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RESEARCH PAPER

Integration of Constructed Wetland Microcosms with Available Wastewater Treatment Technologies for the Polishing of Domestic Wastewater and Their Potential Reuses

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Abstract

Different constructed wetland microcosm units have been designed in single as well as in combinations to study their performance for domestic wastewater treatment. Further, the integration potential of constructed wetland microcosms technology with up-flow anaerobic sludge blanket (UASB) and fluidized aerobic bed (FAB) reactors as a polishing unit was also studied. From the study, it is evaluated that the maximum removal efficiency of all selected parameters such as biochemical oxygen demand (BOD), total phosphorus (TP), soluble reactive phosphorus (SRP), ammonium (NH_4^+–N), nitrate (NO_3^-–N) and nitrite (NO_2^-–N) was expressed by the mixed planting unit of *Pistia Stratiotes* and *Phragmites karka* (Pi + Ph). Several water quality parameters including BOD in the effluent discharged from different constructed wetland microcosm units successfully meet the discharge criteria after three days of retention time. It was observed that both the UASB- and FAB-based reactors alone do not achieve water quality up to discharge standards. However, the available data shows that the performance of the UASB reactors in integration with constructed wetlands in terms of BOD removal reached the highest (up to 98%). Similarly, the removal of other parameters such as chemical oxygen demand (90%), total suspended solids (92%), total nitrogen (89%), NH_4^+–N (70%), and TP (88%) was also recorded as optimum. Consequently, the integration of constructed wetlands systems designed using *Pistia stratiotes* and *Phragmites karka* with UASB-based reactors can significantly enhance the performance and may offer a viable integrated wastewater treatment technology.

Article Highlights

- **CWM unit designed using *Pistia stratiotes* and *Phragmites karka* exhibited maximum removal efficiency for all the selected water quality parameters.**
- **The performance of all CWM units is studied at two different retention times.**
- **Removal efficacy of UASB reactors for several wastewater contaminants is enhanced significantly in integration with CWs technology.**
- **The concentration of BOD in the effluent of different CWM units after three days of retention time successfully meets the discharge criteria.**
- **Around 80% of the total worldwide installed UASB reactors for municipal wastewater treatment are present only in India.**

Keywords Constructed wetland microcosms · Macrophytes · UASB reactors · Domestic wastewater · Treatment

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Introduction

Presently, one-third of countries from Central, Western and Southern Asia to Northern Africa face severe water crises (United Nations SDGs report 2019; Kataki et al. 2021). Developing countries are capable to treat only 8% of their total wastewater generated partially or fully and the rest of the wastewater is discharged into nearby waterbodies (Worku et al. 2018; Ashekuzzaman et al. 2020; Kumar et al. 2020; Alayu and Leta 2021). In India, about 61,948 million liters per day (MLD) wastewater is generated from cities and towns whereas the existing sewage treatment ability is only for 23,277 MLD (Roy 2020). This large gap between generation and treatment may be because of low treatment capability, insufficient sewage networks, lack of technology, and clear policy directions to improve wastewater reuse (MOEFCC 2018; Kalbar 2021). However, the present treatment capability is also not utilized efficiently due to operational and maintenance failures. Almost, 39% of treatment plants are not in compliance with the discharge criteria as per the Central Pollution Control Board report (CPCB 2021). Nearly, 793 UASB technology-based STPs are installed globally displaying their extensive use (Engida et al. 2020). They are extensively used for the treatment of domestic wastewater in Brazil, Africa, Columbia, and India (Fang and Liu 2001; Vassalle et al. 2020). It is reported that 80% of the total worldwide installed UASB reactors for municipal wastewater treatment are present only in India (Engida et al. 2020). However, both anaerobic and aerobic processes alone cannot be seen as giving a ‘complete’ ecological solution as their effluents always do not fulfill the discharge criteria mainly for nutrients, residual carbon, pathogens, and heavy metals (El-Khateeb et al. 2009; De la Varga et al. 2013; Badejo et al. 2014; Tufaner 2015; Arantes et al. 2017). Therefore, the application of a consequent post-treatment system together with these technologies may provide a viable option to protect the water bodies and environment (Vassalle et al. 2020). Integration of constructed wetlands (CW) technology with anaerobic treatment methods such as UASB gained great concern as an environmentally friendly and efficient wastewater polishing technology. Recently, various types of CWs have been applied with dissimilar anaerobic reactors for tertiary treatment of wastewaters (Zeb et al. 2013; Jamshidi et al. 2014; Eginda et al. 2020; Kumar et al. 2020). Pretreatment of wastewater with anaerobic methods may reduce the area of CWs by 30–60% (Alvarez et al. 2008), avoid energy and chemical use (Jamshidi et al. 2014), decrease hydraulic retention time (HRT), and increase their resilience (Ayaz et al. 2015; Menzel et al. 2020). Whereas, the CW removes various contaminants such as organics, nutrient, suspended solids, metals, and infectious pathogens by several physical and biochemical methods (Vymazal 2007; De la Varga et al. 2013). Several studies have been conducted on CWs as post-treatment facilities with anaerobic processes treating different types of wastewaters (De la Varga et al. 2013; Zeb et al. 2013). It is reported that CWs with mixed planting of *Pistia stratiotes* and *Phragmites karka* exhibited excellent removal of organics, nutrients and heavy metals from domestic wastewater (Kumar et al. 2020, 2021, 2022). Further, CWs planted with *Cyperus alternifolius* and *Typha latifolia* also showed better performance for various contaminates from different types of wastewaters (Ciria et al. 2005; Tadese and Seyoum 2015; Sa’at et al. 2017; Gebeyehu et al. 2018). The use of macrophytes in combination may enhance the removal performance by augmenting oxygen supply, growing higher biomass and nutrient uptake, and microbial activity (Rezaie and Sahlezadeh 2014; Geng et al. 2017; Kumar et al. 2020). The removal efficiency of CWs varied significantly depending upon local environmental situations, design, macrophytes types, substrate material, and several other working parameters (Kumar and Dutta 2019) Therefore, the implementation of CWs needs local investigations on prevailing environmental conditions and their performance. Thus, the main aim of this study was to study the performance of constructed wetland microcosms (CWMs) technology in single as well as in integration with UASB-based STPs for domestic wastewater treatment. Wastewater generation and treatment ability of all Indian states and union territories as per the National Inventory of Sewage Treatment Plants has been provided in Table 1.

Materials and Methods

Working of CWM Units

Different CWM units were designed using crushed stone (8 cm), sand (8 cm), and soil (16 cm) as substrate materials in concrete containers with dimensions 1.2 × 0.60 × 0.76 m (L × W × D) as a batch experiment. The whole experiment was performed at the Department of Environmental science, Babasaheb Bhimrao Ambedkar University, Lucknow (26.7697° N, 80.9262° E). The three emergent and free-floating macrophytes, namely *Phragmites karka, Typha latifolia,* and *Pistia stratiotes* with nearly similar length/weight were selected and planted in single as well as in combination. The selection of macrophytes is based on their potential for contaminant uptake as reported earlier (Kumar et al. 2020, 2022). The initial density of macrophytes was 18 plants per CWM unit. All the CWM units were then filled with tap water and left for the stabilization of plants and substrate beds for 1 month as prescribed earlier. After the stabilization period, each CWM unit was filled with 200 L

Table 1 Wastewater generation and treatment ability of all Indian states and union territories (CPCB 2021)

S. no	Union Territory/State	Sewage generated, (MLD)	Existing treatment capacity (MLD)	Proposed treatment capacity (MLD)	Operational treatment capacity (MLD)	Total no. of STPs	Total no. of CETPs
1	Andhra Pradesh	2882	833	20	443	66	11
	Assam	809	0.21	0	0	5	–
2	Arunachal Pradesh	62	0	0	0	–	–
3	Andaman and Nicobar Islands	23	0	0	0	8	–
4	Bihar	2276	10	621	0	1	–
5	Chhattisgarh	1203	73	0	73	3	–
6	Chandigarh	188	293	0	271	7	–
7	Daman and Diu	29	–			3	–
8	Dadra and Nagar Haveli	67	24	0	24		–
9	Gujarat	5013	3378	0	3358	70	30
10	Goa	176	66	38	44	11	–
11	Himachal Pradesh	116	136	19	99	78	1
12	Haryana	1816	1880	0	1880	153	14
13	Jharkhand	1510	22	617	22	2	1
14	Jammu and Kashmir	665	218	4	93	24	1
15	Kerala	4256	120	0	114	7	5
16	Karnataka	4458	2712	0	1922	140	9
17	Lakshadweep	13	0	0	0	0	–
18	Maharashtra	9107	6890	2929	6366	154	27
19	Madhya Pradesh	3646	1839	85	684	126	1
20	Meghalaya	112	0	0	0	–	–
21	Manipur	168	0	0	0	–	–
22	Mizoram	103	10	0	0	1	–
23	Nagaland	135	0	0	0	–	–
24	NCT of Delhi	3330	2896	0	2715	38	13
25	Odisha	1282	378	0	55	14	–
26	Punjab	1889	1781	0	1601	119	4
27	Puducherry	161	56	3	56	3	–
28	Rajasthan	3185	1086	109	783	64	14
29	Sikkim	52	20	10	18	6	–
30	Telangana	2660	901	0	842	37	–
31	Tamil Nadu	6421	1492	0	1492	63	49
32	Tripura	237	8	0	8	1	–
33	Uttarakhand	627	448	67	345	71	4
34	Uttar Pradesh	8263	3374	0	3224	107	8
35	West Bengal	5457	897	305	337	50	1

CETPs stands for common effluent treatment plants

of raw domestic wastewater collected from a wastewater drain. The HRTs were 3 and 7 days and the total experimental time was two years from March 2018 to February 2020. The characteristics of the raw domestic wastewater applied throughout this study have been given in Table 2. Various environmental parameters such as temperature, dissolved oxygen (DO), pH solar intensity, and humidity were also measured on the daily basis. Temperature and humidity were measured by Thermo-hygrometer (Huger-8270), DO and pH through Lutron (DO-5509) and Hanna pH (Hi96107) portable meters, respectively, and solar intensity through the Luxmeter (LX-101A), provided by HTC™ (Kumar et al. 2021).

Sample Collection and Their Analysis

The effluent samples from the outlet of each CWM unit were collected after 3- and 7-day retention times in triplicate,

Table 2 Characteristics of raw domestic wastewater utilized in this study (mean ± SD)

Characteristics of domestic wastewater	Total phosphorus (TP)	Soluble reactive phosphorus (SRP)	Biological oxygen demand (BOD)	Ammonium (NH_4^+–N)	Nitrate (NO_3^-–N)	Nitrite (NO_2^-–N)	pH	Dissolved oxygen (DO)
Concentration (mg L^{-1})	10.17 ± 2.71	7.87 ± 2.15	118.94 ± 9.75	20.24 ± 4.16	8.62 ± 2.16	3.48 ± 1.94	5.78 ± 0.72	0.97 ± 0.25

transported to the laboratory and analyzed for BOD, TP, SRP, NH_4^-–N, NO_3^-–N, and NO_2^-–N as per the procedures specified by American Public Health Association (APHA 2017).

Collection of Data

The performance of CWM units for the removal of pollutants was observed within the laboratory of the department. The removal efficiency of CWM units was recorded at two retention times, i.e., 3 and 7 days, respectively. However, the performance of UASB and FAB reactors was evaluated based on the 2 years of data provided by the Uttar Pradesh Jal Nigam, Lucknow.

Statistical Analysis

The variances among the mean removal efficiencies of different CWM units at two retention times were analyzed through one-way ANOVA analysis using Statistical Package for Social Sciences (SPSS, version 20). However, Microsoft office excel (version 2016) was used to calculate the mean and standard deviation of the experimental data.

Results and Discussion

Environmental Conditions

The temperature varied from 25.70 to 36.3 °C, relative humidity from 66 to 90%, and solar intensity 101 × 100–512 × 100 Lux throughout this study. Temperature, relative humidity, and solar intensity were measured to know their daily variation which ultimately impacts the performance of CWMs. From the study, it is revealed that the concentration of DO varies notably between different CWM units due to dissimilar macrophytic combinations that promote the growth and expansion of diverse microbial populations (Zhang et al. 2010). For the initial 3 days, the concentration of DO decreases rapidly which may be due to chemical oxidation and aerobic respiration (Ding et al. 2018). Several CWM showed an increasing trend because most of the organic matter was oxidized and taken up by microbial populations. The CWM unit designed using *Pistia stratiotes* and *Phragmites karka* exhibited the highest DO concentration at both HRTs as compared to others throughout the experiment (Fig. 1). However, the pH values were also improved from 5.48 to 7.1 after 7 days of retention time.

Performance of CWM Units

The removal efficiency of CWM units varied significantly depending upon the type of CWs and contaminants, retention time, type of macrophyte and substrate material, and several environmental factors such as pH, DO, and temperature. The removal efficiency of BOD ranged from 50.86 to 60.41% between different CWM units after 3 days of retention. However, the efficacy has been increased up to 81.38% with the increase in retention time (7 days) for CWM unit planted with *Phragmites karka* and *Pistia stratiotes* (Fig. 2a). Maximum removal capability for TP and SRP (60 and 58.46%, 77.42 and 73.60% for 3 and 7 days, respectively) was also exhibited by the CWM unit Pi + Ph (Fig. 2b, c). The removal was principally due to the adsorption, precipitation as well as utilization by macrophytes and available microbial populations (Engida et al. 2020). The removal efficiency for NH_4^+–N varied from 51.44 to 77.89% among different CWM units with maximum removal by Pi + Ph (63.12%) and Ph (77.89%) at 3 and 7 days, respectively (Fig. 2d). Maximum removal capability for NO_3^-–N and NO_2^-–N was also expressed by CWM unit Pi + Ph (55.94–77.26%) and (55.17–69.06%) at both retention times (Fig. 2e, f). The removal of nitrogen forms may be due to

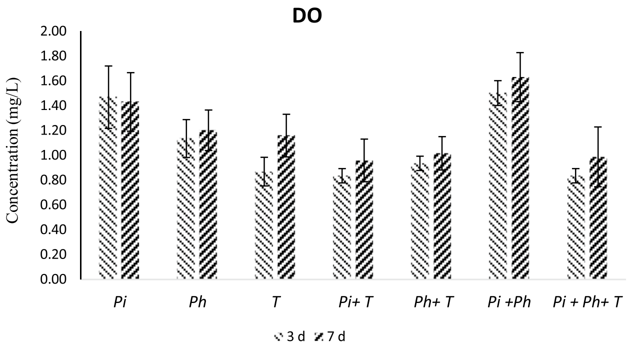

Fig. 1 Average DO concentration in different CWM units at two retention times throughout the experiment (mean ± SD)

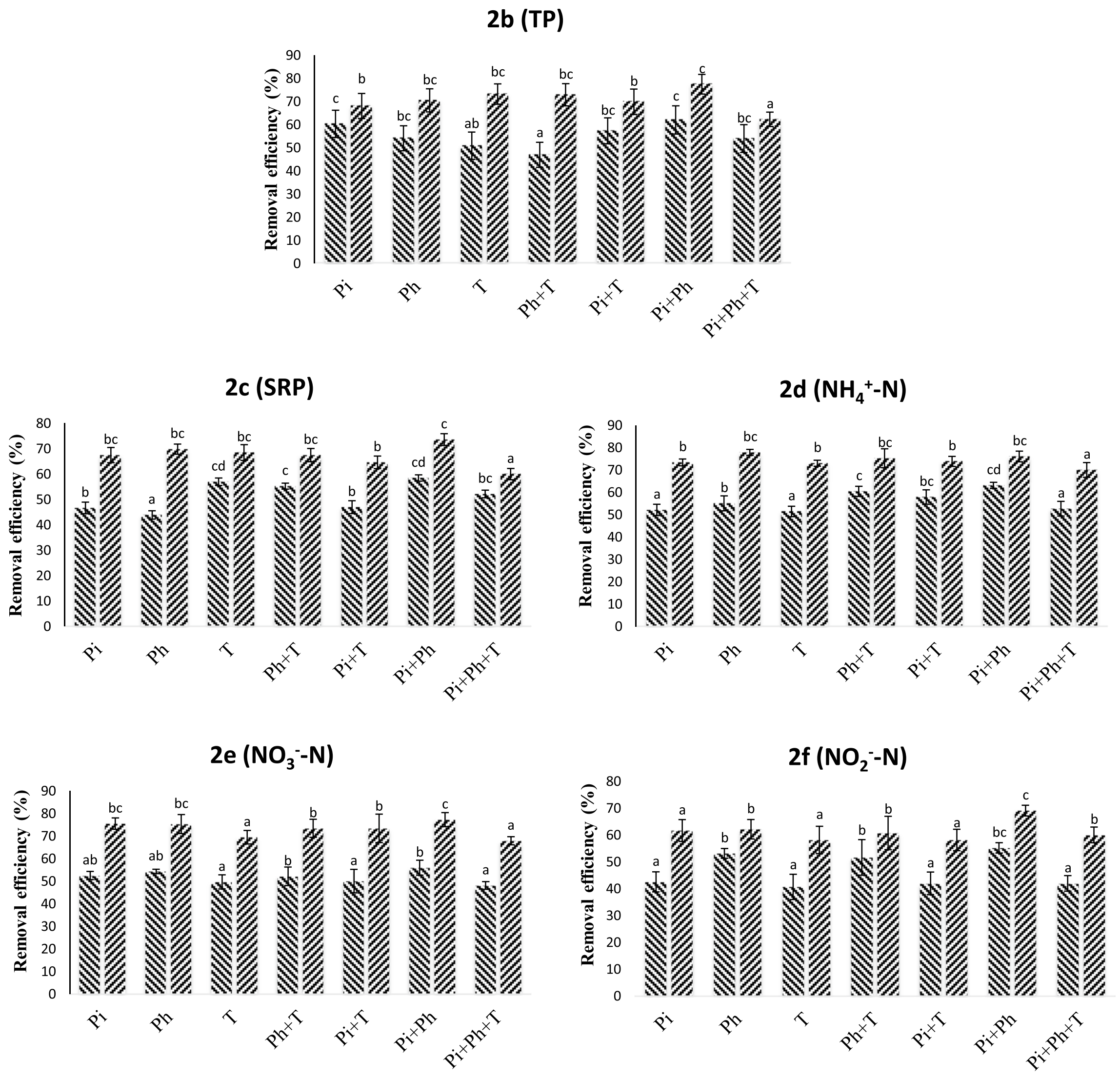

Fig. 2 **a, b, c, d, e**, and **f** represents the removal efficacy of several water quality parameters in different CWM units at two retention times (mean ± SD, *n* = 24). Different letters on the error bars signify the differences in the mean contaminant removal of various CWM units

the assimilation and uptake by macrophytes and microbial populations existing in CWMs as described in earlier studies (Khan et al. 2011, 2015; Engida et al. 2020; Kumar et al. 2020).

Integration of CWs as a Post-treatment System

The UASB-based STPs have been extensively used for the treatment of domestic wastewater in Brazil, Africa, Columbia, and India (Vassalle et al. 2020). Recently, in India, 200 UASB reactors are utilized to treat municipal and industrial wastewater. It is also reported that 80% of the total worldwide installed UASB reactors for municipal wastewater treatment are present only in India (Khan et al. 2011). The main aim of the selection of this method for sewage treatment is due to its low energy requirements, lower capital and operation, maintenance costs, and sustainability aspect. However, both processes alone cannot be seen as giving 'complete' ecological resolution as their effluents always do not fulfill the discharge criteria mainly for nutrients, residual carbon, pathogens, and heavy metals. The major wastewater treatment technology utilized for the treatment of domestic wastewater throughout the world is UASB-based STPs (Engida et al. 2020). The major drawbacks of anaerobic digesters are the requirement of a long retention time for solids, a long start-up period, impure biogas, and incomplete or insufficient removal of organic matter, pathogens, and nutrients. Therefore, researchers are trying to find out new technologies to enhance the performance of anaerobic digesters, especially on the effluent quality, start-up, and biogas purification, to develop global efficient and sustainable wastewater treatment technologies (Chong et al. 2012). Removal of BOD by different CWM units in the present study exhibited that the concentration of BOD after three days of retention time successfully meets the discharge criteria of inland surface water. However, the removal capability of UASB- and FAB-based STPs alone does not meet the discharge standards (Fig. 3).

The removal efficacy of UASB reactors for several wastewater contaminants is enhanced significantly by integrating them with other available wastewater treatment technologies. Several defined treatment technologies utilized for the treatment of domestic wastewater are not economically viable, eco-friendly, and sustainable. However, the integration of CWs with available domestic wastewater treatment technologies may give the best alternative to others due to its cost-effectiveness and environmental friendliness (Tufaner and Avşar 2016, Tufaner 2020). The removal capability of UASB reactors in integration with CWs in terms of BOD (up to 98%) and (fecal coliform) FC (99.99) reached the highest as compared to other available treatment technologies for domestic wastewater (Sharda et al. 2013). However, the removal of chemical oxygen demand (COD) (90%), total suspended solids (TSS) (92%), TN (89%), NH_4^+–N (70%), and TP (88%) was also observed as optimum as reported in previous studies (Comino et al. 2013; Khan et al. 2015; Matos et al. 2017; Tufaner 2020) (Figs. 4, 5). The hydraulic loading rates of UASB and CWs were 3–6 h and 10 days, respectively.

The removal efficiency of UASB reactors for several wastewater contaminants working across India has varied significantly. The data collected from various published articles exhibited that maximum removal of BOD was recorded in Noida (79 ± 0.89%) having the treatment capacity of 34 MLD followed by Kanpur (72 ± 1.41%). However, the highest removal of COD and TSS (75 ± 1.2 and 70 ± 0.87, respectively) was exhibited by the UASB reactor working at the Vadodara, Gujrat (Table 3). Such high removal efficacies of the UASB reactors may be due to the appropriate management and effective functioning of the reactors. However, the minimum removal efficiency observed in Surat, Gujrat, and Ludhiana, Punjab may be due to the improper management and operation of reactors (Bula 2014). The removal capacity for domestic wastewater has been enhanced significantly by integrating the CW system with UASB reactors (Engida et al. 2020). Several UASB-based STPs together with polishing ponds have been set up in several cities of India within the Yamuna action plan. Such integrated systems worked efficiently to enhance the removal capability of several pollutants. The polishing pond was designed as a post-treatment facility in this system having 24 h of retention time with a 1.25 m water depth).

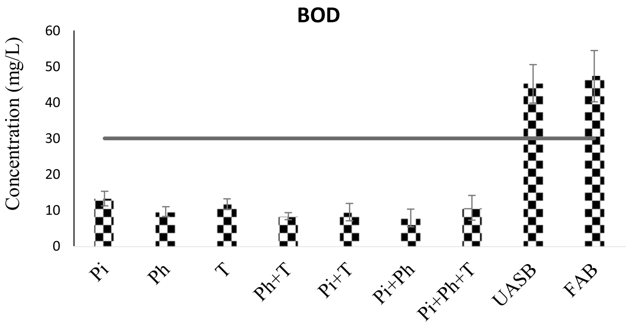

Fig. 3 Comparative removal efficiency of BOD within different CWM units along with UASB- and FAB-based reactors. The horizontal straight line represents the discharge limit of BOD in a freshwater ecosystem as prescribed by the Environmental Protection Agency (EPA 1986)

Reuse of Treated Wastewater

The reuse of treated DW for several activities such as agriculture, maintaining the base flow of rivers, gardening, etc. is a pleasing solution that can provide an alternative water resource, especially in water-scarce regions. After suitable

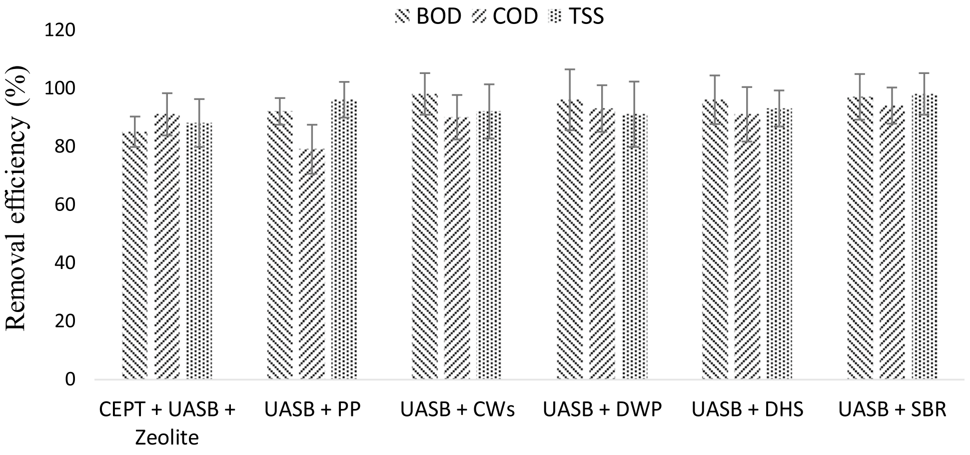

Fig. 4 Performance of UASB-based STPs integrated with several other wastewater treatment technologies for BOD, COD, and TSS removal (mean ± SD) as exhibited earlier (Sharda et al. 2013; Engida et al. 2020)

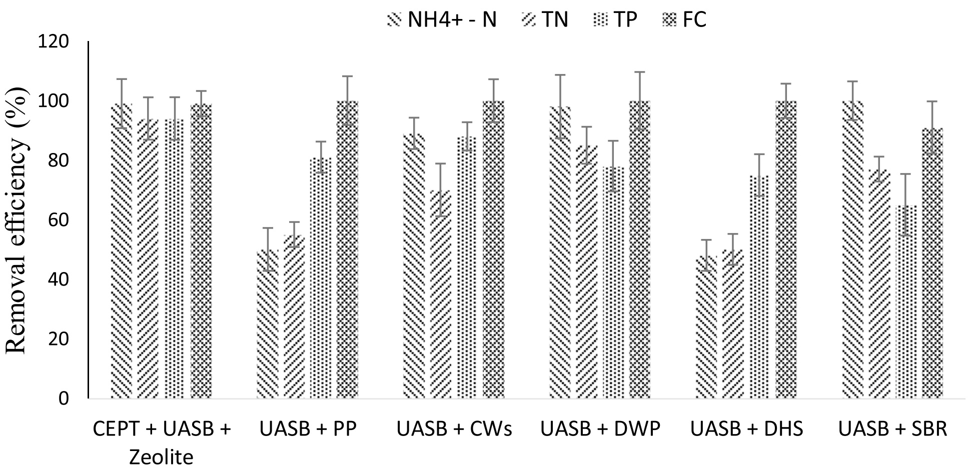

Fig. 5 Performance of UASB-based STPs integrated with several other wastewater treatment technologies for NH_4^+–N, TN, TP, and FC removal (mean ± SD) as shown in various previous studies (Khan et al. 2011; Engida et al. 2020). CEPT, chemically enhanced primary treatment; PP, polishing ponds; CWs, constructed wetlands; DWP, duckweed pond; DHS, down-flow hanging sponge; SBR, sequential batch reactor

Table 3 Treatment performance of some UASB-based STPs working across India

STPs location	Capacity (MLD)	% Removal		
		BOD	COD	TSS
Agra	78	48 ± 2.3	43 ± 2.3	41 ± 4.21
Noida	27	53 ± 1.02	41 ± 3.45	59 ± 3.15
Noida	34	79 ± 0.89	51 ± 2.18	54 ± 4.12
Saharanpur	38	60 ± 2.15	55 ± 1.64	60 ± 3.1
Ghaziabad	56	60 ± 2.6	45 ± 2.4	–
Ghaziabad	70	60 ± 1.52	45 ± 3.64	–
Kanpur	–	72 ± 1.41	–	
Mirzapur	–	63 ± 1.13	–	–
Karnal, Haryana	40	60 ± 0.65	62 ± 2.51	54 ± 0.95
Vadodara, Gujrat	43	62 ± 0.98	75 ± 1.2	70 ± 0.87
Surat, Gujrat	100	47 ± 3.85	42 ± 5.4	40 ± 5.12
Ludhiana, Punjab	111	66 ± 1.92	59 ± 3.1	54 ± 6.23
Ludhiana, Punjab	152	59 ± 5.2	55 ± 4.21	49 ± 4.12
Ludhiana, Punjab	48	45 ± 6.12	29 ± 7.15	51 ± 2.01

treatment, it may be utilized to reduce the water stress by improving the groundwater table via recharge. It can also be further used for the production of crops and the design of green belts to lessen the dependency on natural water reservoirs (Declercq et al. 2020). Around 200 million farmers throughout the globe produce market-based crops using recycled water (Qadir and Scott 2009). For, e.g., approximately 60–100% of green vegetables are grown under-treated water irrigation in West African countries (Pratap et al. 2021). Wetlands are used as an alternative for wastewater treatment and reuse for the production of crops in Vientiane, the capital of Laos (Angelakis and Gikas 2014). In Melbourne, Australia, several vegetables such as cabbage, broccoli, lettuce, and cauliflower are produced by reusing treated water originating from household activities (Barker 2014). Similarly, a variety of green vegetables are grown by irrigation of recycled sewage discharged from the Okhla and Keshopur STPs in New Delhi, India (Kaur et al. 2012). In Southern Italy within the Apulia Region, a huge volume of treated municipal wastewater is utilized for growing nectarine trees (Moretti et al. 2019). However, several villages in Karnataka, India, also use recycled water for irrigation of fruit plants such as mango, sapota (chiku), guava, banana, coconut, pomegranate, and medicinal and flowering plants such as neem, curry leaf, lemon galimara, mulberry, etc. (Pratap et al. 2021). The major advantages of the reuse of treated water are it possesses a considerable amount of nutrients required for plant growth and encourages the metabolic activity of microbial populations. It also increases the production of crops and reduces fertilizers requirement and nutrient recycling. Together with these, several ecological services such as fisheries, valuable wildlife, aesthetic values, and recreational uses are also encouraged by treated wastewater (Kumar and Dutta 2019).

Conclusion

The UASB-based STPs have been extensively used for the treatment of domestic wastewater in several countries including India. Recently in India, 200 UASB reactors are utilized to treat municipal and industrial wastewater. Around 80% of the total worldwide installed UASB reactors for municipal wastewater treatment are present only in India. The removal efficacy of UASB reactors for several wastewater contaminants is enhanced significantly by integrating them with CWs as a post-treatment facility. In the present study, we have evaluated that the concentration of BOD in the effluent of different CWM units after three days of retention time successfully meets the discharge criteria of inland surface water. The maximum removal performance of several contaminants was expressed by the CWM unit planted with *Pistia Stratiotes* and *Phragmites karka*

(Pi + Ph). However, the maximum removal of BOD via the UASB reactor was recorded in Noida (79 ± 0.89%) having a treatment capacity of 34 MLD. From the study, it is concluded that both the UASB- and FAB-based reactors alone have not achieved water quality up to discharge standards. However, the removal capability of the UASB reactor in integration with CWs in terms of BOD reached the highest (up to 98%) as compared to other available treatment technologies for domestic wastewater. The removal of COD (90%), TSS (92%), TN (89%), NH_4^+–N (70%), and TP (88%) was also observed as optimum.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s41742-022-00485-8.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

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