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Phytoremediation of domestic sewage using a floating wetland and assessing the pollutant removal effectiveness of four terrestrial plant species

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ABSTRACT

Several developing countries have limited infrastructure and finance to treat domestic and industrial wastewater. Discharging untreated sewage pollutes the surface and groundwater. Floating wetlands are an alternate method for treating polluted surface water bodies. This study's objective is to investigate the remediation of domestic wastewater using natural buoyant bamboo as a floating raft and terrestrial plants such as *Ocimum tenuiflorum*, *Hibiscus*, *Chrysopogon zizanioides*, and *Canna* in the floating wetland treatment (FWT) system. Floating rafts with a healthy terrestrial plant were planted and made to float in four plastic tanks with domestic wastewater. The water quality analysis was carried out periodically after 0, 3, 5, 10, 15, 20, and 25 days intervals. The experimental results of FWT using *C. indica* showed the highest removal efficiency of the pollutants such as TSS (96%), TP (98%), ammonia (95%), and DO (45%). In contrast, *Ch. zizanioides* showed its maximum removal efficiencies for turbidity (90%), TDS (48%), TN (85%), sodium (53%), potassium (74%), TP (92%), EC (27%), COD (93%), BOD (95%), and *E. coli* (47%). This study finding showed that the best terrestrial plants for removing various nutrients and other contaminants from municipal sewage were *C. indica* and *Ch. zizanioides*. However, further research is required to utilize these terrestrial plants with substrates under long-term study.

Key words: bamboo raft, domestic wastewater, floating wetland treatment, plant species

HIGHLIGHTS

- Floating Wetland Treatment (FWT) system - a natural and sustainable way of treating wastewater effectively through the use of plants and microorganisms.
- Domestic wastewater is treated using FWTs having terrestrial plant species such as *Canna indica*, *Ocimum tenuiflorum*, *Hibiscus rosa-sinensis*, and *Chrysopogon zizanioides*.
- *Canna indica* and *Chrysopogon zizanioides* have shown significant potential in treating domestic wastewater compared to others.

1. INTRODUCTION

The world's modernization accelerates urbanization and the growth of several industries. The daily water demand increases rapidly due to population growth, and the management of wastewater disposal remains a significant challenge for several countries (Ijaz *et al.* 2015; Samal *et al.* 2019). Developing countries have more limited infrastructure for wastewater management than developed countries. The intrusion of untreated municipal and industrial wastewater causes eutrophication and contamination of surface water bodies. Also, they pose a severe threat to groundwater degradation (Gao *et al.* 2017). Therefore, alternate cost-effective wastewater treatment methods are needed to prevent surface water pollution and groundwater degradation (Zimmels *et al.* 2009). Generally, wetlands are referred to as earth kidneys because of their ability to remove excess nutrients and other pollutants washed away into them. Floating wetlands, a new type of technology called constructed floating wetlands or 'artificial floating islands', 'ecological floating beds', or 'floating wetland treatment (FWT)' (Pavlineri *et al.* 2017), are acquiring recognition all over the world. FWTs are a cost-effective and eco-friendly method for purifying contaminated lake water (Samal *et al.* 2019). They are comprised of a floatable structure holding the growth medium to enable plant growth just on the surface of water bodies. The dense root system of the plants hanging into the water column is responsible for excess nutrient removal and entrapping of the solid particles. The floating raft material and the plant roots provide a sufficient area for developing microbial communities, which also put their efforts into removing excess nutrients and other pollutants from the wastewater (Tanner & Headley 2011; White & Cousins 2013). Floating wetland plants obtain their nutrients directly from the wastewater column because of their free-hanging roots. Hanging roots also help in faster uptake rates of nitrogen and other pollutants.

Another positive side of floating wetlands from constructed wetlands is that they can withstand significant changes in water depth owing to their buoyancy (Tanner & Headley 2011). An authenticated, cost-effective, and eco-friendly phytoextraction are more suitable than the conventional treatment techniques, which may not be ideal for smaller regions. In the past few years, FWTs have been used for treating different types of wastewater (Ijaz *et al.* 2016). The recent evolution of FWTs has focused on microbial communities and their role along with the hydrophytes to treat textile effluents (Tara *et al.* 2019). Many studies have focused only on using emergent wetland plants rather than terrestrial plants. However, there is a gap in using terrestrial plants, such as flowering and herbaceous plants, on FWTs to treat different wastewater. This research study focuses on treating domestic wastewater using FWTs and terrestrial plant species such as *Canna indica*, *Ocimum tenuiflorum*, *Hibiscus rosa-sinensis*, and *Chrysopogon zizanioides* and to evaluate their efficacy in pollutant removal.

2. MATERIALS AND METHODS

2.1. Experimental set-up

A laboratory trial was conducted in this study to evaluate the pollutant removal from wastewater using different terrestrial plants (Zimmels *et al.* 2009). The experimental investigation was done in a mesocosms study with a five circular plastic container with an internal diameter of 56 cm, a depth of 64 cm, and a 250-litre operational volume (Jones *et al.* 2017; Benvenuti *et al.* 2018; Gao *et al.* 2018). In addition, a tap provided at 5 cm just above the bottom of the tank helps in sample collection, which will be free of solid particles (Yasin *et al.* 2021; Figure 1).

The experimental set-up of FWT was carried out in four identical plastic tanks and named as listed below (Gao *et al.* 2017):

FWT-CI: Floating wetland treatment with *C. indica* – Indian shot.

Figure 1 | Floating wetland tank.

FWT-OT: Floating wetland treatment with *O. tenuiflorum* – Holy basil or Tulsi.
FWT-HR: Floating wetland treatment with *H. rosa-sinensis* – Hibiscus.
FWT-CZ: Floating wetland treatment with *Ch. zizanioides* – Vetiver (Ijaz *et al.* 2016).

2.2. Floating raft

This study uses bamboo, a naturally buoyant material, to make floating rafts for growing plants in the FWT process (Rehman *et al.* 2019a). First, the fresh bamboo was cut into the desired length to fit into the circular tank without obstruction. Then, a hand-made single-layer bamboo raft of 38 cm × 38 cm square in shape was used to provide floatation and to support plants (Weragoda *et al.* 2012). Finally, a plastic net pot of 5 cm diameter was used to hold the plants without any growth medium, and it was positioned in the bamboo raft at 10 cm maximum spacing (Figure 2).

2.3. Selection of native terrestrial plants

Plants with extensive root systems and the ability to sustain the region's climate should be used for FWT-based phytoremediation treatment processes (Saldanha Vogelmann *et al.* 2016; Rehman *et al.* 2019a; Figures 3 and 4). *C. indica*, *O. tenuiflorum*, an Indian sub-continent herbaceous perennial plant, *H. rosa-sinensis*, a flowering plant, and *Ch. zizanioides*, an Indian-origin perennial grass, were collected from nurseries and other localities (Kiiskila

Figure 2 | Bamboo floating raft.

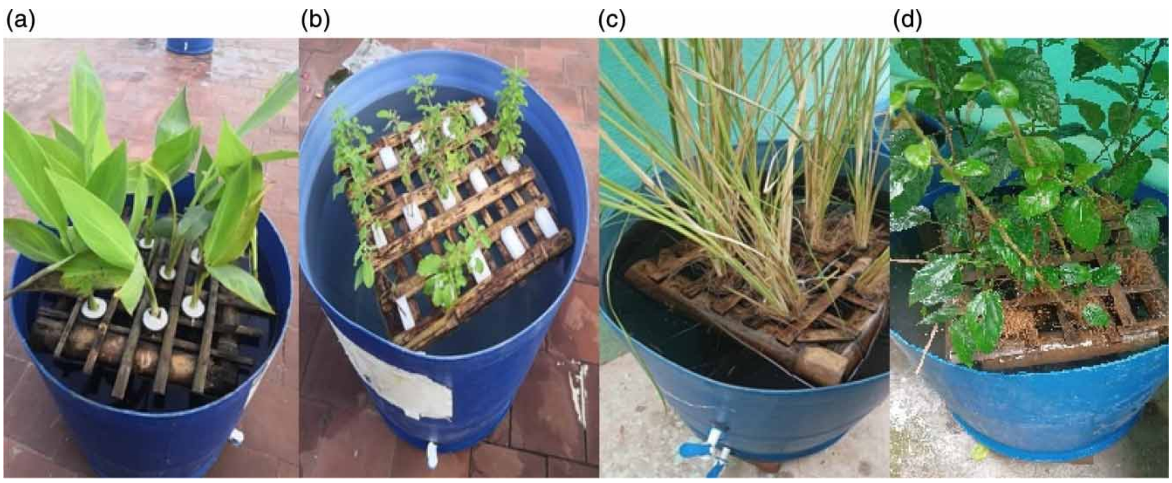

Figure 3 | FWT using (a) *Canna indica*, (b) Holy basil, (c) Vetiver, and (d) Hibiscus.

Figure 4 | Root development of (a) *Canna indica*, (b) Holy basil, (c) Vetiver, and (d) Hibiscus.

et al. 2017). Healthy collected plants, ten of each variety, are placed in the plastic net pot, which was already positioned in the bamboo raft (Effendi *et al.* 2017). They were grown for 2 weeks in freshwater filled in four identical plastic tanks to establish roots (Zimmels *et al.* 2009).

2.4. Domestic sewage

Raw sewage water was collected from the municipal sewage treatment plant's inlet chamber in Arakkonam municipality, Tamilnadu, India. The raw sewage water was filled in the four identical plastic containers up to 60 cm in depth, and 4 cm of free space was left to float the floating wetland (Figure 5).

2.5. Sample collection and analysis

Standard water and wastewater collection procedures were adopted for sewage sample collection. A tap fixed 5 cm above the container's bottom was used to take the samples from the tank. Hydraulic retention time (HRT) in treating domestic sewage using floating wetland mesocosm was kept at 0, 3, 5, 10, 15, 20, and 25 days; treated wastewater samples were collected at the HRT intervals (Faulwetter *et al.* 2011; Nawaz *et al.* 2020). A sufficient 1,000 mL sample was taken out from the tap, and the collected samples were stored in a one-litre plastic container for water quality analysis (Cao *et al.* 2016; Jones *et al.* 2017). During each HRT, one sample was taken from each of the four FWT tanks. Hence, for the seven alternative hydraulic retention times, a total of 28 samples were investigated to determine the water quality. Each tank was topped off with deionized water every 3 days to compensate for the evaporation losses and to maintain a constant water level. The tanks are covered with plastic sheets in the event of precipitation (Nawaz *et al.* 2020).

The experimental investigation was executed between February and April 2021 during summer, to avoid rainwater intrusion into the floating wetland tank which may cause dilution of pollutant concentration of domestic wastewater filled in the tank. Initially, the terrestrial plants were made to float in the FWT filled with fresh water

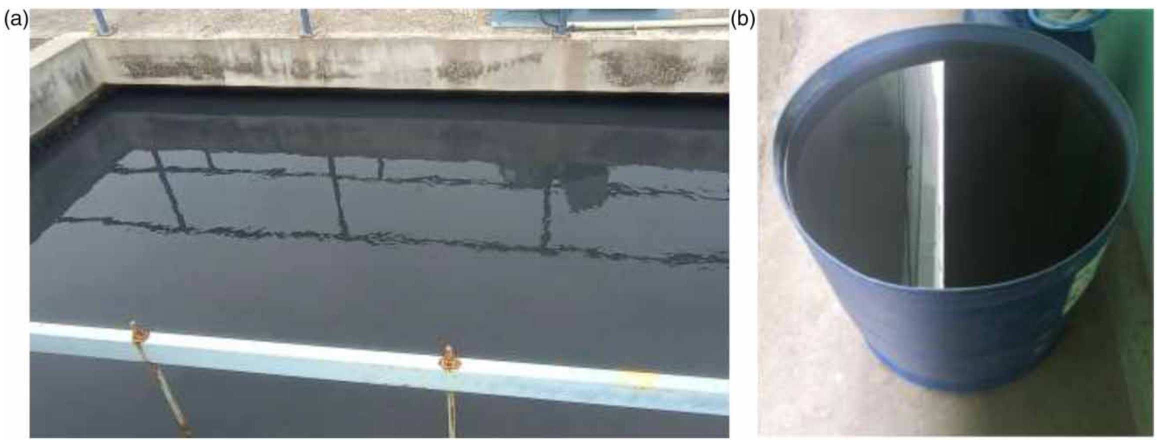

Figure 5 | (a) Domestic sewage collection from treatment plant. (b) Sewage water filling in FW tank.

and left for 4 weeks for the development of roots. The floating island with root establishment was then placed in the FWT tanks filled with domestic sewage. The water quality of FWTs was monitored on the 3rd day to determine the pollutant uptake efficiency of terrestrial plants in domestic wastewater. Furthermore, the water quality analysis was done periodically every 5 days until the 25th day. The maximum temperature recorded during this period varied between 32 and 42 °C.

Sixteen physiochemical parameters such as colour, odour, pH, TDS, TSS, turbidity, BOD_5, COD, EC, DO, ammonia, phosphate, sodium, potassium, total hardness (TH), total nitrogen, total phosphorus, and *E. coli* were analysed in the laboratory immediately after the sample collection from each FWT (Ijaz *et al.* 2015; Benvenuti *et al.* 2018).

COD was measured using APHA 23rd edition: 5220, pH, free ammonia as NH_3, phosphate as PO_4, total phosphorus as P, APHA 23rd edition: 4500, potassium as K, sodium as Na was measured using APHA 23rd edition: 3500, total hardness as $CaCo_3$ was measured using APHA 23rd edition: 2340, colour was measured using APHA 23rd edition: 2120, the dissolved oxygen concentration was measured using portable oxi 340 meters, and the odour was measured using APHA 23rd edition: 2150 (Cao *et al.* 2016).

2.6. Temperature

The higher variations in temperature and solar radiation have a significant impact on plant activity and microbiological processes in floating wetlands. The wetland plant and microbial communities are particularly sensitive to changes in environmental conditions, and temperature variations (Gao *et al.* 2017; Samal *et al.* 2019). Temperature affects plant growth and development, as well as the rates of microbial activity and decomposition. Temperature influences the metabolic rates of both plants and microorganisms, and it can have a profound impact on floating wetland biogeochemistry (Fang *et al.* 2016). A higher temperature is most likely the key modification that will have a positive impact on the removal efficiency. As a result, macrophytes' rapid growth will drive an increase in pollution uptake, and increased microbial metabolism rates will accelerate pollutant breakdown (Van De Moortel *et al.* 2010; Cao *et al.* 2016; Tharp *et al.* 2019; Hwang *et al.* 2020). During the execution of this experimental investigation, the temperature ranged between 32 °C minimum and 42 °C maximum. During the entire experimental investigation, only 10 mm of rainfall was recorded on 15 April 2021. The precipitation may have an impact on the effectiveness of FWT of wastewater. Heavy rainfall can create strong currents and increase in water levels, which may damage or uproot the plants, which can reduce the plant's ability to take up pollutants. On the other hand, moderate rainfall can provide a beneficial source of nutrients and help to maintain the water levels necessary for plant growth and pollutant uptake.

2.7. Sewage water characterization

In FWT processes, the wastewater quality may be improved by plants' and microbes' physiochemical and biological functions (Ijaz *et al.* 2016). Physiochemical characteristics of domestic sewage were collected from the sewage treatment facility in Arakkonam, Tamil Nadu, India (Afzal *et al.* 2019a; Table 1).

2.8. Pollutant removal efficiency calculation

The removal efficiency (E) for each physiochemical parameter of wastewater treated using a floating wetland with four different terrestrial plant species was calculated using the following equation and expressed in terms of percentage (%) (Gao *et al.* 2017):

$$\text{Removal efficiency } (E) = \frac{\text{Initial concentration} - \text{Final concentration}}{\text{Initial concentration}} \times 100$$

$$E = \left(\frac{C_{\text{in}} - C_{\text{out}}}{C_{\text{in}}}\right) \times 100$$

where C_{in} is the average initial concentration of raw domestic sewage for each parameter and C_{out} is each parameter's final average effluent concentration (Bauer *et al.* 2021).

2.9. Statistical analysis

The statistical analysis was performed using IBM SPSSV23 (Lyu *et al.* 2020; Yasin *et al.* 2021); Kolmogorov–Smirnov and Shapiro–Wilks tests were used to determine the normality of data (Li & Guo 2017; Spangler *et al.* 2019). The non-parametric Kruskal–Wallis tests were applied when the data were non-parametric for the

Table 1 | Physiochemical characteristics of domestic sewage

Water parameters	Domestic sewage concentration	Permissible limits as per Indian standards
E. coli	1,600	5,000 MPN/100 mL
BOD @ 5 days	92	30 mg/L @ 3 days
COD	230.8	250 mg/L
EC	2,042	–
DO	6.4	4 mg/L, min
Ammonia	11.3	5.0 mg/L
Phosphate	8.2	5.0 mg/L
Potassium	13	–
Sodium	96	–
Total Hardness	430	–
Total Nitrogen	13.2	100 mg/L
Total Phosphorus	3.6	–
pH	5.8	5.5–9.0
TDS	1,285	1,500 mg/L
TSS	48	100 mg/L
Turbidity	15	–
Colour	40	300 Hazen units

treatment comparison ($p < 0.05$) (Hu *et al.* 2010a; Tharp *et al.* 2019). The Kruskal–Wallis *H*-tests mean rank sums of 16 physiochemical parameters for each species were used to compare the effect of the different species (Lynch *et al.* 2015). In addition, the significance of each component can be assessed using the test statistics (chi-squared statistics, the degrees of freedom, and statistical significance of the test), which presents the result of the Kruskal–Wallis *H*-test (Keizer-Vlek *et al.* 2014). The variance of pollutant removal between four plant species (mean rank of species) was compared using the Kruskal–Wallis *H*-test.

3. RESULTS AND DISCUSSION

3.1. Turbidity, TSS, pH, and TDS removal

FWT-OT reduced the turbidity level to 0.7 NTU from 15 NTU and achieved a maximum removal efficiency of 95.33% within 3 days contact time during 25 days HRT compared to the FWT with other plant species. However, all four plants' turbidity average removal efficiency was ranked as FWT-OT > FWT-CZ > FWT-CI > FWT-HR. Turbidity removal efficiencies for FWT with four different plant species are presented graphically in Figure 6. Among all FWTs, the turbidity levels were found to be statistically significant (χ^2 (3) = 8.156, $p = 0.043 < 0.05$). In a previous publication (Headley & Tanner 2008), a stormwater treatment system utilizing floating islands with four other species of macrophytes found that FWT's turbidity removal efficiency was 73.6% (Headley & Tanner 2008), slightly lower than the present study.

The influent pH value was 5.8; phytoremediation processes using FWT with four different plants stabilized the effluent pH to 7.03, 6.1, 7.22, and 6 by FWT-CI, FWT-OT, FWT-CZ, and FWT-HR, respectively. The pH level was determined to be statistically not significant across all FWTs (χ^2 (3) = 6.879, $p = 0.076 > 0.05$). These variations in pH were due to the CO_2 uptake by microbes during respiration (Prajapati *et al.* 2017). The pH level was stabilized in all four floating wetlands using four terrestrial plants, with an average removal efficiency of −28.48, −24.22, −37.07, and −14.66% by FWT-CI, FWT-OT, FWT-CZ, and FWT-HR, respectively. This neutralization might be achieved due to the respiration of plant roots and microbes, resulting in CO_2 release (Abed *et al.* 2017). pH is a critical physiochemical parameter for measuring turbidity levels in domestic sewage treatment (Table 2).

In the TSS removal, FWT-CI showed a maximum removal efficiency of 96.46% compared with other plant species and is ranked as FWT-CI > FWT-OT > FWT-CZ > FWT-HR. Among all FWTs, the TSS concentration was found to be statistically significant (χ^2 (3) = 11.432, $p = 0.010 < 0.05$). The findings of results from this study are consistent with earlier research works (Borne *et al.* 2013; Abed *et al.* 2019; Kimbonguila *et al.*

2019). The removal efficiency by FWT for TSS and turbidity was achievable due to processes like sedimentation, biofilms and root systems entrapment, and biodegradation (Abed *et al.* 2019).

Figure 6 illustrates the amount of TDS in the effluent throughout the experimental work. The experiment's findings showed that the TDS dropped considerably over time. The physical and biological processes supported by floating wetlands reduced the TDS and TSS loads (Rehman *et al.* 2019b). The biofilms developed on the macrophyte roots trap the suspended solid particles in the water column. They either precipitate at the bottom or might

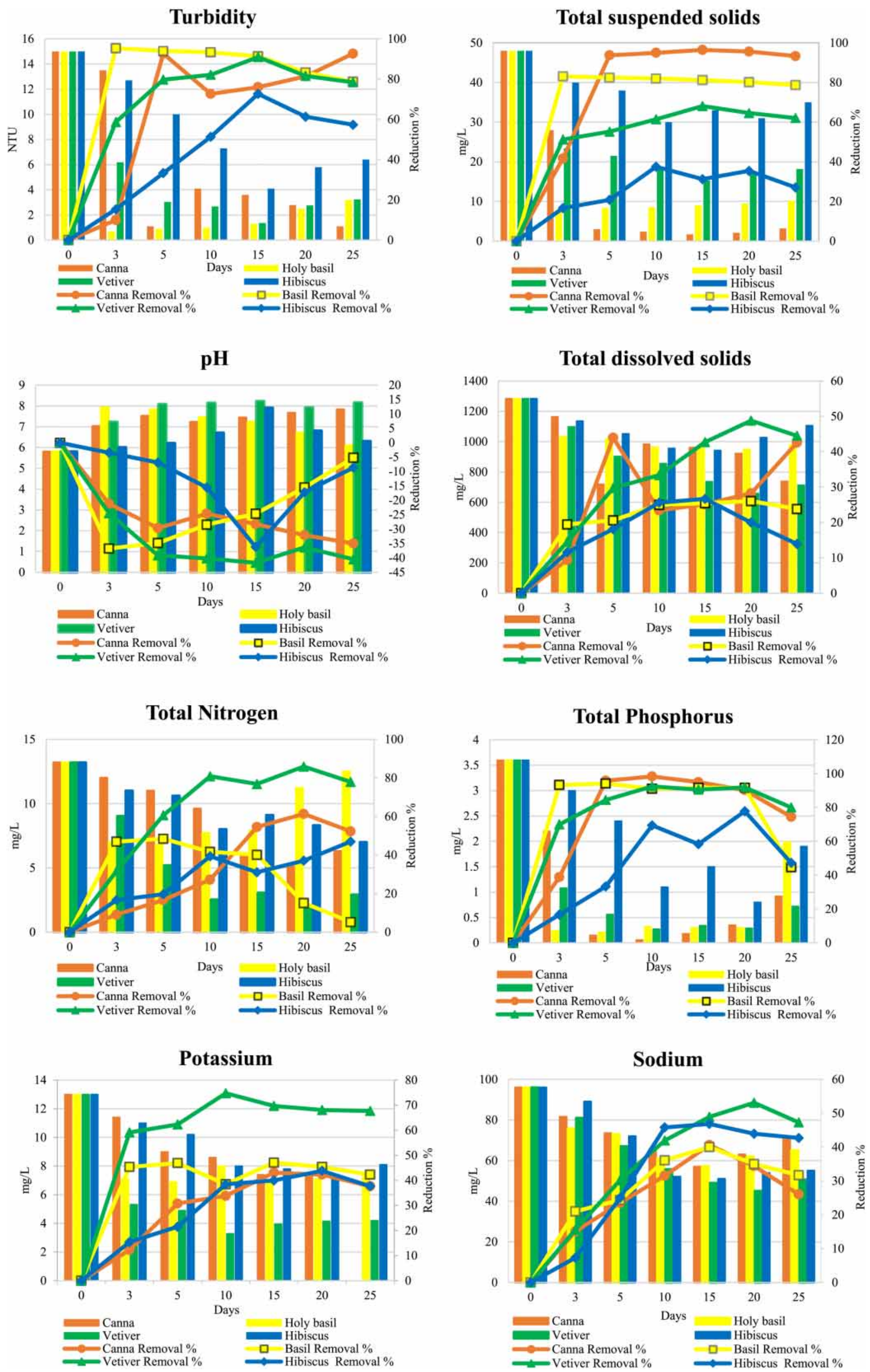

Figure 6 | Pollutant concentration and percentage removal rate of (a) Turbidity, (b) TSS, (c) pH, (d) TDS, (e) TN, (f) TP, (g) Potassium, (h) Sodium, (i) Ammonia, (j) Phosphate, (k) EC, (l) DO, (m) TH, (n) BOD, (o) COD, and (p) E. coli. (*continued.*).

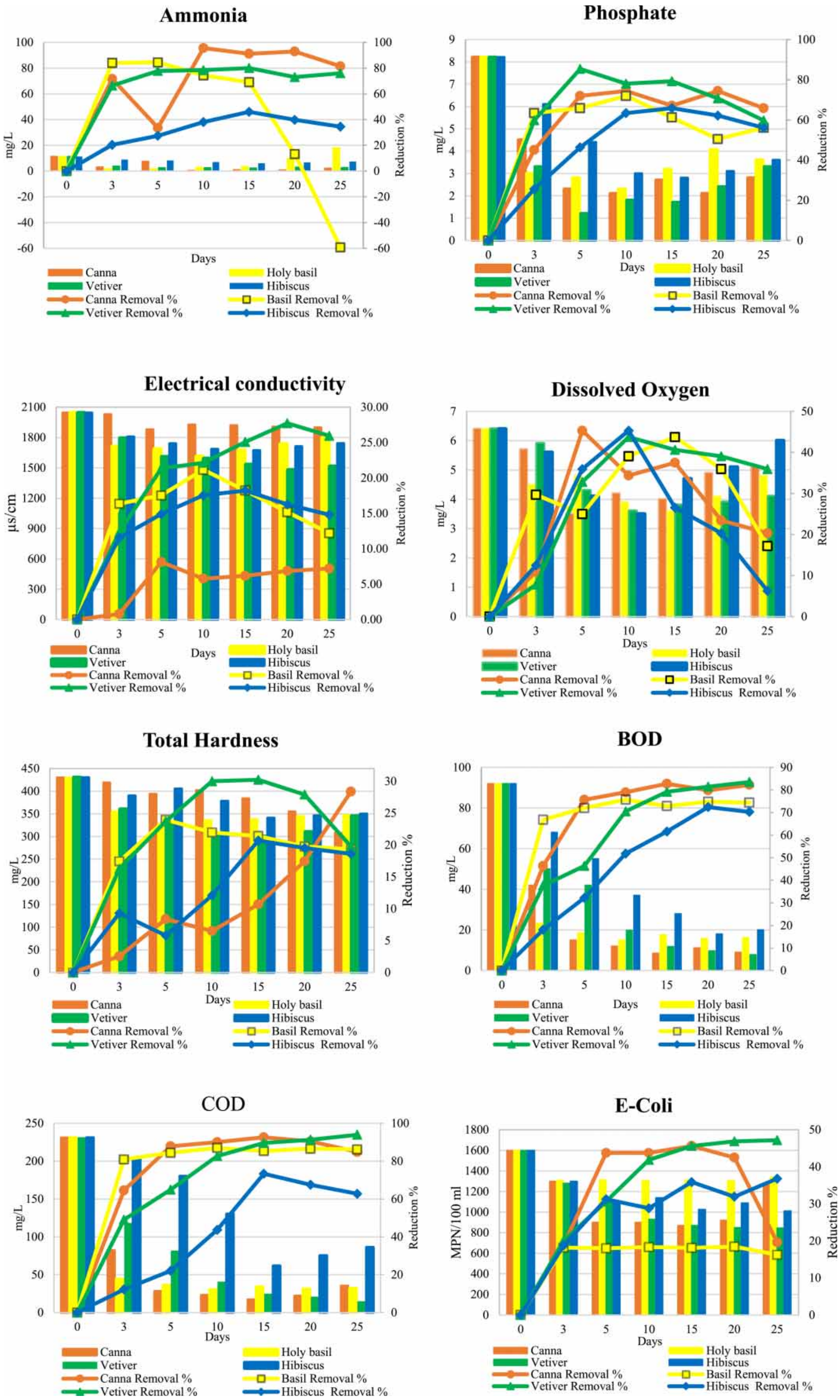

Figure 6 | Continued.

be decomposed by the microbes through adsorption (Borne *et al.* 2013). Natural factors, including oxidation, adsorption, and the native function of microbial communities, may be responsible for the reduction of TDS and TSS. However, the combined effect of plants and bacterial invasion further accelerated the decline of these physical parameters from domestic wastewater. The TDS removal efficiency was observed, similar to the

Table 2 | Physiochemical characteristics of sewage water quality before and after floating wetland treatment during 0–25 days HRT

	pH					TDS					TSS*					Turbidity*				
			Removal rate %					Removal rate %					Removal rate %					Removal rate %		
Floating wetland plants	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**
FWT-CI	5.8	7.03	−21.21	−35.00	−28.48	1,285	720	43.97	9.42	28.79	48	1.7	96.46	41.67	85.97	15	1.1	92.67	10.00	70.89
FWT-OT	5.8	6.1	−5.17	−36.72	−24.22	1,285	950	26.07	19.46	23.40	48	8.1	83.13	78.75	81.32	15	0.7	95.33	78.67	89.33
FWT-CZ	5.8	7.22	−24.48	−41.72	−37.07	1,285	658	48.79	14.55	35.62	48	15.3	68.13	51.25	60.45	15	1.36	90.93	58.67	78.58
FWT-HR	5.8	6	−3.45	−36.21	−14.66	1,285	942	26.69	11.60	19.33	48	30	37.50	16.67	28.13	15	4.10	72.67	15.33	48.56

	Total Nitrogen					Total phosphorus					Potassium*					Sodium				
			Removal rate %					Removal rate %					Removal rate %					Removal rate %		
	Initial	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**
FWT-CI	13.2	5.1	61.36	9.09	36.87	3.6	0.06	98.33	38.89	82.13	13	7.4	43.08	12.31	33.33	96	57	40.63	15.10	28.54
FWT-OT	13.2	6.8	48.48	5.30	32.95	3.6	0.21	94.17	44.72	84.44	13	6.88	47.08	38.46	44.26	96	57.2	40.00	21	31.37
FWT-CZ	13.2	1.86	85.91	31.67	68.96	3.6	0.27	92.5	70	84.91	13	3.28	74.77	59.15	66.95	96	45	53.13	15.62	39.53
FWT-HR	13.2	7.0	46.97	16.67	31.82	3.6	0.8	77.78	16.67	50.46	13	7.3	43.85	15.38	32.82	96	51	46.88	7.29	35.28

	Total Hardness					Phosphate					Electrical conductivity*					Ammonia				
			Removal rate %					Removal rate %					Removal rate %					Removal rate %		
	Initial	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**
FWT-CI	430	308	28.37	2.56	12.33	8.2	2.1	74.39	45.12	66.46	2,042	1,876	8.13	0.78	5.82	11.3	0.5	95.58	33.63	77.73
FWT-OT	430	327	23.95	17.44	20.64	8.2	2.3	71.95	50.49	61.50	2,042	1,610	21.16	12.19	16.77	11.3	1.75	84.51	−59.29	44.32
FWT-CZ	430	300	30.23	16.28	24.65	8.2	1.2	85.37	59.76	72.15	2,042	1,476	27.72	12.34	22.43	11.3	2.26	80	66.37	75.27
FWT-HR	430	341	20.70	5.81	14.34	8.2	2.8	65.85	25.61	53.25	2,042	1,670	18.22	11.56	15.54	11.3	6.1	46.02	20.35	34.37

	BOD					COD					Dissolved Oxygen					*E. coli**				
			Removal rate %					Removal rate %					Removal rate %					Removal rate %		
	Initial	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**	**Initial**	**Final**	**Max**	**Min**	**Avg.**
FWT-CI	92	5.4	94.13	72.83	88.28	230.8	17	92.63	64.56	85.07	6.4	3.5	45.31	10.94	28.65	1,600	870	45.63	18.75	35.67
FWT-OT	92	9.8	89.35	85.65	87.21	230.8	30	87	80.94	85.08	6.4	3.6	43.75	17.19	31.77	1,600	1,305	18.44	16.25	17.89
FWT-CZ	92	4.5	95.11	60.87	83.55	230.8	14	93.93	49.09	78.59	6.4	3.6	43.75	7.81	33.33	1,600	845	47.19	20	38.7
FWT-HR	92	19.6	78.70	30.43	57.79	230.8	61.5	73.35	12.18	46.91	6.4	3.5	45.31	6.25	24.48	1,600	1,011	36.81	18.75	30.57

*The experimental data set pertaining to Table 2 is provided in the supplementary file.

earlier research works studied with *Cyperus ustulatus* (swamp grass), *Schoenoplectus tabernaemontani*, *Brachiaria mutica* (wetland plants), and *Leptochloa fusca* (terrestrial plant) (Borne *et al.* 2014; Karstens *et al.* 2018; Yasin *et al.* 2021). FWT-CZ removed a maximum TDS of 48.79%, as shown in Figure 6(b). In contrast, FWT-CI, FWT-OT, and FWT-HR achieved their maximum removal of 43.97, 26.07, and 26.69% at 5, 20, and 15 days of contact time, respectively, during 25 days HRT as illustrated graphically in Figure 6(c). The TDS concentration was determined as statistically not significant across FWTs (χ^2 (3) = 4.488, $p = 0.213 > 0.05$). The root structure that reaches the bottom of the system might be involved in the filtration or trapping of the suspended particles. Since the roots had direct contact with the wastewater, very fine or dissolved particles would have changed the microbial populations. Additionally, several earlier studies revealed that FWTs might enhance water quality by removing organic and inorganic pollutants from wastewater (Afzal *et al.* 2019b). In this study, the floating wetland with plants like *Ch. zizanioides* and *C. indica* developed a denser and more extensive root system in the water column, which is responsible for trapping the suspended and dissolved solid particles present in the wastewater column.

3.2. TN, TP, and potassium removal

The domestic sewage influent and effluent concentration of TN, TP, and potassium before and after treatment using a floating wetland was graphically represented in Figure 6(e)–6(g). Compared with the other three plants, the TN concentration was reduced more in FWT-CZ, with a maximum TN removal rate of 85.91%. FWT-CI, FWT-OT, and FWT-HR showed TN removal efficiency of 61.36, 48.48, and 46.97% at 25 days HRT. However, FWT-CZ showed a maximum TN removal efficiency after 15 days of interaction, reducing the TN concentration from 13.2 to 1.86 mg/L. The total nitrogen concentration was found to be statistically not significant among all FWTs (χ^2 (3) = 5.449, $p = 0.142 > 0.05$). The nitrogen removal pathway was attained by floating wetland plant uptake; the microenvironment of the plants' rhizosphere was changed when the plants above water were harvested, which directly impacted the nitrogen absorption capacity of emergent aquatic perennial plant roots (*Iris pseudacorus*) (Sun *et al.* 2019).

FWT-CI significantly reduced TP concentration from 3.6 to 0.06 mg/L within 10 days of contact during their 25 days HRT with a maximum removal efficiency of 98.33% (avg. 82.13%) compared with the other three plants. However, the other plants, FWT-OT, FWT-CZ, and FWT-HR, achieved removal efficiency of 94.17% (avg. 82.13%), 92.5% (avg. 84.9%), and 77.78% (avg. 50.46%), respectively, as illustrated in Figure 6(f). The total phosphorus concentration was found to be statistically not significant among all FWTs (χ^2 (3) = 5.654, $p = 0.130 > 0.05$). TP removal was achieved due to the FWT's ability to remove phosphorus being influenced by the growth rate power of tissues of the *C. indica* species to absorb phosphorus. A previous study reported that TP removal by FWTs in treating stormwater after 7 days ranged from 28 to 58% (Tanner & Headley 2011).

FWT-CZ reduced potassium from an initial concentration of 13 to 3.28 mg/L within 10 days of HRT. Figure 6(h) shows this potassium reduction level and its removal efficiency at 3, 5, 10, 15, 20, and 25 days of HRT. The reduction was observed for FWT-CI from 13 to 7.4 mg/L, FWT-OT from 13 to 6.88 mg/L, and FWT-HR from 13 to 7.3 mg/L (Figure 6(h)). FWT-CI, FWT-OT, FWT-CZ, and FWT-HR were observed, with a maximum efficiency of 43.08, 47.08, 74.77, and 43.85% and an averaging removal efficiency of 33.33, 44.26, 66.95, and 32.82%, respectively, at 25 days HRT. The potassium concentration was statistically significant among all FWTs (χ^2 (3) = 10.624, $p = 0.014 < 0.05$).

In artificial wetlands, macrophytes are crucial to the nitrogen removal process. Plants can directly contribute by absorbing nitrogen from water bodies for growth. In addition, the root's perspiration provides a carbon source as an electron donor in microbial denitrification (Wang *et al.* 2014). In this study, the TN removal efficiency observed aligns with the efficiency achieved (78.2 and 65.5%) by floating constructed wetlands using substrates (Cao *et al.* 2016). The test results of the terrestrial plant employed in this study are similar to the TN removal reported in earlier studies (39% at 3 days HRT) (Gao *et al.* 2017). According to results observed from this study on TN and TP removal, microbial conversion was the main pathway for nitrogen removal (Spangler *et al.* 2019). Many earlier studies reported TN and TP removal efficiencies of 41 and 37% using *Carex appressa* – perennial grass (Benvenuti *et al.* 2018). Similarly, the FWTs with *C. indica* reduced TP and TN up to 10.5 and 11.8% from polluted river water (Fang *et al.* 2016); this removal efficiency was lower than our study findings. In addition to this, a previous study also reported that the combined effects of adsorption by the microbes, plant uptake ability, and sedimentary process of FWT would probably result in the overall removal of TP (47.7%) and TP (79.0%) using *Juncus effusus* (a terrestrial perennial plant) (Bin Chang *et al.* 2013).

3.3. Sodium, ammonia, and phosphate removal

The influent sodium concentration is 96 mg/L, and the sodium concentration in the effluent ranged between 45 and 89 mg/L; the average removal efficiency of 28.54, 31.37, 39.53, and 35.28% was observed for FWT-CI, FWT-OT, FWT-HR, and FWT-CZ, respectively, at 25 days HRT. In the sodium removal, it was observed that FWT-CZ (max. 53.13%) showed higher removal efficiency than FWT-HR (max. 46.88%), FWT-CI (40.63%), and FWT-OT (max. 40%), as shown in Figure 6(g). Among all FWTs, the sodium concentration was found to be statistically not significant (χ^2 (3) = 2.706, $p = 0.439 > 0.05$).

Ammonia initial concentration was recorded as 11.3 mg/L in domestic raw sewage, and their removal efficiency by FWT-CI was achieved with min. 33.63% and max. 95.58% (average 77.73%), for FWT-OT with min. −59.29% and max. 84.51% (average 44.32%), for FWT-CZ with min. 66.37% and max. 80% (average 75.27%), and for FWT-HR min. 20.35% and max. 46.02% (average 34.37%). Figure 6(i) shows that FWT-CI removed more ammonia than FWT-OT, FWT-HR, and FWT-CZ. Among all FWTs, the ammonia concentration was found to be statistically not significant (χ^2 (3) = 5.580, $p = 0.134 > 0.05$). The rapid decrease in NH_3 concentration was due to increased NH_4 and NO_3 levels, indicating that the nitrification process used more energy to convert NH_3 to NO_3 (Effendi *et al.* 2020). Most effluents have a lower overall removal of NH_3 than nutrient solutions, and unknown factors may be at play in this phenomenon. The amount of NH_3 in the water can also be decreased by the volatilization of ammonium ions into ammonia (Tchobanoglous *et al.* 2014). 51.1% of NH_3-N was removed, and the overall variations in hydrological conditions and the biogeochemical cycles already functioning in the pond impacted nutrient removal (Bin Chang *et al.* 2013). The concentration of ammonia in wastewater is known to increase with rising temperatures. This is because the bacteria responsible for converting ammonia to nitrate and nitrite, which are less harmful compounds, thrive in warm conditions. Thus, in warm water, the bacteria are more active, and more ammonia is converted to nitrate and nitrite, leading to a decrease in ammonia levels (Bin Chang *et al.* 2013). However, when temperatures drop suddenly due to rainfall, the ability of floating plants to remove ammonia may be reduced. In this investigation, a sudden drop in the removal rate of ammonia between 69 and 13% (3.5–9.8 mg/L) was observed, which is attributed to the decrease in temperature from 42 to 32 °C due to the sudden change in weather. Plants like *O. tenuiflorum* are cold-blooded and their metabolic processes slow down as temperature decreases; as a result, their ability to take up ammonia may be reduced. It was also documented that at low temperatures, macrophyte growth and root development rates were reduced in constructed floating wetlands with a lower removal rate of ammonia (Hu *et al.* 2010b; Van De Moortel *et al.* 2010; Li *et al.* 2012; Cao *et al.* 2016; Fang *et al.* 2016; Gao *et al.* 2017; Samal *et al.* 2019; Tharp *et al.* 2019; Effendi *et al.* 2020).

The phosphate concentration of raw sewage was reduced from 8.2 to 2.1, 2.3, 1.2, and 2.8 mg/L for FWT-CI, FWT-OT, FWT-CZ, and FWT-HR, respectively. The removal efficiency of FWT-CI, FWT-OT, FWT-CZ, and FWT-HR varied as min. 45.12% and max. 74.39% (average 66.46%), min. 50.49% and max. 71.95% (average 61.50%), min. 59.76% and max. 85.37% (average 72.15%), and min. 25.61% and max. 65.85% (average 53.25%), respectively. However, the vegetated FWT showed enhanced removal of PO_4 from the polluted water (Ijaz *et al.* 2015).

3.4. Electrical conductivity, dissolved oxygen, and total hardness

At the beginning of the experiment, the electrical conductivity of the raw sewage was recorded as 2,042 µs/cm. Then, it was considerably reduced to 1,876, 1,610, 1,476, and 1,670 µs/cm with an average removal efficiency of 5.82, 16.77, 22.43, and 15.54% concerning FWT-CI, FWT-OT, FWT-CZ, and FWT-HR at 25 days HRT. In addition, the EC levels among all FWTs were found to be statistically significant (χ^2 (3) = 10.536, $p = 0.015 < 0.05$). Among all FWTs, the dissolved oxygen level was found to be statistically not significant (χ^2 (3) = 0.863, $p = 0.834 > 0.05$). Although nutrient uptake by plants is influenced by the availability of dissolved oxygen levels in the wastewater, a greater DO level is advantageous for N and P removal under aerobic conditions. The effluent DO increase in all four treatment units is shown in Figure 6 (Bu & Xu 2013). The growth of floating plants on the water surface reduced the oxygen exchange between the water surface and atmosphere, which caused the DO content to tend to decline during the treatment. Plant respiration, mainly via root systems, may also be responsible for decreased dissolved oxygen concentration (Sudiarto *et al.* 2019).

The TH concentration among all FWTs was found to be statistically not significant (χ^2 (3) = 5.841, $p = 0.120 > 0.05$). The removal efficiency of TH in FWT-CI, FWT-OT, FWT-CZ, and FWT-HR was observed as min. 2.56% and max. 28.37% (average 12.33%), min. 17.44% and max. 23.95% (average 20.64%), min. 16.28% and max. 30.23% (average 24.65%), and min. 5.81% and max. 20.70% (average 14.34%), respectively. The TH concentration of raw sewage was decreased from 430 to 308, 327, 300, and 341 mg/L for FWT-CI, FWT-OT, FWT-CZ, and FWT-HR, respectively.

3.5. BOD, COD removal, and *E. coli* removal

Microorganisms developed on the roots and rhizomes of the plants in floating wetlands are imperative in removing organic matter from domestic wastewater. However, additional procedures, including filtration, nutrient absorption, and oxygenation, remove organic compounds from the water column. The relationship between BOD and COD is the primary factor in identifying the presence of organic matter and its degradability. According to earlier studies, BOD/COD ratio greater than 0.5 contains a more incredible amount of organic matter. In the present study, this ratio ranged between 0.3 and 0.8, indicating the absence of toxic components and the readiness in biodegradable conditions (Shahid *et al.* 2018).

When domestic sewage was treated using *C. indica* and vetiver plants, the concentration of BOD was dramatically reduced to 4.5 mg/L. Among all four FWT systems, BOD removal efficiency during the HRT of 0–25 days was the maximum for FWT-CZ at 95.11%. Based on the average removal rates, FWT-CI (average 88.28%) > FWT-OT (average 87.21%) > FWT-CZ (average 83.55%) > FWT-HR (average 57.79%). Among all FWTs, the BOD concentration was found to be statistically not significant (χ^2 (3) = 6.733, $p = 0.081 > 0.05$). According to previous publications, biological oxygen demand levels were significantly lowered using floating wetlands; as a result, elimination efficiency ranged from 87.2 to 95% (Prajapati *et al.* 2017). The results of this investigation are also consistent with earlier removal rates of BOD (93%) (Rehman *et al.* 2019b).

Concerning COD removal efficiency, both the *C. indica* and vetiver plant species showed COD removal rates of max. 92.63% and min. 64.56% (avg. 85.07%), and max. 93.93% and min. 49.09% (avg. 78.59%), respectively. In contrast, *O. tenuiflorum* and *H. rosa-sinensis* plants achieved a maximum removal efficiency of 87% and min. 80.94% (average 85.08%) and max. 73.35% and min. 12.18% (average 46.91%), respectively. Among all FWTs, the COD concentration was found to be statistically not significant (χ^2 (3) = 6.584, $p = 0.086 > 0.05$). The COD removal efficiency of our study is higher than the findings of previous publications of 90% removal efficiency using *Vetiveria zizanioides* (terrestrial plant) (Rehman *et al.* 2019b) and an average removal of 60% using *Pistia stratiotes* (hydrophytes) and *Eichhornia crassipes* (free floating plant) (Prajapati *et al.* 2017; Tusief *et al.* 2019).

Out of four FWTs, those with *C. indica* and Vetiver grass considerably decreased the initial concentration of *E. coli*, dropping to 850 and 870 MPN/100 mL with an efficiency of 46.88 and 45.63% to other treatments. FWT-OT and FWT-HR achieved the maximum and minimum removal efficiencies of 18.44 and 16.25% and 36.81 and 18.75%, respectively, at 25 days HRT. However, vetiver and *C. indica* plants showed higher *E. coli* removal efficiencies of 47.19 and 45.63%, respectively, than the other two plant species. The *E. coli* concentration among all FWTs was found to be statistically significant (χ^2 (3) = 9.268, $p = 0.026 < 0.05$).

4. CONCLUSION

This study demonstrated and evaluated the ability of terrestrial plant species such as *C. indica*, *O. tenuiflorum*, *Ch. zizanioides*, and *H. rosa-sinensis* in the FWT to reduce pollutant concentration levels in domestic sewage. The floating wetland treatment with *C. indica* (FWT-CI) was found to be the best in the removal of turbidity (92.67%), TSS (96.46%), TP (98.33%), ammonia (95.58%), and DO (45.31%) but *Ch. zizanioides* (FWT-CZ) showed the highest reduction for TDS (48.79%), TN (85.91%), sodium (53.13%), potassium (74.77%), phosphate (85.37%), EC (27.72%), COD (93.93%), BOD (95.11%), *E. coli* (47.19%), TH (30.23%), and pH (−24.48%). However, the other floating wetland system with *O. tenuiflorum* plant showed the highest removal for turbidity (95.33%) and also effectively removed TP (94.17%), potassium (47.08%), ammonia (84.51%), DO (43.75%), and EC (21.16%). Additionally, FWT-HR (*H. rosa-sinensis*) considerably removed pollutants from the municipal sewage like turbidity (72.67%), TP (77.78%), TN (46.97%), potassium (43.85%), phosphate (65.85%), ammonia (46.02%), DO (45.31%), EC (18.22%), COD (73.35%), and BOD (78.70%). The findings of this research made it clear that terrestrial plants had the highest rate of removal of different pollutants from domestic sewage, emphasizing that *C. indica* and *Ch. zizanioides* have significant potential for treating domestic wastewater. However, before implementing FWT, it is essential to thoroughly analyse these plants' diverse capacities for effective plant-microbe interaction over an extended period. Our investigation leads us to the conclusion that the FWTs with terrestrial plants could be a potential alternative to traditional wastewater technology to treat domestic sewage and polluted water. In arid and semi-arid regions, the use of an FWT system can be a crucial management measure for addressing water scarcity. The system is sustainable, cost-effective, and easy to maintain, making it a practical solution for areas with limited resources. Furthermore, regular maintenance is necessary to ensure that the floating wetland remains healthy and effective in treating water. This includes removing any dead or decaying plant material, monitoring the water quality, and adding new plants, growth medium or compost as needed. The recognition of this system's effectiveness promotes more sustainable and effective water management practices in water-scarce areas.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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