition, filtration, microbial degradation (aerobic & anaerobic), and plant uptake. Microbial degradation is the predominant process in removing the BOD which is removed.

Mechanism for nitrogen removal

CWs have been proven successful in removing the nitrogen in an economical and ecologically sustainable way from municipal wastewater and industrial wastewater [46, 48]. Our results to remove nitrogen from primary treated sewage agreed with many of the studies [48]. The removal process of nitrogen from CW is regulated by various steps, i.e., volatilization, ammonification, nitrification/denitrification, and plant uptake [46, 48]. More than half of the nitrogen content of municipal wastewater is found to be in the form of ammonia and organic nitrogen. In wetlands, the main removal mechanism for nitrogen is essentially a microbial process, which consists of nitrification followed by denitrification. In wetlands, the nitrogen cycle is coupled with the carbon cycle, mainly through the denitrification process [42]. Organic nitrogen is converted to ammonia in the wetland by the process of decomposition and mineralization. Biological nitrification followed by denitrification is a major pathway for nitrogen removal in wetlands [42].

Mechanism for removal of phosphate

Phosphate is required for biological growth, but an excess of phosphate leads to eutrophication and other water quality problems in the ecosystem. Phosphate removal mechanisms in wetland include adsorption, filtration, precipitation, assimilation, and sedimentation [10, 36, 47]. The configuration of CW provides broad uptake of phosphate by biofilm, plant growth as well as by sedimentation and filtration of suspended materials. It is stored in the sediments, biota, and the water. The process of phosphate removal in CW depends upon redox chemistry, pH, and temperature of the wetland. At low oxygen concentration phosphate is liberated from the sediments and if the anaerobic condition is not reversed it leaves the wetland. Due to the limited contact opportunity between the wetland and phosphate, its removal in most of the CWs is not very efficient, however, our study removed almost 60% of phosphate by CW 3 which can be treated as an efficient performance. The use of sand increases the phosphate retention capacity for large systems due to the reduced hydraulic conductivity of sand compared to gravel [17, 24].

Conclusions

Horizontal sub-surface flow constructed wetland under present investigation treated strong strength primary treated sewage after HRT of 48 h. Three different setups of CWs (CW 1; CW 2; and CW 3) have achieved good removal efficiency for the removal of various physicochemical and biological parameters. Using gravel as a substrate, at different HRTs (12, 24, 36, and 48 h) it was effective in reducing almost all the physicochemical as well as some microbial parameters. The performance of planted CW was found better in comparison to the unplanted wetland and the removal of various parameters increased with increasing HRT (up to 48 h). The easy and economical operation of CW suggested that the HSSFCW can act as a better alternative in comparison to conventional wastewater treatment plants. During approximately 1 year of operation, the performance of the different CWs has continuously enhanced for the treatment of primary treated sewage. The quality of wetland treated effluent was within the permissible limits prescribed by a regulatory authority such as the CPCB of India [44]. This methodology can be an ideal solution to achieve the goal of complete sewage treatment in India.

Various factors such as easy availability of land, availability of wetland filter media (gravel and sand) in the local area, and availability large number of native macrophytes in the study area makes this technology an ideal option for the sewage treatment in such areas of India.

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Authors' contributions
The corresponding author VKM has conceptualized and designed the study, also supervised in manuscript writing, data interpretation the first author RS have performed fieldwork and lab work as well as for manuscript writing. The authors DG and GS have helped in lab work manuscript writing and analysis of data. The author(s) read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request. All data generated or analysed during this study are included in this published article [and its supplementary information files].

Declarations

Competing interests
The authors declare that they have no competing interests.

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References

1. Veldkamp TIE, Wada Y, Aerts JCJH, Ward PJ. Towards a global water scarcity risk assessment framework: incorporation of probability distributions and hydro-climatic variability. Environ Res Lett. 2016;11:024006.
2. Wilhite DA, Sivakumar MVK, Pulwarty R. Managing drought risk in a changing climate: the role of national drought policy. Weather Clim Extremes. 2014;3:4–13.
3. Mishra VK, Otter P, Shukla R, Goldmaier A, Alvarez JA, Khalil N, et al. Application of horizontal flow constructed wetland and solar driven disinfection technologies for wastewater treatment in India. Water Pract Technol. 2018;13:469–80.
4. CPCB. Inventorization of Sewage Treatment Plants. Delhi: Central Pollution Control Board; 2015.
5. Kamyotra JS, Bhardwaj RM. Municipal wastewater management in India. In: India infrastructure report 2011. Water: policy and performance for sustainable development. New Delhi: Oxford University Press; 2011. p. 299–311.
6. Poach ME, Hunt PG, Vanotti MB, Stone KC, Matheny TA, Johnson MH, et al. Improved nitrogen treatment by constructed wetlands receiving partially nitrified liquid swine manure. Ecol Eng. 2003;20:183–97.
7. Mello D, Carvalho KQ, Passig FH, Freire FB, Borges AC, Lima MX, et al. Nutrient and organic matter removal from low strength sewage treated with constructed wetlands. Environ Technol. 2019;40:11–8.
8. Laber J, Haberl R, Shrestha R. Two-stage constructed wetland for treating hospital wastewater in Nepal. Water Sci Technol. 1999;40:317–24.
9. Coleman J, Hench K, Garbutt K, Sexstone A, Bissonnette G, Skousen J. Treatment of domestic wastewater by three plant species in constructed wetlands. Water Air Soil Poll. 2001;128:283–95.
10. Kadlec RH, Wallace S. Treatment wetlands. 2nd Boca Raton: CRC Press; 2009.
11. Taylor CR, Hook PB, Stein OR, Zabinksi CA. Seasonal effects of 19 plant species on COD removal in subsurface treatment wetland microcosms. Ecol Eng. 2011;37:703–10.
12. Zhu DL, Sun C, Zhang HH, Wu ZL, Jia B, Zhang Y. Roles of vegetation, flow type and filled depth on livestock wastewater treatment through multi-level mineralized refuse-based constructed wetlands. Ecol Eng. 2012;39:7–15.
13. Rai UN, Tripathi RD, Singh NK, Upadhyay AK, Dwivedi S, Shukla MK, et al. Constructed wetland as an ecotechnological tool for pollution treatment for conservation of Ganga river. Bioresour Technol. 2013;148:535–41.
14. Priya, Sharma G, Brighu U. Comparison of different types of media for nutrient removal efficiency in vertical upflow constructed wetlands. Int J Env Eng Man. 2013;4:405–16.
15. Sirianuntapiboon S, Kongchum M, Jitmaikasem W. Effects of hydraulic retention time and media of constructed wetland for treatment of domestic wastewater. Afr J Agr Res. 2006;1:27–37.
16. Zhu LD, Li ZH, Ketola T. Biomass accumulations and nutrient uptake of plants cultivated on artificial floating beds in China's rural area. Ecol Eng. 2011;37:1460–6.
17. Brix H, Arias CA, del Bubba M. Media selection for sustainable phosphorus removal in subsurface flow constructed wetlands. Water Sci Technol. 2001; 44:47–54.
18. Kumar M, Singh R. Assessment of pollutant removal processes and kinetic modelling in vertical flow constructed wetlands at elevated pollutant loading. Environ Sci Pollut R. 2019;26:18421–33.
19. Calheiros CSC, Rangel AOSS, Castro PML. Constructed wetland systems vegetated with different plants applied to the treatment of tannery wastewater. Water Res. 2007;41:1790–8.
20. Rana V, Maiti SK. Municipal wastewater treatment potential and metal accumulation strategies of *Colocasia esculenta* (L.) Schott and *Typha latifolia* L. in a constructed wetland. Environ Monit Assess. 2018;190:328.
21. Bhagwat RV, Boralkar DB, Chavhan RD. Remediation capabilities of pilot-scale wetlands planted with *Typha aungstifolia* and *Acorus calamus* to treat landfill leachate. J Ecol Environ. 2018;42:23.
22. Sudarsan JS, Srihari V. Evaluation of adsorption capacity of biochar mixed substrate to treat tannery wastewater by constructed wetland. AIP Conf Proc. 2019;2112:020176.
23. APHA. Standard methods for the examination of water and wastewater. 22nd. Washington, DC: American Public Health Association; 2012.
24. Sotirakou E, Kladitis G, Diamantis N, Grigoropoulou H. Ammonia and phosphorus removal in municipal wastewater treatment plant with extended aeration. Global Nest J. 1999;1:47–53.
25. Burton FL, Stensel HD, Techobanoglous G. Wastewater engineering: treatment and resource recovery. 5th New York: McGraw-Hill Higher Education; 2014.
26. Manios T, Stentiford EI, Millner P. Removal of total suspended solids from wastewater in constructed horizontal flow subsurface wetlands. J Environ Sci Heal A. 2003;38:1073–85.
27. Wu SB, Austin D, Liu L, Dong RJ. Performance of integrated household constructed wetland for domestic wastewater treatment in rural areas. Ecol Eng. 2011;37:948–54.
28. Brix H, Schierup HH. Soil oxygenation in constructed reed beds: the role of macrophyte and soil-atmosphere interface oxygen transport. In: Cooper PF, Findlater BC, editors. Constructed wetlands in water pollution control. Oxford: Pergamon Press; 1990. p. 53–66.
29. Reed SC, Brown D. Subsurface flow wetlands – a performance evaluation. Water Environ Res. 1995;67:244–8.
30. Vymazal J. The use constructed wetlands with horizontal sub-surface flow for various types of wastewater. Ecol Eng. 2009;35:1–17.
31. Paruch AM, Mæhlum T, Haarstad K, Blankenberg AGB, Hensel G. Performance of constructed wetlands treating domestic wastewater in Norway over a quarter of a century – options for nutrient removal and recycling. In: Vymazal J, editor. Natural and constructed wetlands. Cham: Springer; 2016. p. 41–55.
32. Prochaska CA, Zouboulis AI. Removal of phosphates by pilot vertical-flow constructed wetlands using a mixture of sand and dolomite as substrate. Ecol Eng. 2006;26:293–303.
33. Green MB, Griffin P, Seabridge JK, Dhobie D. Removal of bacteria in subsurface flow wetlands. Water Sci Technol. 1997;35:109–16.
34. Stevik TK, Aa K, Ausland G, Hanssen JF. Retention and removal of pathogenic bacteria in wastewater percolating through porous media: a review. Water Res. 2004;38:1355–67.

35. Kaseva ME. Performance of a sub-surface flow constructed wetland in polishing pre-treated wastewater – a tropical case study. Water Res 2004;38:681–7.
36. Vacca G, Wand H, Nikolausz M, Kuschk P, Kastner M. Effect of plants and filter materials on bacteria removal in pilot-scale constructed wetlands. Water Res. 2005;39:1361–73.
37. Vymazal J. Removal of enteric bacteria in constructed treatment wetlands with emergent macrophytes: a review. J Environ Sci Heal A. 2005;40:1355–67.
38. Soto F, Garcia M, de Luis E, Becares E. Role of *Scirpus lacustris* in bacterial and nutrient removal from wastewater. Water Sci Technol. 1999;40:241–7.
39. Brix H. Do macrophytes play a role in constructed treatment wetlands? Water Sci Technol. 1997;35:11–7.
40. Hench KR, Bissonnette GK, Sexstone AJ, Coleman JG, Garbutt K, Skousen JG. Fate of physical, chemical, and microbial contaminants in domestic wastewater following treatment by small constructed wetlands. Water Res. 2003;37:921–7.
41. Dong Y, Scholz M, Harrington R. Statistical modeling of contaminants removal in mature integrated constructed wetland sediments. J Environ Eng. 2012;138:1009–17.
42. Li M, Liang ZL, Callier MD, d'Orbcastel ER, Ma XN, Sun LL, et al. Nitrogen and organic matter removal and enzyme activities in constructed wetlands operated under different hydraulic operating regimes. Aquaculture. 2018;496:247–54.
43. Brix H, Arias CA. The use of vertical flow constructed wetlands for on-site treatment of domestic wastewater: new Danish guidelines. Ecol Eng. 2005;25:491–500.
44. Vymazal J. Removal of nutrients in various types of constructed wetlands. Sci Total Environ. 2007;380:48–65.
45. USEPA. Manual – constructed wetlands treatment of municipal wastewaters. Washington, DC: US Environmental Protection Agency; 2000.
46. Vymazal J, Brix H, Cooper PF, Herberl R, Perfler R, Laber J. Removal mechanisms and types of constructed wetlands. In: Vymazal J, Brix H, Cooper PF, Green MB, Herberl R, editors. Constructed wetlands for wastewater treatment in Europe. Leiden: Backhuys Publishers; 1998. p. 17–66.
47. Gopal B, Goel U. Competition and allelopathy in aquatic plant communities. Bot Rev. 1993;59:155–210.
48. Williams J, Bahgat M, May E, Ford M, Butler J. Mineralisation and pathogen removal in gravel bed hydroponic constructed wetlands for wastewater treatment. Water Sci Technol. 1995;32:49–58.

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