Water Practice & Technology

Water Practice & Technology Vol 19 No 4, 1427 doi: 10.2166/wpt.2024.071

Demonstration and performance analysis of on-beach public toilet with a decentralised modified French vertical flow constructed wetland and *ex situ* electrochlorination integrated treatment system

Jayanta Kumar Gogoi, Priya Sharma, Guruprasad Talekar, Swapnil Punyapwar, Keyur Namdev and Srikanth Mutnuri*

Water, Sanitation and Hygiene Laboratory, Department of Biological Sciences, Birla Institute of Technology and Science, K K Birla Goa Campus, NH 17 B, Zuarinagar, Goa 403 726, India
*Corresponding author. E-mail: srikanth@goa.bits-pilani.ac.in

SM, 0000-0001-6956-0143

ABSTRACT

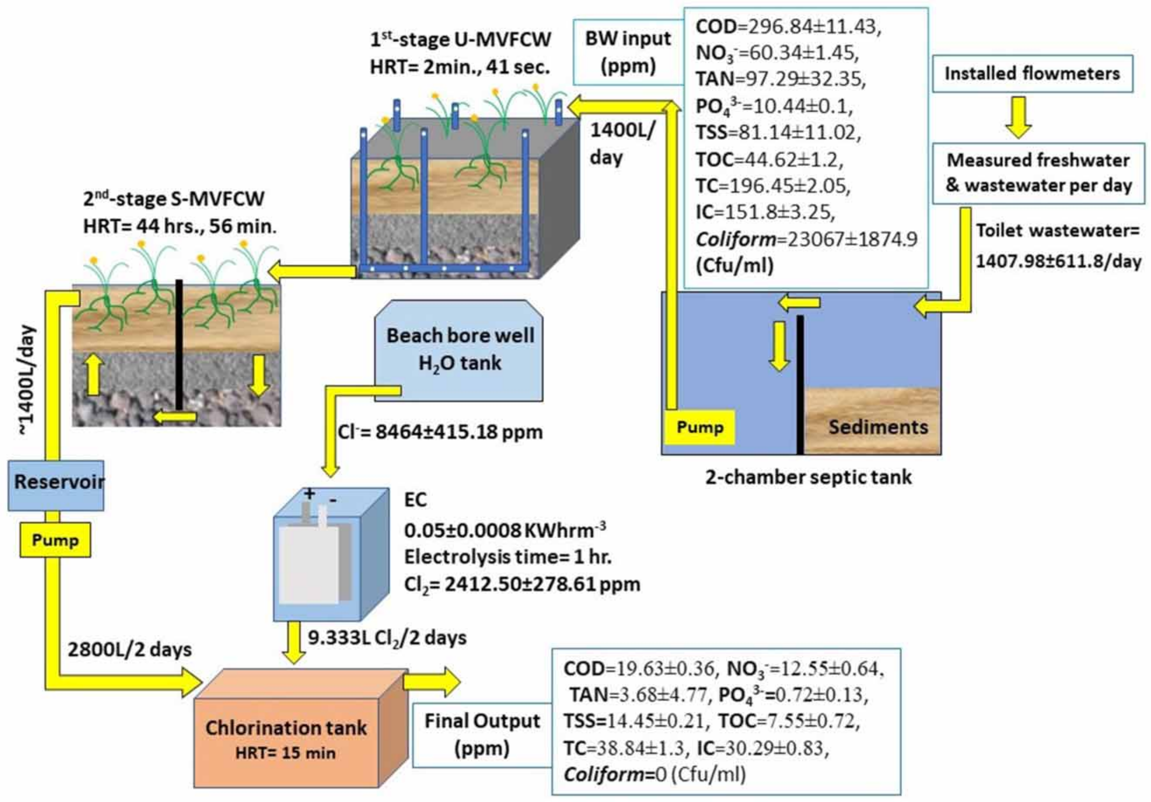
This study demonstrated an on-beach public toilet equipped with a sustainable decentralised treatment system in Goa, India. The number of toilet users, freshwater demand, and wastewater (WW) generated per day were documented. The treatment system consisted of a modified French-type vertical flow constructed wetland (MVFCW) and electrochlorinator. The first and second stage MVFCW were an unsaturated and saturated type, respectively. The onsite beach bore well water with a chloride concentration of 8464 ± 415.18 mg/L was electrolysed for 1 h at 40.49 Am^{-2}. Then MVFCW effluent was disinfected by dosing 2412.50 ± 278.61 mg/L of chlorine (Cl_2) generated at a disinfectant dilution ratio of 1:300 (Cl_2:WW). The average daily toilet users, freshwater usage, and WW generated were 96 ± 17.02, 1381.38 ± 380.35 L, and 1407.98 ± 611.8 L, respectively. The integrated treatment system treated 1,400 L/day. The integrated treatment system achieved an average percentage removal of 93.38 ± 0.38% chemical oxygen demand, 79.18 ± 1.55% NO_3^-, 98.45 ± 0.22% total ammoniacal nitrogen, 93.13 ± 1.19% PO_4^{-3}, 87.28 ± 0.2% total suspended solids, 83.09 ± 1.16% total organic carbon, 80.22 ± 0.87% total carbon, 80.05 ± 0.12% inorganic carbon, and 100% coliform. The power consumption cost was 0.17 INR m^{-3}.

Key words: decentralised, electro-chlorinator, *ex situ* electrochlorination disinfection, modified French vertical flow constructed wetland, public toilet, wastewater

HIGHLIGHTS

- This is India's first study of on-beach public toilets equipped with a decentralised treatment system.
- Research gaps of per day public toilet users, freshwater usage, and wastewater generated were documented.
- Modified French vertical flow constructed wetland optimised redox potential achieved simultaneous nitrification and denitrification.
- The onsite beach bore well water chloride was utilised for chlorine production.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Access to safe, clean water and sanitation is essential for public health. However, it is challenging to provide it in public areas of developing countries like India (Hutton & Chase 2017; Hans 2023). Unhygienic sanitation in developing countries is mainly due to improper or unavailability of infrastructure, the cost of waste management, or the failure of toilet maintenance. The Indian government, through the Swachh Bharat mission scheme, has been trying to provide a toilet to every individual household. However, the problem arises in managing the blackwater (BW) generated. According to the Central Pollution Control Board (CPCB) – India 2020 report, the sewage generated was 72,368 million litres per day (MLD), whereas the central treatment capacity was only 26,869 MLD. Thus, accounting for 72% of urban sewage is disposed of in the surface water bodies of India. Hence, 75% of surface water bodies across India are contaminated (Showkat 2016).

Thus, the importance of a decentralised treatment system is the need for the hour. Therefore, understanding their potential and feasibility is necessary to promote the nationwide implementation of decentralised treatment systems. It could be empowered by documenting preliminary significant parameters like toilet users, freshwater demand, and wastewater (WW) generated daily to design decentralised and upscale treatment systems. This would aid in optimising the decentralised treatment units in terms of ease of operation, maintenance, and costs.

The constructed wetland (CW) is widely used as the sustainable secondary WW treatment method due to its treatment efficiency, low power, and maintenance requirements (Vymazal 2010; Sharma *et al.* 2022; Shirgire *et al.* 2023; Gogoi & Mutnuri 2024). The treatment is achieved by a complex interaction of filter bed (sand, soil, or gravel), microorganisms, and plants. The filter bed factors like filter media size, filter layers distribution, zonation (saturated and unsaturated), and water flow direction significantly affect the WW treatment (Sharma *et al.* 2022; Gogoi & Mutnuri 2024). The treatment mechanisms involved are the physical treatment (sieve filtration, adsorption, and sedimentation) and biological treatment (microbial degradation/accumulation and phytoremediation) (Punyapwar & Mutnuri 2020; Sharma *et al.* 2022; Gogoi & Mutnuri 2024).

The CW vegetation majorly contributes to removing nutrients like nitrogen (total ammoniacal nitrogen (TAN), NO_3^-), phosphates, and potassium, hosting the microorganisms in the rhizosphere, and aerates the filter layer (Konnerup & Brix 2010; Sharma *et al.* 2022). The CW microbial group contributes to various pollutant removal majorly by nitrification, denitrification, enhanced biological phosphorous removal (EBPR), and aerobic and anaerobic organic matter degradation, based on the CW-designed conditions (Sharma *et al.* 2022; Gogoi & Mutnuri 2024). Nitrification is an obligate aerobic process which oxidises ammonia to nitrate in a two-step process by a group of chemoautotrophic bacteria. Both the nitrifying bacteria groups use oxygen as a terminal electron acceptor for energy production, e.g., *Nitrobacter, Nitrosococcus, Nitrosomonas* (Burghate & Ingole 2013). Nitrification is preceded by ammonification, where the organic-bound nitrogen matter is degraded into inorganic ammonium. The denitrification process removes NO_3^- by reducing it to nitrogen by facultative aerobic bacteria in a strict anaerobic condition, with NO_3^- as an alternative terminal electron acceptor. The external carbon source or the carbon:nitrogen ratio (C:N) acts as a reaction rate-limiting factor (Kostrytsia *et al.* 2018; Gogoi & Mutnuri 2024). However, some bacteria can perform denitrification by an autotrophic pathway, e.g., *Paracoccus, Thiobacillus*, and *Ferrobacillus ferrooxidans* (Carboni *et al.* 2021). The EBPR process removes orthophosphate (PO_4^{-3}) from WW by taking up extracellular orthophosphate and storing it as polyphosphate reserve (polyhydroxyalkanoates or polyhydroxy butyrate). The process is favoured by exposing polyphosphate-accumulating organisms to sequential anaerobic to aerobic conditions, e.g., *Acinetobacter, Corynebacterium, Pseudomonas* (Kim & Lenz 2001; Yuan *et al.* 2012; Gogoi & Mutnuri 2024).

Vertical flow constructed wetlands (VFCWs) are the most common type of CWs used for various WW treatments (Yadav *et al.* 2018; Punyapwar & Mutnuri 2020; Gogoi & Mutnuri 2024). The VFCW shows higher efficiency in the removal of chemical oxygen demand (COD), TAN, total suspended solids (TSS), and ortho-phosphates (PO_4^{3-}) than the horizontal flow CW and surface flow CW (Vymazal 2007; Sharma *et al.* 2022). However, the VFCW types show a hike in NO_3^- (Gogoi *et al.* 2023; Yaragal & Mutnuri 2023; Gogoi & Mutnuri 2024). Hence, the scope of modifying the VFCW design for holistic nitrogen removal (simultaneous ammonium and nitrate removal) can be studied. The VFCW can either be a single-stage VFCW or a two-stage VFCW (French VFCW type). The French VFCW is popularly used for the WW with higher pollutants than the single-stage VFCW due to double or two-stage treatment exposure (Yadav *et al.* 2018; Sharma *et al.* 2022).

Electrochemical systems have gained importance in the disinfection or oxidation of WW treatment. The electrochemical reactor (ECR), with high treatment efficiency and a small footprint, can be easily used as a component of a decentralised treatment system. The electro-oxidation or disinfection is achieved by either direct oxidation (by free hydroxide radicals and active oxygen species) or indirect anode oxidation (by generating reactive oxidative species such as chlorine, hypochlorite, and hypochlorous acid) (Gogoi *et al.* 2023). Chlorination can kill many human pathogens like bacteria and viruses by knocking electrons from the cell membrane or disrupting the cellular enzymes and nucleic acids (Huang *et al.* 2016).

In the previous study by Gogoi & Mutnuri 2024 and Gogoi *et al.* 2023, complete faecal coliform disinfection was achieved by the *in situ* electrochlorination disinfection of BW by electrolysing a dosed commercial-grade sodium chloride (NaCl) in the ECR containing BW. However, the scope of reducing the NaCl and power consumption cost, treatment time, and electrode fouling can be studied. Sea water is a rich source of chloride; hence, its potential for onsite chlorine generation by electrolysis for various disinfection purposes can be explored. Thus, the concept of *ex situ* electrochlorination disinfection using seawater can significantly reduce the cost of sodium chloride (commercial grade) and transportation and treatment time and slow the rate of electrode fouling. Dimensionally stable anodes like titanium or tantalum coated with a layer of RuO_2, IrO_2, PbO_2, SnO_2, or a mixture of these metal oxides (MMOs) are popularly used for chlorine generation (Gogoi & Mutnuri 2024; Gogoi *et al.* 2023; Talekar *et al.* 2018). A mixed metal oxide (MMO) is a dimensionally stable anode with high conductivity and corrosion resistance; hence highly preferred for electrolysis (Gogoi *et al.* 2023; Talekar *et al.* 2018).

One of Goa's famous beaches was chosen to install a public toilet system with decentralised integrated treatment. The treatment systems comprised a double-chambered septic tank, a modified French-type vertical flow constructed wetland (MVFCW), and an electro-chlorinator (EC). The BW treatment efficiency was verified by analysing various physio-chemical parameters over 8 months. The amount of freshwater used for different toilet purposes and the amount of WW generated per day were documented.

2. MATERIALS AND METHODS

2.1. Field site survey and construction

Bogmalo Beach in Goa, India (15.37°N, 73.83°E), was selected to demonstrate a public toilet integrated with decentralised treatment systems. The toilet block consisted of two rectangular containers placed 90 cm above the ground. The total dimensions were 7.7 m in length (L), 2.63 m in width (W), and 2.63 m in height (H) (Figure 1). The first container comprised one changing room, three ladies' toilets, and one accessible toilet, and second container comprised three male toilets, three male urinal pots, and one ECR room (Figures 1 and 2). The MVFCW was installed behind the toilet compartments as shown in Figure 2.

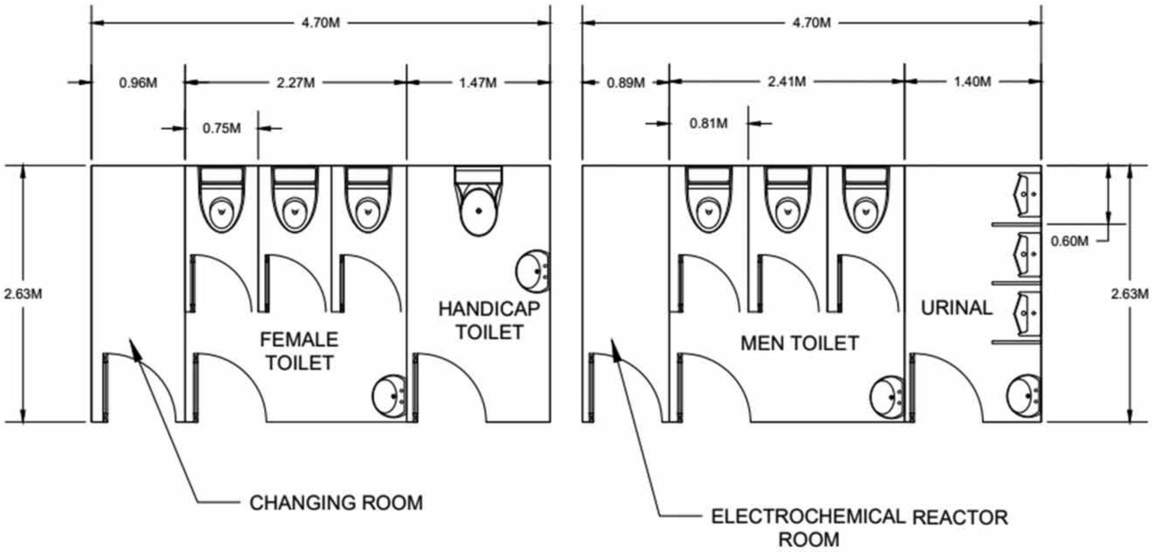


Figure 1 | Distribution and dimensions of public toilet compartments (Autodesk® AutoCAD®, 2021).

Figure 2 | Public toilet with decentralised integrated treatment system at Bogmalo Beach, India. (a) Changing room, (b) female toilet, (c) accessible toilet, (d) ECR, (e) male toilet, (f) male urinal, (g and h) fresh water tank, (i) toilet keeper, (j) first stage unsaturated MVFCW, and (k) second stage saturated MVFCW.

The septic tank measures 7.92 m in L, 1.9 m in W, and 1.9 m in H. It is underground beside the male urinal compartment and divided into two compartments using fibre-reinforced polymer (FRP) sheets for sedimentation. The tank has a headspace of 30 cm (Fig. S1). MVFCW and chlorination-reservoir tanks were placed underground below the female toilet compartments and had dimensions of 4.38 m (L), 1.9 m (W), 1.9 m (H) and 3 m (L), 1.9 m (W), 1.9 m (H), respectively (Fig. S1). All the tanks were made of FRP material.

2.2. Toilet preliminary data collection (toilet users, freshwater demand, and WW generated)

The two volunteers appointed for that task reported the number of toilet users per day data. Five flowmeters were installed at various outlet points to measure freshwater demand and WW generated per day by interpreting the respective flowmeter readings every 24 h (Figure 3). Japsin Kranti Kamg water meter with 20 mm waterline diameter (B0BVRJWS64) was used for flowmeter (a) and (b), whereas Kranti Kamg water meter of 15 mm waterline diameter (B06ZZ623VX) was used for flowmeter (c)–and (e), as shown in Figure 3.

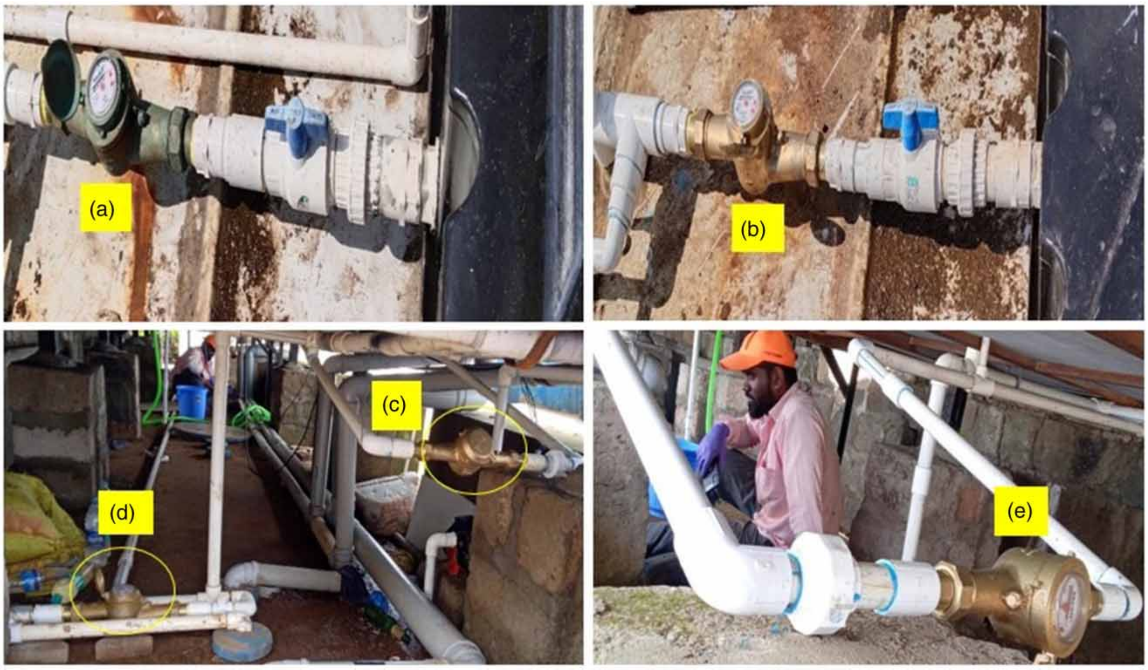


Figure 3 | Water flowmeters installed: (a) male (M) freshwater flowmeter, (b) female (F) freshwater flowmeter, (c) M hand wash & urinal flush flowmeter, (d) M hand wash, urinal flush, and urine flowmeter, and (e) F hand wash flowmeter.

2.3. Modified French-type vertical flow constructed wetland

Each of the two-stage modified MVFCW tanks was of FRP material, with dimensions of 8 m (L), 1 m (H), and 1.91 m (W). The two-stage MVFCW design was based on our previous study of single household toilet WW treatment by hybrid-VFCW (Gogoi & Mutnuri 2024). The MVFCW's first stage was unsaturated, and the second stage was saturated. The second stage MVFCW was saturated by partitioning the container into equal halves with a bottom space of 10 cm, which directed water to flow downwards in the first chamber and then upwards in the second chamber (Figures 4 and 5).

The sedimented BW from the second chamber of the septic tank was pumped into the first stage unsaturated MVFCW (U-MVFCW) at the flowrate of 350 L/min four times a day. The U-MVFCW outlet is made at the bottom drainage layer. Thus, BW percolates down the filter layers to the drainage layer and drains out to the second stage saturated MVFCW (S-MVFCW) by the gravity flow. Then, the S-MVFCW effluent drains from the outlet pipe in the second chamber just below 5 cm from the top filter layer. The S-MVFCW outlet was directly connected to the adjacent MVFCW reservoir tank. The passive aeration in the U-MVFCW was provided by employing perforated polyvinyl chloride (PVC) pipes at the drainage layer. The river gravels were used for the MVFCW filter media. The comparative filter media sizes and layering for U-MVFCW and S-MVFCW are shown in Figure 4. The filter media size for filter layer and transition layer of U-MVFCW was smaller than S-MVFCW as demonstrated in Figure 4. The MVFCW was planted with *Canna indica* due to its perennial growth type, rhizome root type, and adaptability to the soggy and Goa's tropical climate conditions (Figure 5).

2.4. Electro-chlorinator

2.4.1. Laboratory-scale studies

Initially, the Bogmalo Beach bore well water was analysed for chloride concentration to utilise it for electrolytic chlorine production. The lab-scale optimisation of the EC was studied for various parameters like electrode

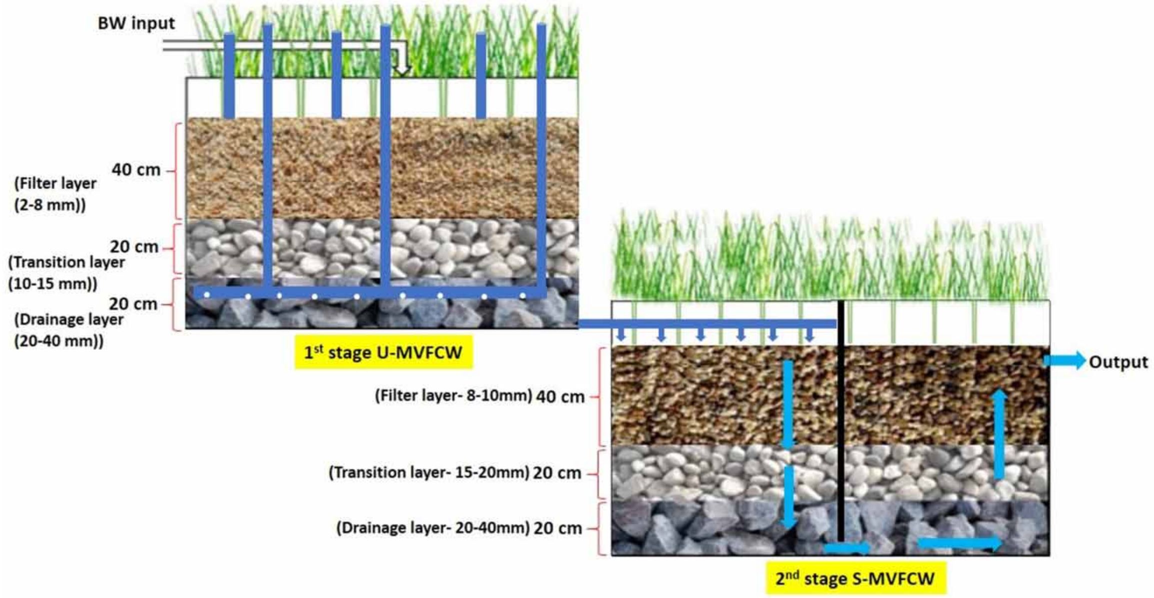


Figure 4 | Schematic diagram of MVFCW with filter media profile and feed flow path.

Figure 5 | Pictures of field site demonstrated MVFCW.

surface area, current density, electrolysis time, and disinfectant dilution ratio (Cl_2:WW). The titanium plate coated with 6-μm-thick MMO (70% ruthenium, 20% iridium, and 10% titanium) was used as the anode, while stainless steel (SS 304) mesh was used as the cathode (Gogoi & Mutnuri 2024; Gogoi *et al.* 2023; Talekar *et al.* 2018). The EC was set up in a glass beaker (500 mL) with a pair of electrodes connected to a variable direct current (DC) power supply unit (GW Instek GPS-4303) (Fig. S2). A magnetic stirrer was used to mix the EC contents at 100 rpm. The anode and cathode surface areas were 220.2 cm^2, respectively, and had a thickness of 1 mm. The 1 cm gap was maintained between the electrodes. Several experimental batches of electrolysis with time (30 min, 40, 50, and 60 min) and constant DC supply of 1.0 A, 1.5 A, 1.8 A, and 2 A were investigated to generate the targeted 2,000–3,000 mg/L of Cl_2.

Then, the Cl_2 generated was mixed with S-MVFCW effluent at various ratios (1:100, 1:150, 1:200, 1:250, and 1:300) to optimise the disinfectant dilution ratio (Cl_2:WW) and contact time (5 min, 10, 15, and 20 min) in another set of auxiliary experiments. The dilution ratio that caused complete faecal *coliform* disinfection while maintaining the residual Cl_2 within the World Health Organization discharge limit (less than 5 mg/L) was used for upscaling.

2.4.2. Field-scale setup

The field-scale EC was designed in reference to the lab-scale EC optimised parameters. The EC reactor was a rectangular tank with a total volume capacity of 12 L and 10 mm thick polyacrylic sheets. The electrode materials were like those used in laboratory-scale experiments, except the cathode was SS 316 grade plate. The total electrode surface area was scaled up to 8,149.6 cm^2. The EC reactor operation was automated for 1 h as shown in Figure 6. The overhead beach bore well water (electrolyte) tank was connected to the EC through an automated input solenoid valve (Figure 6). The 9.333 L of electrolyte was dosed in the EC tank by opening the solenoid valve. Then, the EC reactor was subjected to electrolysis for 1 h with a constant current from a DC power supply (GW Instek PSW 30-108) to generate Cl_2. The contents of the reactor were mixed with a circulating automatised DC water pump. The DC water pump fixed at the bottom of the EC drained the Cl_2 produced after electrolysis into a chlorination tank containing 2,800 L of final MVFCW-treated effluent for disinfection. This *ex situ* electrochlorination disinfection (*ex situ* ECl_2) process was carried out every 48 h.

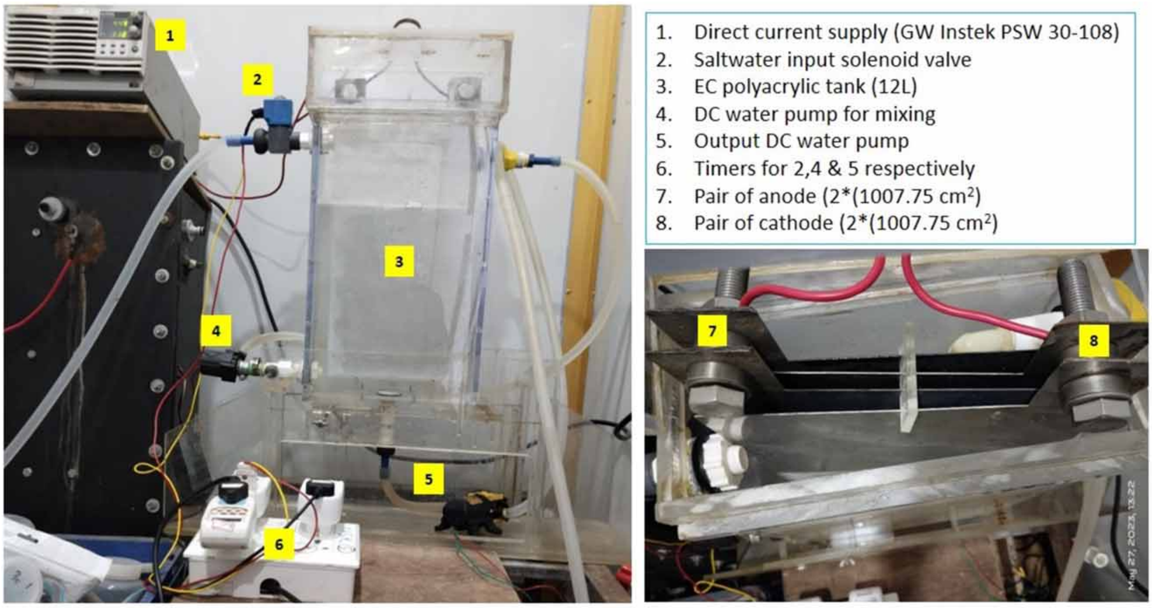


Figure 6 | Field-scale automatised electro-chlorinator design.

2.5. Sampling and analysis

The samples were collected twice a week and analysed within 24 h throughout testing. The samples were analysed using the standard methods for various WW parameters, i.e., COD-5220 D closed reflux colourimetric method, orthophosphate (PO_4^{3-})-Vanado-molybdophosphoric acid colourimetric method, TSS-2540 D method, total organic carbon (TOC), inorganic carbon (IC), and total carbon (TC)-the Shimadzu TOC-TNM-L ROHS analyser. Further, the chlorine (Cl_2), chloride (Cl^-), nitrate (NO_3^-), and TAN concentrations were analysed by Spectroquant® kits such as chlorine test kit (1.00602.0002), chloride test kit (1.14730.0001), nitrate test kit (1.01842.0001), and ammonium test kit (1.00683.0001) using Spectroquant® Prove 100 spectrophotometer, respectively. The pH was measured using Oakton pH 510 Series Meter P/N 54X002608, and the faecal coliform count was obtained by MacConkey's standard plate count method (APHA/AWWA/WEF 2012; Gogoi *et al.* 2023).

3. RESULTS AND DISCUSSION

3.1. Preliminary data collection of (toilet users, freshwater demand, and WW generated per day)

The study attempted to document data on the frequency of public toilet usage, freshwater usage, and WW generation per day. Male toilet users were more than female toilet users per day (Table 1). The accessible toilet was used only once in the 8 months of study.

The average freshwater utilised and WW generated daily were 1,381.38 ± 380.35 L and 1,407.98 ± 611.8 L, respectively (Table 2). The daily male urine waste was 26.6 ± 22.49 L (Table 2). However, the female urine

Table 1 | Various toilet facilities users per day

Toilet facilities	Average users/day
Male toilet	31 ± 15.68
Male urinal	35 ± 18.93
Female toilet	30 ± 16.45
Female changing room	27 ± 19.64
Shower	37 ± 23.81
Total	*161 ± 86.66*

Table 2 | Fresh water usage and wastewater generated per day interpretation by flowmeters

Outlet points	Litres/day
Male freshwater outlet	874.78 ± 472
Male hand wash and urinal flush	93.94 ± 95.61
Male toilet flush and anal cleansing	780.84 ± 450.85
Male urine	26.6 ± 22.49
Female freshwater outlet	506.6 ± 288.7
Female toilet flush and anal cleansing	472.99 ± 76.28
Female hand wash	33.61 ± 74.65
Average wastewater/day	1,407.98 ± 611.8

generated per day was not documented due to the lack of a separate pan for the female urinal facility. As per Tables 1 and 2, interpretations of per day freshwater usage for toilet flush and anal cleansing per male and female were 25.19 L (780.84 L/31) and 15.77 L (472.99/30), respectively. In contrast, per day, freshwater used for overall toilet facilities per male and female were 13.25 L (874.78 L/66) and 16.89 L (506.6 L/30), respectively. Hence, overall, female water usage was more than male toilet users. These data can significantly improve public sanitation understanding regarding freshwater demand, WW generation, and decentralised treatment efficiency for scaling up the systems.

All the toilet facilities' usage was charged 10 INR per person (0.095 GBP per person per usage) for the maintenance of the toilet. The average number of users per day for various toilet facilities is shown in Table 1, with a total average of 161 ± 86.66 users per day. This accounted for the monthly money collection of 48,300 INR (458.69 GBP). Hence, the significant risk of toilet systems failing shortly after installation in India due to a lack of financial support and maintenance was resolved.

3.2. Modified French-type vertical flow constructed wetlands

The MVFCW was developed by changing the filter bed profile, hydraulic flow pattern, and hydraulic retention time (HRT) of the traditional French VFCW, as shown in Figure 4. The U-MVFCW HRT is 2 min and 41 s, while the S-MVFCW HRT is 44 h and 56 min. The septic tank effectively removed 28.73 ± 7.55% of TSS during primary treatment.

The U-MVFCW comparatively showed the highest removal for COD (78.74 ± 1.04%), TAN (89.16 ± 7.36%), TSS (78.45 ± 2.33%), TOC (70.27 ± 1.38%), TC (84.79 ± 0.63%), IC (89.05 ± 0.62%) and faecal coliform (93.00 ± 5.4%) than the S-MVFCW (Figure 7). The prominent reason can be due to the proper aerobic filter zonation's or ventilated filter layers, which enhances the nitrification, organic matter degradation, and IC escapes to the atmosphere than the saturated-anaerobic condition of S-MVFCW. The TC sums the total concentration of TOC and IC. Further, the higher removal of TSS and faecal coliform can be prominently due to the smaller filter media size than the S-MVFCW, as shown in Figure 4.

The U-MVFCW also showed NO_3^- removal by 44.45 ± 7.05%, indicating the presence of pockets of the anoxic zone, which favoured the denitrifying microorganisms (Figure 7). The carbon-to-nitrogen ratio (C: N) input for U-MVFCW was 4.92 ± 0.07 mg/L. The U-MVFCW was designed majorly for TSS removal and to maintain aerobic filter zones for nitrification (TAN removal), favoured more by an unsaturated type design.

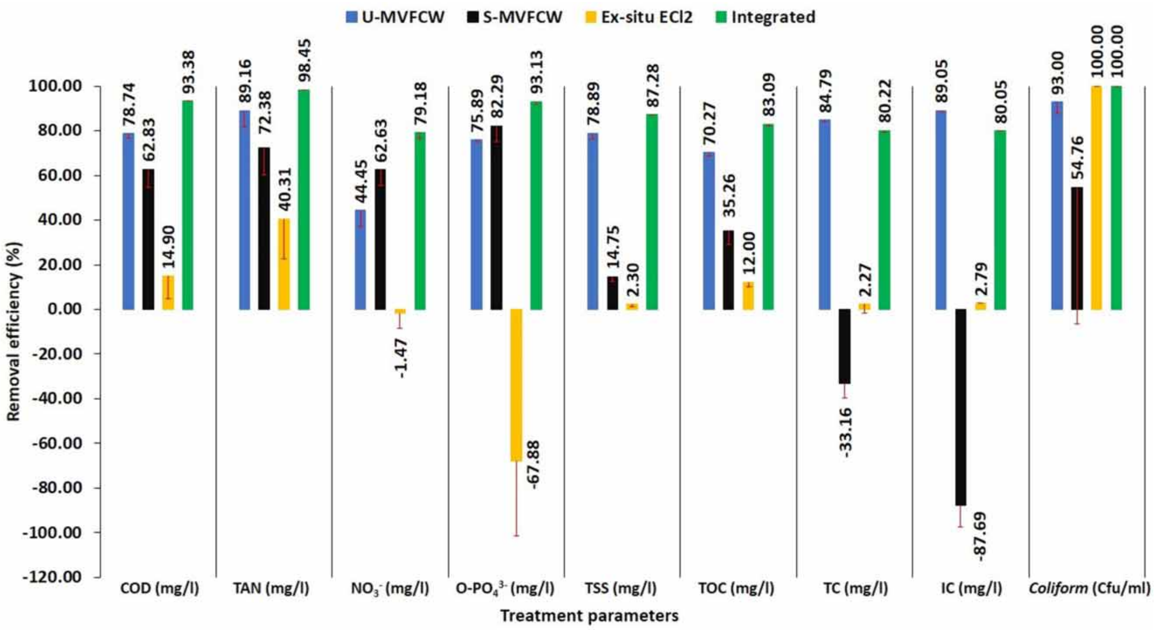


Figure 7 | Sequential wastewater treatment efficiency by decentralised integrated treatment systems.

The S-MVFCW showed the highest removal for NO_3^- (62.63 ± 7.08%) and PO_4^{3-} (82.29 ± 6.88%) than the U-MVFCW and EC-integrated treatment system (Figure 7). The C:N input for S-MVFCW was 1.89 ± 0.12 mg/L. The saturated volume capacity of the S-MVFCW (with filled gravels) is 2,621.11 L. Thus, per day, 1,400 L fed (U-MVFCW effluent) in S-MVFCW drains out after 44 h, 56 min retention by volume displacement mechanism. The HRT was optimised based on the efficient nitrate removal in reference to our previous study (Gogoi & Mutnuri 2024). The anaerobic (drainage and transition layers) and aerobic (filter layer) zones in S-MVFCW for simultaneous denitrification and EBPR were favoured by the saturated type design. The anaerobic zones in S-MVFCW can be determined by the increase in IC concentration due to the anaerobic degradation of TOC, as shown in Table 3. This resulted in more efficient denitrification than the U-MVFCW. The TAN removal observed was 72.38 ± 12.11% due to the nitrification in the aerobic zone of the filter layer or/and the ammonia assimilation metabolism (Gogoi & Mutnuri 2024; Nelson *et al.* 2015).

Table 3 | Results of the public toilet wastewater parameters treatment by decentralised integrated treatment system

	Average reduction observed			
Parameters	**Septic tank**	**U-MVFCW**	**S-MVFCW**	***Ex situ* ECl_2**
COD (mg/L)	296.84 ± 11.43	63.16 ± 5.53	23.25 ± 3.18	19.63 ± 0.36
TAN (mg/L)	97.29 ± 32.35	19.61 ± 5.25	6.69 ± 6.01	3.68 ± 4.77
NO_3^- (mg/L)	60.34 ± 1.45	33.57 ± 5.06	12.37 ± 0.49	12.55 ± 0.64
PO_4^{3-} (mg/L)	10.44 ± 0.1	2.52 ± 0.03	0.44 ± 0.17	0.72 ± 0.13
TSS (mg/L)	81.14 ± 11.02	17.36 ± 0.49	14.79 ± 0.03	14.45 ± 0.21
TOC (mg/L)	44.62 ± 1.2	13.26 ± 0.26	8.57 ± 0.65	7.55 ± 0.72
TC (mg/L)	196.45 ± 2.05	29.89 ± 1.55	39.75 ± 0.18	38.84 ± 1.3
IC (mg/L)	151.8 ± 3.25	16.64 ± 1.29	31.16 ± 0.82	30.29 ± 0.83
Faecal *coliform* (Cfu/mL)	23,067 ± 1,874.9	1,533.33 ± 1,665.3	516.67 ± 980.93	0
pH	7.55 ± 0.01	6.97 ± 0.18	7.56 ± 0.11	7.29 ± 0.19
Residual Cl_2 (mg/L)	–	–	–	1.6 ± 0.92

Note: First chamber septic tank TSS: 113.67 ± 3.43 mg/L.

Further, the scope of denitrification in S-MVFCW can be enhanced by increasing the input's C:N ratio (Gomez *et al.* 2000; Burghate & Ingole 2013; Kostrytsia *et al.* 2018). There was no clogging issue faced in the S-MVFCW. However, the tertiary disinfection treatment was required as incomplete faecal *coliform* removal was observed post the MVFCW (Table 3). Hence, EC was integrated for complete disinfection.

In U-MVFCW, passive aeration was accomplished using a PVC aeration pipe, *Canna indica* roots (~15–20 cm long), and atmospheric gas exchange in the filter layer. *Canna indica* also enhanced the filter layer's atmospheric gas exchange by its movement due to wind. To maintain an anaerobic zone in drainage and transition layers, the S-MVFCW was saturated up to 35 cm of the filter layer (40 cm). Meanwhile, the filter layer was maintained aerobic by the plant's root and atmospheric gas exchange (passive aeration). The two-stage MVFCW was designed prominently with a high redox gradient for the simultaneous removal of TAN and NO_3^- in U-MVFCW and S-MVFCW, respectively. At the same time, the EBPR was achieved in a sequential exposure of anaerobic (drainage and transition layers) to aerobic (filter layer) zones of S-MVFCW (Yuan *et al.* 2012; Gogoi & Mutnuri 2024). The varying IC concentration can be an approximate indicator of anaerobic and aerobic conditions in the S-MVFCW and U-MVFCW, respectively (Table 3).

3.3. Electro-chlorinator

3.3.1. Laboratory-scale results

The chloride concentration of beach bore well water was 8,464 ± 415.18 mg/L. The other parameters of beach bore well water were also analysed, i.e., pH, 7.53 ± 0.01; TOC, 4.74 ± 2.01 mg/L; PO_4^{-3}, 0.36 ± 0.08 mg/L; IC, 31.19 ± 25.68 mg/L; and TC, 35.9 ± 27.65 mg/L. The pair of electrodes' surface area was 440.4 cm^2. After several trial batches of experiments, the optimum current density and the electrolysis time for generating 2,304.88 ± 57.78 mg/L of chlorine solution (500 mL) were found to be 45.41 Am^{-2} and 1 h, respectively. The optimum disinfectant dilution ratio based on complete faecal *coliform* disinfection and permissible limit of residual chlorine was found to be 1:300 (Cl_2:WW), with a residual Cl_2 of 1.13 ± 0.92 mg/L (World Health Organization discharge limits: less than 5 mg/L). Then, the lab-scale EC optimised parameters were scaled to design the field-scale EC.

3.3.2. Field-scale results

The optimised 33A DC supply was provided for 1 h of electrolysis to generate Cl_2 of 2,412.50 ± 278.61 mg/L. The lab-scale optimised disinfectant dilution ratio (1:300) was applied to the field scale by dosing 9.333 L of Cl_2 into a chlorination tank containing 2,800 L MVFCW effluent. The final MVFCW effluent contained 516.67 ± 980.93 Cfu/mL of faecal *coliform* (Table 3). The *ex situ* electrochlorination method achieved complete faecal *coliform* removal with permissible residual Cl_2 discharge limits of 1.6 ± 0.92 mg/L (Figure 7 and Table 3). The EC was automatically operated every 48 h to disinfect 2,800 L WW. The power consumption and cost were just 0.05 ± 0.0008 kWh m^{-3} and 0.17 INR m^{-3} of BW, respectively. The total cost of the electrodes was 42,135.46 INR.

The electrode fouling began after 67 days of treatment, confirmed by an increase in voltage requirement and white colour precipitation (probably sodium) on the surface of the cathode. However, there was no visual deposition on the anode surface. The cathode was cleaned with freshwater through scrubbing or dip washing in 10% nitric acid, while the anode was solely rinsed with fresh water (Gogoi *et al.* 2023). The *ex situ* ECl_2 disinfection method dosed the generated Cl_2 in WW separately in the highest disinfectant dilution ratio. However, the latest study by Gogoi *et al.* 2023 *in situ* electrochlorination disinfection method (*in situ* ECl_2) directly electrolysis WW with dosed chloride in the ECR itself and does not require a separate chlorination tank like the *ex situ* ECl_2 method. However, the *ex situ* ECl_2 method showed more advantages over the *in situ* ECl_2. That is, it can treat more WW in less electrolysis time (2,800 L WW/1 h) and less ECR size (2,800 L WW/9.333 L ECR (vol:vol)). However, the *in situ* ECl2 comparatively treated less WW, i.e., 8.5 L WW/8.5 L ECR in 1 h (vol:vol) (Gogoi *et al.* 2023). Hence, the *ex situ* ECl_2 method favoured less power consumption and its cost of just 0.05 ± 0.0008 kWh m^{-3} and 0.17 INR m^{-3} of BW, respectively. However, the power consumption and the price for the *in situ* ECl2 method were 6.24 ± 0.12 kWh m^{-3} and 36.13 INR m^{-3}, respectively, which is more expensive than the *ex situ* ECl_2 method by 35.96 INR m^{-3} (Gogoi *et al.* 2023). Another vital advantage of the *ex situ* ECl_2 method is a slower electrode (specifically cathode) fouling, observed after 67 days of treatment. Meanwhile, the *in situ* electrode fouling was observed within 63 days in both electrodes (anode and cathode) (Gogoi *et al.* 2023). The *in situ* ECl_2 also showed that anode fouling might be due to the deposition of organic matter, which can degrade the coating by frequent washing and increase the cost of operation. Hence, *ex situ* ECl_2 disinfection shows more sustainability for long-term operation.

The present EC applied current density (40.49 Am^{-2}), and its WW feed containing TOC of 8.57 ± 8.11 mg/L was considerably lower than the cases where disinfection by-products (DBPs) were detected as per the earlier work by the Hoffman group (Jasper *et al.* 2017). The intensity of current density and the amount of organic carbon drive the chlorine production and oxidation of organic matter potential, leading to the high possibility of DBP formation, e.g. tri-, di- and mono-chloromethane and chloroacetic acid (Huang *et al.* 2016; Jasper *et al.* 2017). The *ex situ* ECl_2 removed or reacted to only 1.02 mg/L of total organic matter (TOC); thus, the chances of DBP formation are negligible (Table 3). Thus, primary treatment systems like CWs with highly efficient removal of organic matter are preferable to pre-electrochlorination treatment to reduce the chances of DBPs.

Public toilets with a decentralised integrated treatment system promise to be efficient and cost-effective. The integrated treatment system efficiency in pollutant removal was $93.38 \pm 0.38\%$ COD, $79.18 \pm 1.55\%$ NO^{-3}, $98.45 \pm 0.22\%$ TAN, $93.13 \pm 1.19\%$ PO_4^{-3}, $87.28 \pm 0.2\%$ TSS, $83.09 \pm 1.16\%$ TOC, $80.22 \pm 0.87\%$ TC, $80.05 \pm 0.12\%$ IC, and 100% faecal *coliform* (Figure 7). The toilet was designed to be operational even in the monsoon or flood by raising the toilet compartments above 90 cm from the ground. The physical appearance of sequentially treated WW is shown in Fig. S3.

4. CONCLUSION

This study aimed to demonstrate a safe and clean public toilet equipped with a decentralised treatment system facility at Bogmalo Beach in India. The toilet unavailability or inadequacy faced by beach tourists has been effectively resolved. The study successfully addressed data gaps in Indian literature per day – beach public toilet usage, freshwater demand, and WW generation. The study documentation can serve as a critical reference for sanitation professionals and researchers for the ease of implementation of a public toilet along with a decentralised treatment system. The local government charged a toilet usage fee of 10 INR (0.0.095 GBP) per person, which accounted for approximately 48,300 INR (459.43 GBP) monthly collection. This generated income is used for the maintenance of toilets and treatment systems. The MVFCW has demonstrated high efficacy in the removal of pollutants from BW. Thus, this nature-based technology can help sustainably reduce WW's environmental impact. The *onsite* beach treatment of BW has made Cl_2 production through EC possible by utilising natural chloride sources of beach bore well water without commercial sodium chloride salt. This approach has reduced material and transportation expenses, making the process more cost-effective and efficient. *Ex situ* ECl_2 achieved 100% disinfection at a low energy input of just 0.05 ± 0.0008 kWh m^{-3}, lower than any employed WW electro-oxidation treatment.

Thus, a decentralised integrated treatment system promises an innovative and sustainable business model and effective climate-resilient WW treatment technology. Adopting this technology can reduce the need for costly and complex centralised infrastructure while addressing critical public health and environmental protection issues.

However, the scope of enhancing denitrification in S-MVFCW can be studied by increasing the input's C:N ratio by dosing the suitable external carbon. The comparative treatment efficiency and risk of DBP production by *in situ* electrochlorination and *ex situ* electrochlorination disinfection of WW need to be studied.

ACKNOWLEDGEMENTS

This research was funded by DBT-BIRAC and the Bill & Melinda Gates Foundation project entitled 'Empowered Septic Tank as Decentralised Wastewater Treatment System' under Phase II of the 'Reinvent the Toilet Challenge' (Grant number: BIRAC/GCI/2018/RTTC – BITS Phase 2). The village panchayat of Chicolna-Bogmalo (India) provided the site and sociopolitical support for the study.

AUTHOR CONTRIBUTIONS

Jayanta Kumar Gogoi is the first author. All the authors conceived and designed the complete toilet unit and constructed wetland treatment system. Jayanta Kumar Gogoi completed all the experiments, analysis, electrochlorinator design, and manuscript writing. Prof. Srikanth Mutnuri supported us with his technical expertise throughout the study. All the authors were involved in revising and editing the manuscript.

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.

REFERENCES

APHA/AWWA/WEF 2012 *Standard Methods for the Examination of Water and Wastewater*, 21st edn. APHA/AWWA/WEF, Washington DC, USA.

Burghate, S. P. & Ingole, N. W. 2013 Biological denitrification. *Journal of Environmental Science, Computer Science and Engineering Technology* **3**(1), 009–028.

Carboni, M. F., Florentino, A. P., Costa, R. B., Zhan, X. & Lens, P. N. L. 2021 Enrichment of autotrophic denitrifiers from anaerobic sludge using sulfurous electron donors. *Frontiers in Microbiology* **12**, 678323. https://doi.org/10.3389/fmicb.2021.678323.

Gogoi, J. & Mutnuri, S. 2024 Removal of nitrogen and phosphorous from blackwater via an integrated nature-based system: Hybrid-vertical flow constructed wetland, upflow anaerobic fixed biofilm reactor, and granular activated charcoal column along with in situ electrochlorination disinfection. *Journal of Water, Sanitation and Hygiene for Development* **14**(1), 1–14. doi:10.2166/washdev.2024.064.

Gogoi, J., Sharma, P., Talekar, G. & Mutnuri, S. 2023 Effect of salt dosage on the performance efficiency of the electro-oxidation process employed for integrated blackwater treatment. *International Journal of Environmental Science and Technology* **20**, 9029–9040. https://doi.org/10.1007/s13762-022-04528-7.

Gomez, M. A., Lopez, J. G. & Garcia, E. H. 2000 Influence of carbon source on nitrate removal of contaminated groundwater in a denitrifying submerged filter. *Journal of Hazardous Materials* **B80**, 69–80. https://doi.org/10.1016/S0304-3894%2800%2900282-X.

Hans, V. 2023 Sanitation – An economic perspective. doi:10.13140/RG.2.2.35811.12320.

Huang, X., Qu, Y., Cid, C. A., Finke, C., Hoffmann, M. R., Lim, K. & Jiang, S. C. 2016 Electrochemical disinfection of toilet wastewater using wastewater electrolysis cell. *Water Research* **92**, 164–172. https://doi.org/10.1016/j.watres.2016.01.040.

Hutton, G. & Chase, C. 2017 Water Supply, Sanitation, and Hygiene In: (Mock, C. N., Nugent, R., Kobusingye, O. & Smith, K. R. eds.). *Injury Prevention and Environmental Health*. 3rd ed. Washington (DC): The International Bank for Reconstruction and Development/The World Bank; Chapter 9. PMID: 30212108.

Jasper, J. T., Yang, Y. & Hoffmann, M. R. 2017 Toxic byproduct formation during electrochemical treatment of latrine wastewater. *Environmental Science & Technology* **51**, 7111–7119.

Kim, Y. B. & Lenz, R. W. 2001 Polyesters from microorganisms. *Advances in Biochemical Engineering/Biotechnology* **71**, 51–79. doi:10.1007/3-540-40021-42.

Konnerup, D. & Brix, H. 2010 Nitrogen nutrition of *Canna indica*: Effects of ammonium versus nitrate on growth, biomass allocation, photosynthesis, nitrate reductase activity and N uptake rates. **92**, 142–148. doi:10.1016/j.aquabot.2009.11.004.

Kostrytsia, A., Papirio, S., Frunzo, L., Mattei, M. R., Porca, E., Collins, G., Lens, P. N. L. & Esposito, G. 2018 Elemental sulfur-based autotrophic denitrification and denitrification: Microbially catalyzed sulfur hydrolysis and nitrogen conversions. *Journal of Environmental Management* **211**, 313–322. doi:10.1016/j.jenvman.2018.01.064.

Nelson, M. B., Berlemont, R., Martiny, A. C. & Martiny, J. B. H. 2015 Nitrogen cycling potential of a grassland litter microbial community. *Applied Environmental Microbiology* **81**, 7012–7022. doi:10.1128/AEM.02222-15.

Punyapwar, S. & Mutnuri, S. 2020 Diversity and functional annotation of microorganisms in French vertical flow constructed wetland treating greywater. *World Journal of Microbiology and Biotechnology* **36**, 1–17. doi:10.1007/s11274-020-02923-1.

Sharma, P., Talekar, G., Gogoi, J. & Mutnuri, S. 2022 Chapter 20 – Integration of bio-electrochemical systems and wetlands for wastewater treatment and resource recovery. In: *Novel Approaches Towards Wastewater Treatment and Resource Recovery Technologies*. Elsevier, pp. 353–370. ISBN 9780323906272, https://doi.org/10.1016/B978-0-323-90627-2.00007-1.

Shirgire, A., Pawar, H., Jagdale, S. & Sathe, R. 2023 Waste Water Treatment by Using Constructed Wetlands. doi:10.1007/978-3-031-34648-4_19.

Showkat, N. 2016 Coverage of sanitation issues in India. *SAGE Open*. **6**. https://doi.org/10.1177/2158244016675395.

Talekar, G. V., Sharma, P., Yadav, A., Clauwaert, P., Rabaey, K. & Mutnuri, S. 2018 Sanitation of blackwater via sequential wetland and electrochemical treatment. *npj Clean Water* **1**, 1–9. doi: 10.1038/s41545-018-0014-x.

Vymazal, J. 2007 Removal of nutrients in various types of constructed wetlands. *Science of the Total Environment* **380**(1), 48–65. https://doi.org/10.1016/j.scitotenv.2006.09.014.

Vymazal, J. 2010 Constructed wetlands for wastewater treatment: Five decades of experience. *Environmental Science and Technology* **45**, 61–69. doi:10.1021/es101403q.

Yadav, A., Chazarenc, F. & Mutnuri, S. 2018 Development of the ‘French system’ vertical flow constructed wetland to treat raw domestic wastewater in India. *Ecological Engineering* **113**, 88–93. https://doi.org/10.1016/j.ecoleng.2018.01.001.

Yaragal, R. R. & Mutnuri, S. 2023 Nitrates removal using ion exchange resin: Batch, continuous column and pilot-scale studies. *International Journal of Environmental Science and Technology* **20**, 739–754. doi.org/10.1007/s13762-021-03836-8.

Yuan, Z., Pratt, S. & Batstone, D. J. 2012 Phosphorous recovery from wastewater through microbial processes. *Current Option in Biotechnology* **23**(6), 878–883.

First received 19 December 2023; accepted in revised form 14 March 2024. Available online 25 March 2024