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Performance of Horizontal Surface Free Flow Integrated Constructed Wetland Developed for Treatment of Sewage Water at Neela Hauz Biodiversity Park, Delhi, India

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ABSTRACT
Constructed wetlands (CWs) are widely used in the treatment of sewage. Since land is the limiting, treatment of sewage by CWs, *in situ* bioremediation using CW is the best option. The problem with in situ remediation is the low hydrological retention time and low levels of Dissolved Oxygen (DO). To overcome these constraints, an integrated Constructed Wetland System (CWS) was developed and functionalized at Neela Hauz Biodiversity Park, Delhi, India. The present study aimed to evaluate the performance of a newly - developed integrated CWS for the removal of pollutants from sewage. The integrated CWS has two stabilizing ponds, three filtration chambers with rough filters, and CW with macrophytes. The performance efficiency of the system was assessed in terms of removal efficiency of pH, TSS, TDS, COD, BOD, NH_3-N, PO_4-P, some heavy metals and the enhancement of DO. The removal efficiency for TSS, TDS, COD, BOD, NH_3-N, and PO_4-P varied from 0.64 to 89.02%. The DO concentration enhanced from 0.0 to 3.5 mg/l in CW and 7.5 mg/l in lake. The reduction in heavy metals varied from 16.63 to 100%. The integrated CW design performed more efficiently in the removal of pollutants within 14 hours of HRT than most of the CWs used by many workers and hence can be used for *in situ* remediation of sewage.

Key words: Sewage, integrated constructed wetland, water quality parameters, removal efficiency, *in situ* remediation

INTRODUCTION

Many countries, including India are facing water scarcity (Anonymous 2019). In fact 50%of the Indian population will not have water or no access to drinking water by 2030 (Nivala et al. 2014). One way to overcome a water crisis is to recycle and reuse waste water, particularly sewage (Trulli et al. 2016, Elbana et al. 2017). A number of physical and chemical methods (conventional technologies) have been used for treatment of waste water. But these are expensive, high energy consuming and leave residues which cannot be disposed in an environmentally friendly way (Li and Zhou. 2011, Chen et al. 2014). Bioremediation Technologies have been used as primary/ secondary/ tertiary treatment of waste water as an alternative to conventional technologies (Kumar et al. 2015, Maktoof and Enazi 2020, Rahman et al. 2020, Hadidi et al. 2021, Parde et al. 2021). Among different biotechnologies, Constructed Wetlands (CWs) are widely used for the treatment of sewage across the world because of their relatively low cost, ease of operation, maintenance ability of working with little or no energy and the fact that they leave no hazardous wastes (Cao et al. 2017, Hadidi 2021, Sanchez et al. 2022). These are engineered wetlands of different types and designs, but all of them function based on physical, chemical and biological processes and the interactions that occur in natural wetlands (Rai 2013, Wu et al. 2015, Cheng et al. 2018, Corbella and Puigagut 2018). The Performance efficiencies of different design and type of CWs was reviewed by Rahman et al. (2020), Hadidi (2021), Parde et al. (2021), Wang et al. (2022) and Sanchez et al. (2022) in different regions across the world.

All the CWs studied have been developed outside the drains that carry waste water / sewage, and require additional land for their development. Further, most of the CWs studied are not integrated with stabilizing ponds and filtration chambers. The performance efficiency of CWs depends on two critical factors – the hydrological retention time (HRT) and levels of dissolved oxygen. The HRT for most of the CWs studied varied from 2 to 10 days (Hadidi 2021) and there is no enrichment of DO levels. However, CWs for *in situ* remediation of sewage with shorter HRTs and higher levels of DO are yet to be developed. The present paper gives performance efficiency of a novel integrated CWS with a stabilizing pond, filtration chamber with rock filters and a CW that has ridges and furrows with plants, used for in situ remediation of sewage.

MATERIALS AND METHODS

Location and design of CWS

The site is the Neela Hauz Lake Biodiversity Park of Delhi Development Authority, Delhi, India (Fig. 1), where the integrated Constructed Wetland System (CWS) was set up for the in situ remediation of 1 mld (million litres per day) of raw sewage that enters into the lake. The integrated CWS setup has the following components: (a) two stabilization ponds: pond 1 (49 m length, 10 m width and 0.5 m depth) and pond 2 (36 m length, 29 m width and 0.7 m depth). Both ponds are part of the lake system. However they are separated from the lake system by physical barriers and from each other by a brick wall, except for 3 m wide connecting channel for the flow of sewage. (b) The stabilising pond 2 was connected with a concrete gradient channel of 36 m long, 2 m wide and 3 m depth and filled at the bottom with stones up to a depth of 2 m. It has 4 Gabions (rock filters) of 0.5 m high and 0.5 wide with 300-400 mm size stones. (c) To remove solid wastes, a screen of 14 mm mesh size was fixed before the Gabion that separates stabilising pond 2 and gradient channel. (d) The gradient channel was connected with 3 filtration chambers - one was 3.76 m length, 3 m width, and 1 m depth; the second was 8 m length, 3 m width and 1 m depth; and the third was 4m length, 3 m width, and 1m depth. Each chamber had 2 gabions of 0.5m height, 3 m long and 0.5 m wide with loose 300-400 mm size stones. (e) The physical treatment unit is connected to the Constructed Wetland. It is of 38 m long, 31m wide and 0.5m deep. It has 13 ridges and 14 furrows. Each ridge is 0.7 m high and 0.5 m wide and is composed of loose stones of the size of 300 mm. The furrows have rooted emergent and submerged plants and floating plants. The depth of water in all components is 0.35m. (f) The CW unit is connected to the lake of 200 m length, 250 m wide and 3 m depth. The outlet from the lake is connected to a storm drain to drain the overflow of the lake. The schematic layout of the integrated CWS set up is illustrated in Figure 2. It may be noted that the biofilm mostly composed of bacteria, green algae and blue green algae found on the rocks and the rhizosphere of plants grown on constructed wetland were part of integrated constructed wetland system.

The flow of water is through a gradient channel. The purpose of stabilizing ponds is not only to allow sedimentation of the suspended particulate matter but also to biodegrade organic pollutants through activated sludge and to enhance the hydrological retention time (HRT). The gradient channel is meant to promote natural flow and the rock filters are used for enhancing hydrological retention time and DO levels. The physical treatment unit enhances HRT, DO levels and provides a longer time for the sewage to interact with biofilm on rocks. It also enables filtration and chemical precipitation of pollutants through interaction with rocks. The ridges in CW are used for longer HRT, filtration, higher DO dissolution and longer interaction with biofilm of rocks and rhizosphere of plants.

The species of plants used in the furrows are aquatic perennial macrophytes such as *Pistia stratiotes*, *Typha angustifolia, Phragmites australis, Cyperus* species, S*cirpus* species, *Alternanthera philoxeroides, Polygonum* species, *Ipomoea aquatica, I. fistulosa*, and *Paspalum* species. A microbial community inhabiting the rhizosphere biodegrades/biotransforms pollutants, and predates on pathogens. All of these rhizospheric microbes in CW enhance absorption and ion exchange in the root surface of plants, trap the sediments, substrate and litter. Ridges and furrows that have aquatic plants in CW also enhance HRT and DO levels. Plants in furrows not only take up nutrients but biodegrade pollutants.

Sampling and assessment of water

The water samples were collected from inlets and outlets at discharging points of stabilising pond, filtration chamber, CW, lake and lake outlet as per

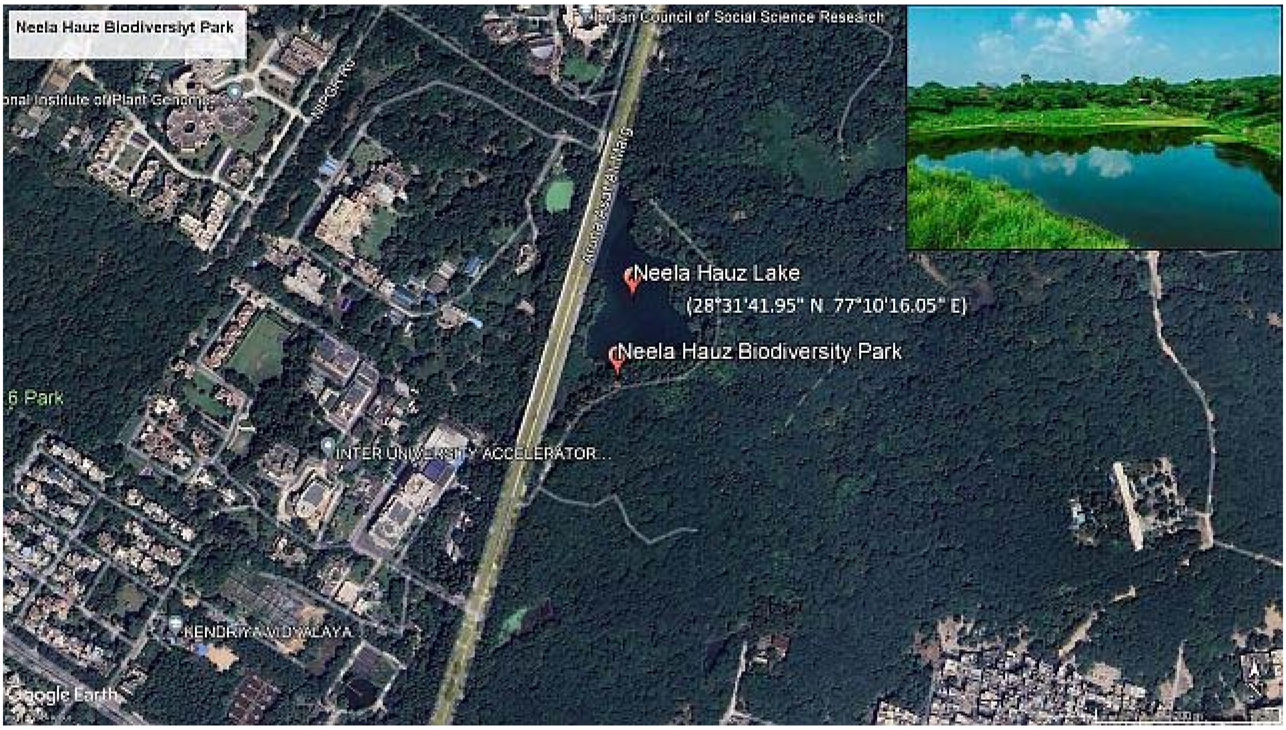

Figure 1. Google earth map of Neela Hauz Biodiversity Park and Neela Hauz Lake

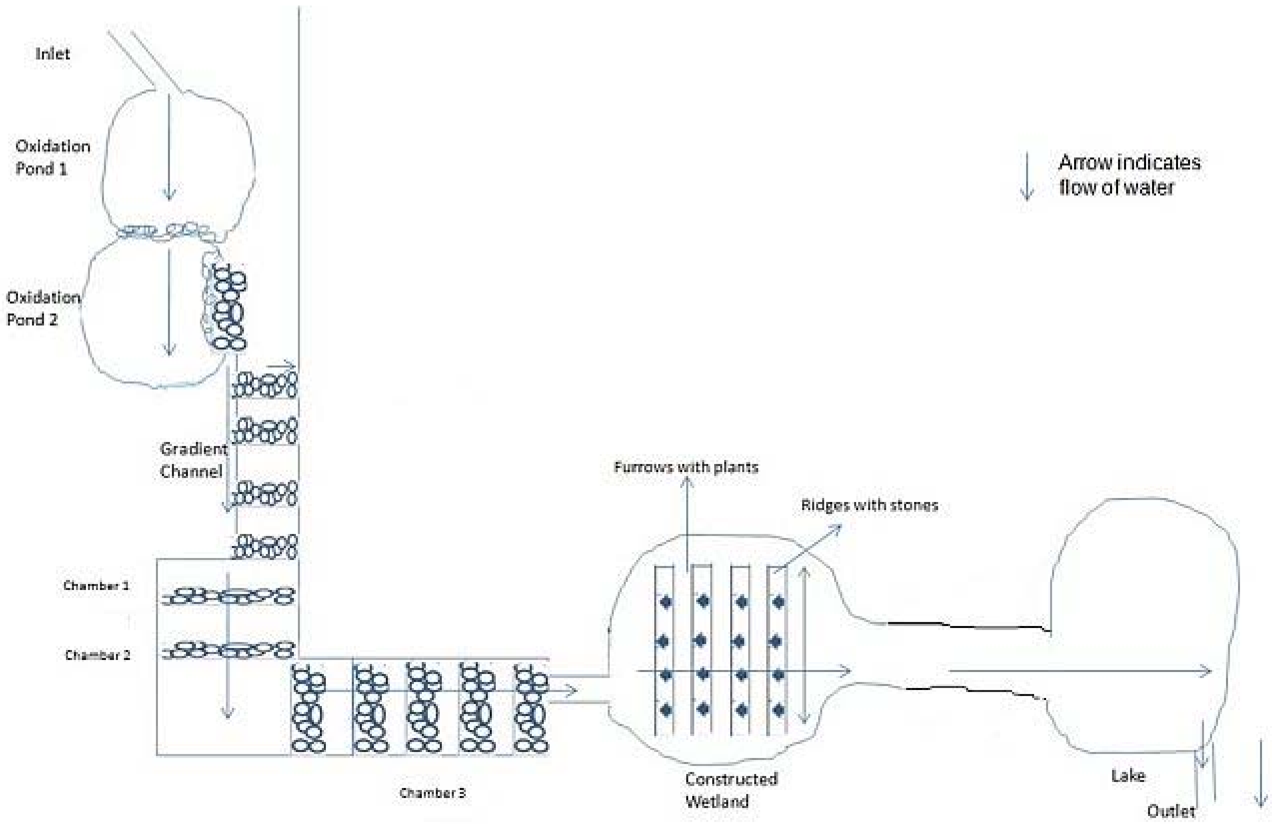

Figure 2. Schematic layout of Integrated Constructed Wetland System

the guidelines given by Anonymous (2005). The samples collected for DO estimation were fixed in Manganese sulphate and sodiumazide (2%) immediately after collection at the site itself. The samples were collected in triplicate. The hydrological features of the sewage such as the flow of water and total hydrological retention time in CWS were estimated as per the procedures described by Gerardi (2023). The performance of each components of CWS was evaluated by a set of water quality parameters viz., pH, DO, TSS, TDS, COD, BOD, NH_3-N and PO_4-P. All these parameters were estimated as per the procedures described by Anonymous (2005). Besides this heavy metals such as Lead (Pb), Copper (Cu), Zinc (Zn), Chromium (Cr), Cobalt (Co), Iron (Fe), Cadmium (Cd) and Nickel (Ni) levels were also estimated by Atomic Absorption Spectrophotometry method as per the procedures described by Allen (1978).

Removal efficiency of different components

The enhancement/ reduction (measured as removal efficiency) in different water quality parameters for different components of CWS was calculated as percent enhancement/ reduction in different water quality parameters using the following formula:

Removal Efficiency (r%) = $[(C_{in} - C_{out})/C_{in}]$ X 100

where, C_{in} = Concentration of the parameter in water samples at inlet and C_{out} = Concentration of parameter in water samples at outlet.

Statistical analysis

The data was subjected to one-way ANOVA to find out the extent of variation (expressed as mean squares) in water quality parameters (excluding heavy metals) between inlet I (raw sewage) and lake outlet (treated water), and the differences in means among different components was also analysed statistically. The statistical significance of the differences in means of water quality parameters (excluding heavy metals) among different components of CWS were put through the Turkeys test. The statistical significance of differences between means of water quality parameters between Inlet I (raw sewage) and Outlet of lake (treated water) was also tested by using the‘t’ test as a test of statistical significance. All statistical tests were performed using SPSS package. To understand the relationships (associations) among different hydrological parameters analysed (excluding heavy metals), correlation analysis was carried out using Pearson’s product moment Correlation coefficient (Polepaka et al. 2021).

RESULTS AND DISCUSSION

The variability in different water quality parameters among different units of CWS is shown in Figure 3.

Dissolved Oxygen (DO)

DO was below detectable limits at the first inlet, stabilising pond, physical treatment unit, but 3.17 mg/l DO at outlet of the CW. It was 7.53 mg/l in the lake water (Table 1, Fig. 3). The high levels of degradation in the physical treatment unit might be responsible for the absence of detectable levels of DO in spite of turbulence and enhanced air volume fraction than the water volume fraction as the sewage passed through the rock filters (unpublished data from CFD simulation model). This is also evident from the fact that the bulk of organic pollutants were removed in the physical treatment unit itself (Table 1).

The difference in DO between the inlet I (raw sewage) and the outlet of lake (treated water) and the mean values between different components of CWS with lake and without lake as a component were statistically significant ($P < 0.05$) suggesting that the effective performance of CWS in removal efficiency of pollutants is due to enrichment of DO during flow of sewage through different components and its utilization in degradation of pollutants. It may be noted that enhanced DO in the outlet of CW unit may be due to enrichment of DO through photosynthesis of aquatic plants.

The performance efficiency of the integrated CWS in enrichment of DO is higher than that reported for other CWs studied. For example, CWs with submerged plants showed a greater oxygen level (1.2 to 2.0 mg/l) than CWs with floating plants (0.2 to 1.1 mg/l) (Sewwandi et al. 2010). Barbera (2009) observed that DO was very low in horizontal flow constructed wetland (HFCW) whereas 4-5 mg/l was recorded in Vertical Flow Constructed Wetland (VFCW). Saeed et al. (2018) reported an increase in DO in VFCW and a decrease when sewage passed

Table 1. Variation in water quality parameters among different components of Integrated Constructed Wetland System developed including the lake

	Oxidation pond			Physical treatment unit			Constructed wetland			Overall performance of CW alone			Lake			Overall system performance (CW+Lake)		
	Inlet	Outlet	Change (%)	Inlet	Outlet	Change (%)	Inlet	Outlet	Change (%)	Inlet	Outlet	Change (%)	Inlet	Outlet	Change (%)	Inlet	Outlet	Change (%)
pH	7.99 ±0.05	7.94 ±0.08	0.63	7.94 ±0.08	6.90 ±0.07	13.09	6.90 ±0.07	6.72 ±0.08	2.61	7.99 ±0.05	6.72 ±0.08	15.89	6.72 ±0.08	7.30 ±0.08	8.63	7.99 ±0.24	7.30 ±0.08	8.63
TSS (mg/l)	99.02 ±0.02	91.673 ±2.7	7.43	91.67 ±2.73	19.00 ±4.58	79.27	19.00 ±4.58	10.33 ±0.88	45.61	99.02 ±0.02	10.33 ±0.88	89.57	10.33 ±0.88	17.67 ±1.45	71.05	99.02 ±0.23	17.67 ±1.45	82.16
TDS (ppm)	680.66 ±9.93	668.67 ±22.92	1.76	668.62 ±22.92	225.0 ±13.23	66.35	225.00 ±13.23	190.00 ±20.82	15.56	680.66 ±9.93	190.00 ±20.82	72.09	190.00 ±20.82	214.00 ±7.02	12.63	680.66 ±7.36	214.00 ±7.02	68.56
COD (mg/l)	220.08 ±0.64	210.00 ±15.28	4.58	210.00 ±15.28	85.00 ±20.21	59.52	85.00 ±20.21	9.33 ±0.33	89.02	220.08 ±0.64	9.33 ±0.33	95.76	9.33 ±0.33	10.00 ±1.15	7.18	220.08 ±5.12	10.00 ±1.15	95.46
BOD (mg/l)	84.88 ±0.87	84.33 ± 2.33	0.64	84.33 ±2.33	46.67 ±8.82	44.66	46.67 ±8.82	16.00 ±3.06	65.72	84.88 ±0.87	16.00 ±3.06	81.15	16.00 ±3.06	6.67 ±0.33	58.31	84.88 ±2.26	6.67 ±0.33	92.15
NH3-N (mg/l)	50.33 ±1.85	50.00 ±2.89	0.66	50.00 ±2.89	14.33 ±2.33	71.33	14.33 ±2.33	10.33 ±2.60	27.91	50.33	10.33	79.48	10.33 ±2.60	12.33 ±0.33	19.36	50.33 ±1.33	12.33 ±0.33	75.50
Phosphates (mg/l)	2.22 ±0.22	2.06 ±0.04	7.21	2.06 ±0.04	0.99 ±0.06	51.94	0.99 ±0.06	0.89 ±0.07	10.10	2.22	0.89	59.91	0.89 ±0.07	0.73 ±0.14	17.97	2.22 ±0.27	0.73 ±0.14	67.12

through HFCW. Kumar et al. (2015) reported enhancement of DO ranging from 0.53 to 3.2 mg/l in an 8 mld sewage-fed aquaculture system. These observations indicate that the integrated CWS showed higher DO resulting in higher removal efficiency of pollutants than the CWS used in other studies.

pH

The range of variation in pH was 6.72-7.99 across different components. The range of reduction was 0.63 to 13.09% across the CW units with lowest in stabilising pond and highest (13.09 %) in physical treatment unit. The pH of raw sewage was 7.99 but after passing through physical treatment unit of the Integrated CWS, it reduced to neutral range. The pH was further enhanced from neutral range in physical treatment unit to alkaline range at the outlet of lake (7.30) (Table 1, Fig. 3). But in the integrated system as a whole the pH was reduced from 7.99 (at the first inlet) to 7.30 (at the last outlet). The difference in pH between inlet (before treatment), and lake outlet (after treatment) and the differences in means of pH among components of CWs were statistically significant at $P<0.05$.

Polepaka et al. (2021) also reported 3% reduction in pH from 7.85 to 7.59 in CW (with *Canna indica* and *Ageratum conyzoides*). However, in the present integrated CWS the reduction was 8.63% (for CW alone it was 15.89%) suggesting that the integrated CWS is more efficient in reducing the pH level close to neutral as compared to other CWs in use. The physical treatment unit of the integrated CWS enhanced the overall efficiency in the reduction of pH value of raw sewage (Table 1, Fig. 3).

As per Sanchez et al. (2021) neutral pH is known to promote metabolic activity of microbes leading to higher removal efficiency of pollutants by CWs. For example Torrijos et al. (2016) reported that pH 4.5 impaired both nitrification and denitrification processes. This is because the activity of nitrifying bacteria decreases rapidly when the pH drops below 6.5 in CWs used for waste water treatment (Henze 2008). When the pH was maintained above 6.0 through alkali action, both nitrification and removal of TN (Total Nitrogen) increased. Similar results have been reported by Sanchez et al. (2021) for Winery water treatment by VFCW. In the present

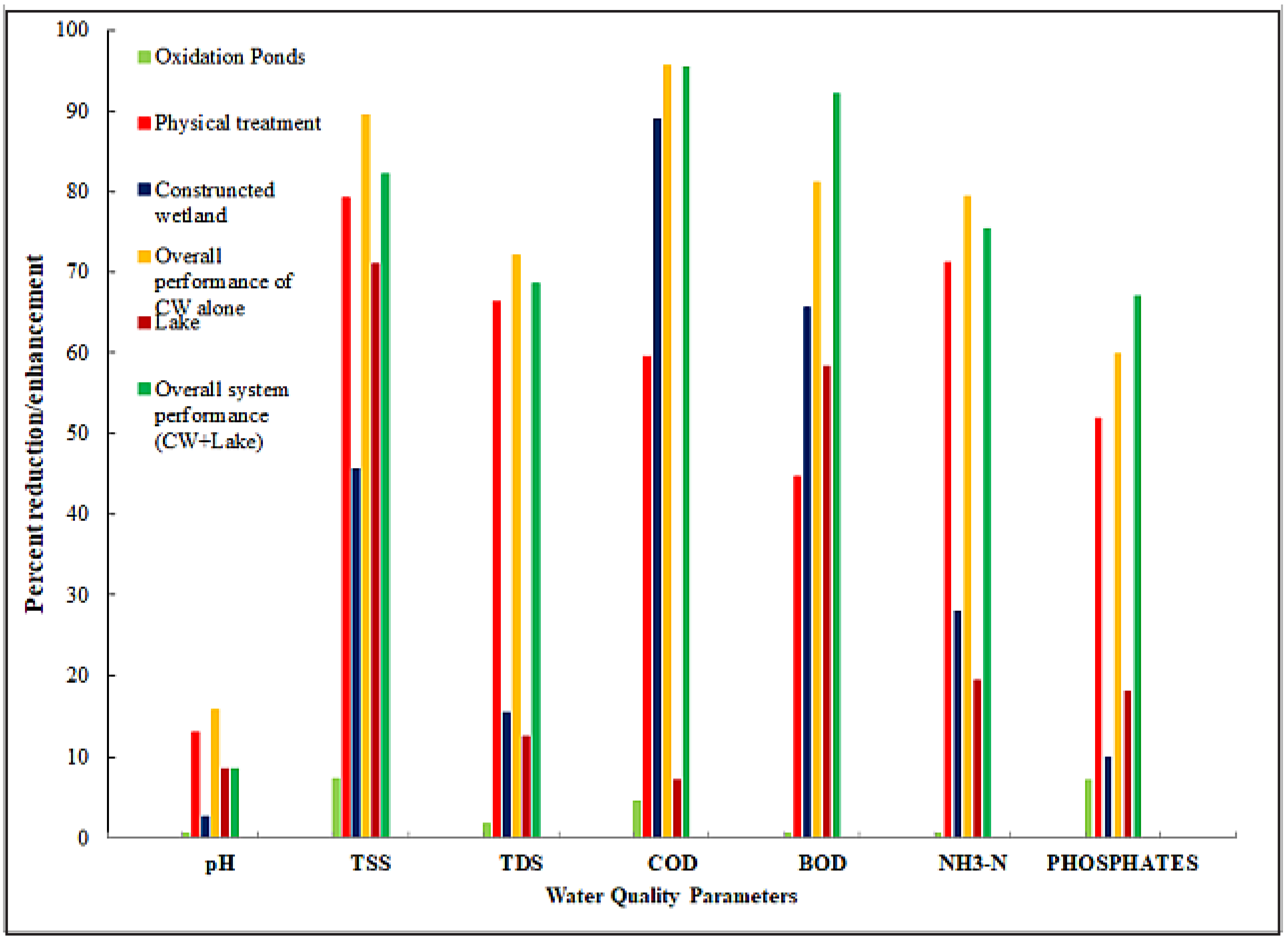

Figure 3. Reduction/enhancement (%) in different water quality parameters among different components of CWS

study the integrated CWS changed pH towards neutral from alkaline, which might have enhanced the removal efficiency of pollutants and hence superior than the CWs studied by other workers. This is also evident from the statistically significant positive correlation of pH with NH_4-N, TSS, and TDS.

Total Suspended Solids (TSS)

The range of variation among different components of CWS was 10.33 to 99.02 mg/l, with maximum reduction in the physical treatment unit (79.27%). The range of reduction was 7.43 to 79.27 % across the CWS units with lowest reduction in stabilising pond (7.43 %) and highest in physical treatment unit (79.27%); and the overall reduction in system was 82.16 % (Fig. 3). For CW alone the removal efficiency was 89.57% (Table 1, Fig. 3). The high reduction in physical treatment unit might be due to enhanced dispersion and diffusion of suspended solids caused by filtration and turbulence as the sewage while passing through pores of rock filters (gabions) (Table 1) resulting in greater degradation. Further, the results of CFD model (unpublished data) also indicate higher retention time by decreasing the velocity of flow and longer period of interaction with rock surface and higher air fraction in the volume of flowing sewage led to high removal of TSS. The difference in the reduction in TSS between inlet I and in the outlet of the lake and the differences in mean values of TSS among different components were statistically significant at $P< 0.05$ suggesting that different components of CWS are contributing to overall efficiency of CWS.

A large number of studies reported the removal of TSS by different types of CWs using a wide range of substrates and different species of plants with varying HRT for domestic and municipal waste waters, While Rahman et al. (2020) reported the TSS reduction ranged from 34% (Paulo et al. 2009) to

97% (Singh and Srivastava 2016), Parde et al. (2021) reported TSS reduction values varied from 38.4 to 97.1% (Ghrabi et al. 2011). Yeh and Wu (2009) while studying the performance of hybrid constructed wetland system, which included an oxidation pond, two serial surface flow wetlands with a cascade in between, and a subsurface flow wetland receiving secondary treated dormitory sewage, have reported 86.7%removal efficiency for TSS. Similarly in hybrid system (coupling of horizontal and vertical submerged flow beds) used by Masi and Martinuzzi (2007) the efficiency of removal of TSS was 84.81%. While Kimwaga et al. (2004) reported TSS removal was 89.35% in waste stabilization pond lined with rough filters, Maktoof and Enazi (2020) reported only 12.5% removal efficiency through sand filters. Haydar et al. (2020) reported 74% removal efficiency for Hybrid CW using *Typha angustifolia* and HRT of 8 days. Sehar et al. (2015) reported removal efficiency of 58% for hybrid CW with HRT of 8 days. The performance efficiency of the integrated CWS with 14 hours HRT in the present study is significantly higher than the performance of all CWs reported in removal efficiency of TSS, taking into account the shortest retention time and in situ mode of remediation.

Total Dissolved Solids (TDS)

The range of variation in TDS was 190.00 - 680.66 mg/l across different components. The range of reduction was 1.76 - 66.35% across the CWS units with lowest reduction in stabilising pond (1.76%) and highest reduction in physical treatment unit (66.35%) (Table 1, Fig.3). A higher dissolution of O_2 as the sewage passes through rock filters and longer interaction with rock surface might have degraded the dissolved solids through chemical precipitation and adsorption. This is perhaps the reason for high removal efficiency of pollutants in physical unit. The statistically significant negative correlation of DO with both TDS and TSS (Table 2) also substantiate that physical treatment unit is a critical component and contributes to the efficiency of integrated CWS performance in the removal of TDS. While the reduction in the overall system was 68.56%, for CW alone it was 72.09% (Table 1). It may be noted that the differences between the first inlet and last outlet of the lake and the differences in means between components of the CWS were statistically significant at $P<0.05$. The efficiency of the integrated CWS is higher in reducing TDS levels as compared to other CWs with or without rough filters.

Most studies on the performance of CWs in terms of removal efficiency of pollutants (Rahman et al. 2020, Parde et al. 2020) do not mention the removal efficiency of TDS. While Maktoof and Enazi (2020) report that the removal efficiency for TDS by CW used by them was only 30.3%, Saumya et al. (2015) studied the removal efficiency of pollutants by prototype subsurface flow wetland planted with *Heliconia angusta* and reported that the removal efficiency of TDS was just 14%. These observations suggest that the performance of integrated CWS of the present study is markedly higher than that of CWs used by other workers.

Biochemical Oxygen Demand (BOD)

The variation in BOD ranged from 6.67 to 84.88 mg/l with highest reduction (65.72%) in constructed wetland. The range of reduction was 0.64 to 65.72% across the CW units with lowest reduction in stabilising pond (0.64%) and highest in the constructed wetland (65.72%).The percent reduction in physical unit and lake was also high (Table 1, Fig. 3). The high removal efficiency of BOD in CW is probably due to high microbial activity in the rhizosphere of plants because of high levels of nutrients and DO. The higher removal efficiency in physical unit is due to longer HRT, longer period of interaction with rock surface, higher air fraction in the flowing sewage through pores of rock filters and higher dissolution of DO in the flowing sewage through rock filters, all of which might have contributed to chemical and biological degradation of organic pollutants. The reduction in the overall system was 92.15% but for CW alone it was 81.15% with HRT of about 14 hours.

The levels of BOD in the outlet of lake were significantly lower than the level observed in inlet I and the difference in means was statistically significant at $P<0.05$. The means of BOD between different components were also statistically significant at $P<0.05$ indicating that 92.15% removal of BOD is due to contribution of different components of CWS. The statistically significant ($P<0.05$) negative correlation of DO with BOD (Table 2) is also indicative of enrichment of DO in the CWS developed leading to higher degradation

Table 2. Correlation matrix showing relationships among different water quality parameters

	pH	DO	TSS	TDS	COD	BOD	NH_3-N	PO_4-P
pH	1	-0.18	0.90*	0.90*	0.75	0.65	0.82*	0.77
DO		1	-0.50	-0.49	-0.69	-0.84	-0.66	-0.59
TSS			1	0.10	0.94**	0.87*	0.90*	0.97**
TDS				1	0.93**	0.86*	0.90*	0.96**
COD					1	0.97**	0.83*	0.96**
BOD						1	0.87*	0.90*
NH_3-N							1	0.83*
PO_4-P								1

** Correlation is significant at .01 level (2-tailed), * Correlation is significant at .05 level (2-tailed)

of organic pollutants.

Recent reviews (Rahman et al. 2020, Padre et al. 2020) extensively analysed the performance of different types of CWs with different types of substrates and different plant species with respect to removal efficiency of BOD for domestic and municipal sewage. The variation reported in removal efficiency of BOD was 11% (Chyan et al. 2016), BOD 69.54% (Panwar and Makvana 2017), 95% (Paulo et al. 2009) to 97.2% (Ghrabi et al. 2011). Shukla et al. (2021) reported lower reduction of BOD (79%), whereas in hybrid systems used by Yeh and Wu (2009) and Masi and Martinuzzi (2007), the efficiency of removal of BOD was 86.5 and 95%, respectively. Haydar et al. (2020) reported the removal efficiency for BOD was 78% in Hybrid CW with *Typha angustifolia* and HRT of 8 days. Taking into account the shortest retention time of 14 hrs and in situ mode of remediation, the performance of the integrated CWS of the present study is markedly superior than most of the CWs studied by others.

Chemical Oxygen Demand (COD)

COD content varied from 9.33 to 220.08 mg/l across the components of CWS. The range of reduction was 4.58 to 89.02% across the CW units, lowest in stabilising pond and highest in the constructed wetland (Table 1, Fig. 3). The reduction in the overall system was 95.46%. The enhanced microbial activity due to high DO levels and nutrients in rhizosphere of aquatic plants and plant biomass in CW might be responsible for higher reduction of COD. The difference in COD between inlet I and outlet of the lake was statistically significant at $P < 0.05$. The range of removal efficiency of COD by different types of CWs having different types of substrates and different kinds of plant species was 35% (Belmont and Metcalfe 2003) to 97% (Singh and Srivastava 2016) as reported by Rahman et al. (2020) and 26.6% (Ghrabi et al. 2011) to 94.4% (Saeed et al. 2014) as reported by Parde et al. (2021). Further, Kumar et al. (2015) reported maximum removal percentage for COD was 80.1%. While Yeh and Wu (2009) reported 57.8% removal efficiency for a hybrid CW system, Masi and Martinuzzi (2007) reported 94%. Wu et al. (2015) reported the removal efficiency of 71.04% for Vertical Flow Constructed Wetland (VFCW) with intermittent aeration and with *Canna indica* and *Hydrocotyle vulgaris*. Jizheng et al. (2019) reported 67% removal efficiency for aerated VFCW + HFCW system. These observations suggest that the integrated CWS of the present study with HRT of 14 hours showed better performance in removal of COD as compared to different types of CWs with different substrates and plant species and longer HRTs.

It may be noted that differences in means of COD among components were statistically significant at $P<0.05$ suggesting that the overall efficiency in percent removal of COD is due to the contribution made by different components of CWS. In other words integration of the Physical treatment unit with CW played a major role in enhancing the performance of CWS developed.

Ammonia-Nitrogen (NH_3-N)

The variation in NH_3-N ranged from a minimum of 10.67 mg/l to a maximum of 50.33 mg/l across the components of CWS. The range of reduction was 0.66 to 71.33%, maximum in the Physical treatment unit (71.33%) (Table 1, Fig.3). The overall reduction in CWS was 75.50% but within CW alone it was 79.48%. The differences in means of NH_3-N levels between different components of CWS were statistically significant at P<0.05 indicating that the overall efficiency of CWS is due to contributions of its components. The high reduction in NH_3-N in the Physical unit might be due to chemical transformation and also due to biofilms on the rock filters. Rahman et al. (2020) report on the performance efficiency in removal of NH_4-N by different types of CWs having different substrates and different plant species was 64% (Garzon Zuniga et al. 2016) to 91% (Tunçsiper 2009), whereas Parde et al. (2020) in their review reported it was 28.9% (Saeed et al. 2014) to 65.1% (Huang et al. 2015). Further, Wang et al. (2005) reported that NH_3-N reduction rate was 59.4% in the stabilizing pond, and for CW it was 61.3%. While Polepaka et al. (2021) reported that nitrate reduction rate was 60 - 62% for CWs, Patil and Chakravorty (2017) reported 78% removal efficiency for HFCW with intermittent aeration; Jizheng et al. (2019) reported 75% removal efficiency for a Hybrid CW. These observations suggest that performance efficiency of integrated CWS of the present study with HRT of 14 hours is superior in removal of NH_3-N than most of the CWs studied.

Phosphates (PO_4-P)

Phosphate levels varied between 0.73 to 2.22 mg/l across the components of CWS (Table 1). The range of reduction was 7.21 to 51.94 % across the CW units, lowest in stabilising pond and highest in the physical treatment unit (51.94 %) (Table1, Fig. 3). The overall efficiency of PO_4-P reduction in the integrated CWS was 67.12 % but within CW it was 59.91 (Table 1). Although the removal efficiency of PO_4-P by the integrated CWS with 14 hr HRT is lower than all the water quality parameters tested, but when compared to the range of values reported for different types of CWs used by other workers for municipal and domestic waste water, the performance efficiency of integrated CWS is far better than other CWs.

For example in the review of literature on the performance efficiency of CWs in removal of PO_4-P by different types of CWs having different substrates and different kinds of plants, the range recorded for municipal and domestic sewage was 20% (Parde et al. 2021) to 87% (Zhang et al. 2007) as reported by Rahman et al. (2020), and 38.08% (Ghrabi et al. 2011) to 78.56% (Aziz et al. 2015) as reported by Padre et al. (2020). While Maktoof and Enazi (2020) reported removal efficiency was just 26.6% in a CW, Dong et al. (2012) reported 35% removal efficiency for a VFCW of polluted river with intermittent aeration. Jizheng et al. (2019) reported 62.3% removal efficiency of P for aerated hybrid CW and Wang (2020) reported 95% removal efficiency for VFCW with intermittent aeration and *Canna indica* and *Hydrocotyle vulgaris* as CW plants. Ali et al. (2018) reported the overall removal of 67% for system I (anaerobic baffled reactor, saturated vertical submerged flow CW and free water surface) designed by them. Statistical significance (P<0.05) in the means among different components also indicate that overall efficiency of CWS depends upon its components. Unlike other hydrological parameters analysed, the differences in PO_4-P between the first inlet and outlet of the lake was statistically non-significant at (P<0.5).

The patterns of reduction in all water quality parameters (except for DO) across the components of integrated CWS demonstrate that the physical treatment unit has significantly contributed to performance efficiency of CWS, in contrast to the contribution of stabilising pond which showed less reduction in studied water quality parameters. The contribution of the lake itself to the overall efficiency of CWS is also not high. Since DO increase as the sewage passes through the different components of integrated CWS, it may be a critical constituent that contributes to reduction in water quality parameters (Figs. 3, 4). This is also evident by the negative relationships of DO with other water quality parameters tested.

Relationship among water quality parameters

To understand the relationships among water quality parameters, 'r' values were calculated for paired associations (Table 2). There was a strong positive statistically significant correlation for different paired associations (P< 0.05) involving TSS, TDS, COD, BOD, NH_3-N and PO_4-P suggesting strong association among the parameters of water quality due to their common origin or source, i.e. organic origin.

The relationship of DO with all other variables

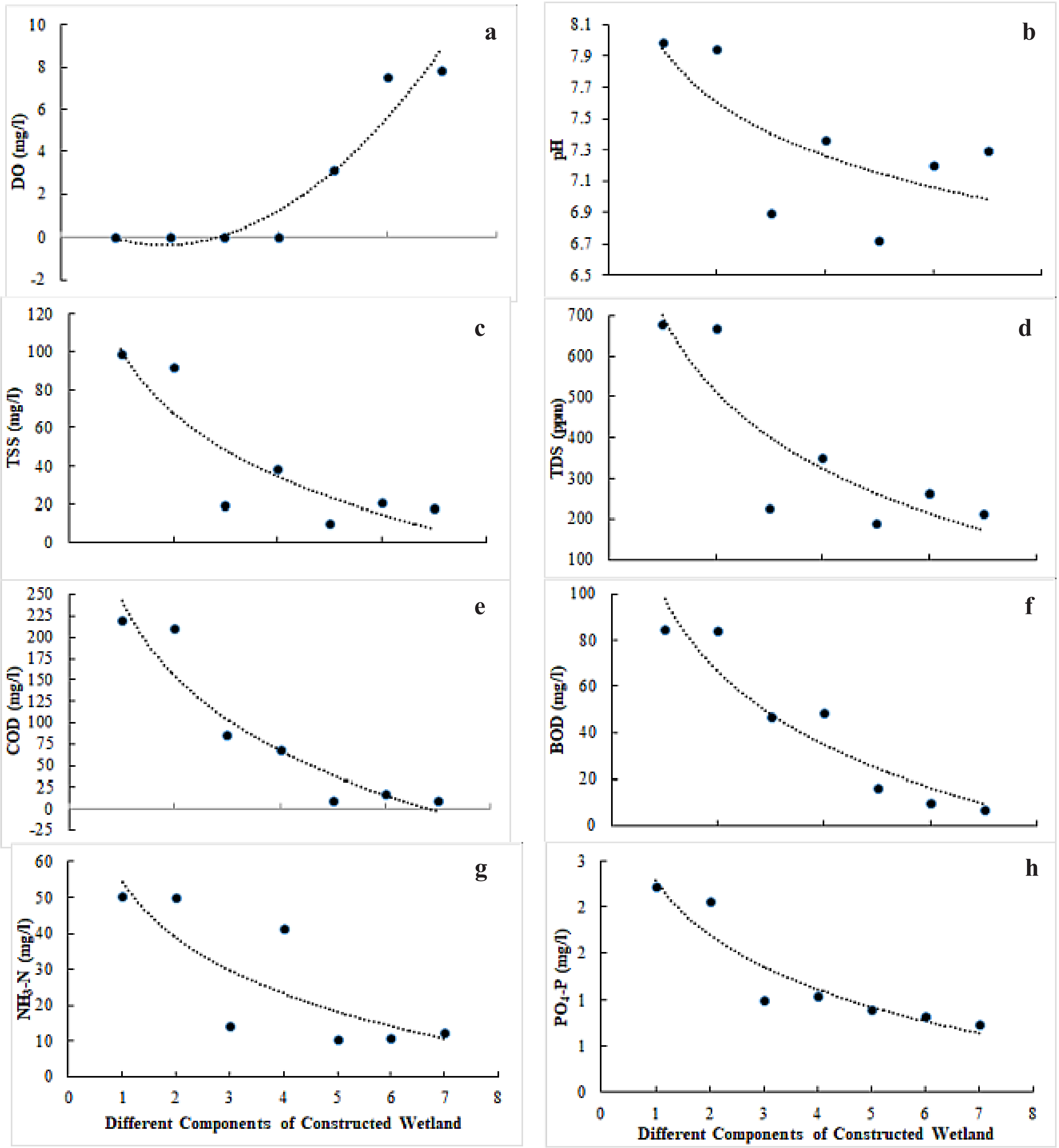

Figure 4. Variability in water quality parameters of sewage passing through different components of CWS: (a) DO; (b) pH; (c) TSS; (d) TDS; (e) COD; (f) BOD; (g) NH_3-N; and (h) PO_4-P. *1: Inlet (raw sewage); 2 : Stabilising Pond; 3 : Physical treatment Unit; 4 : Constructed wetland; 5: Outlet of Constructed Wetland; 6 : Lake; and 7 : Outlet of lake (treated water)

was negative (P<0.05) except for the combination with BOD which was significant at P<0.01 suggesting the higher the DO, the greater the reduction in BOD level. With respect to pH, the correlations for all paired associations were positive but statistically significant at P<0.05 only for associations with TSS, TDS, NH_3-N.The relationship between pH and DO was negative and statistically significant at P<0.05. These results suggest that DO and pH are critical in reducing pollutants by CWs.

Heavy metals and their removal efficiency by the integrated CWS

To assess the efficiency of CWS developed in removal of heavy metals, the water quality in the first inlet and outlet of the lake was also analysed with respect to some heavy metals. The inlet that brings sewage into CWS showed low levels of Cd (0.10 ppm), Co (0.02 ppm), Cu (0.01 ppm), Fe (0.15 ppm), Pb (0.08 ppm) and undetectable levels of Zn and Ni suggesting that the sewage entering into CWS did not carry any industrial effluent and it is essentially domestic sewage. The outlet of CW showed marked reduction in levels of all the metals, and the concentrations were 0.01 ppm (86.87% removal efficiency), 0.0 ppm (100% removal efficiency), 0.13 ppm (16.63% removal efficiency) and 0.04 ppm (47.97% removal efficiency) for Cd, Cu, Fe and Pb, respectively, suggesting that the integrated CWS is also effective in removal of heavy metals.

The reduction in heavy metals might be due to uptake by macrophytes used in CW. Similar observations have been made by other workers also. Hassan et al. (2021) reported that removal efficiency for Cd, Cu, Fe and Pb was 80, 84, 83 and 75%, respectively. While Sewwandi et al. (2010) reported the removal efficiency for Cd, Cu and Pb was 20, 33.3 and 23%, respectively, Kimwaga et al. (2004) reported it as 24.8, 25 and 25%, respectively.

CONCLUSIONS

The integrated CWS developed with HRT of 14 hrs for the in situ remediation of sewage water is found to be more efficient and effective than CWs, and hybrid systems used by other workers. The integration of modules like stabilizing ponds without aerators and physical treatment unit with CW enhanced the efficacy of the integrated CWS which can be used for in situ biological remediation of sewage water. Aerator in stabilising pond may further enhance the performance of the integrated CWS.

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Authors' contributions: Nidhi Seth worked on the CW design, collection of samples and data analyses; Sharad Vats and Suman Lakhanpaul contributed to the preparation of the draft Manuscript; Yasir Arafat and C.R. Babu contributed to the development of the CW and its functioning and in the preparation of draft manuscript. All authors read and approved the manuscript.

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