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Treatment of septage using lab-scale hybrid constructed wetland system

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ABSTRACT

A lab-based hybrid constructed wetland system (1.645 m^2) consisting of a sludge drying bed (0.135 m^2), vertical sub-surface flow bed (0.58 m^2), and horizontal sub-surface flow bed (0.93 m^2) was operated for the treatment of septage. All the beds were filled with gravel of varied sizes (5-40 mm), sand (0.25 mm), and planted with *Canna indica L*. The average concentration in the influent and effluent was observed as BOD_5 (2395.6±1196.4 and 41.87±8.9 mg L^{-1}), COD (7442±7342.6 and 29.6±7.6 mg/L), TSS (4965.9±801.69 and 336.1±152.9 mg/L), TN (1774.8±693.5 and 55.7±13.7 mg/L), and Total P (849.3±237.7 and 7.05±3.5 mg/L) during the study period. The hybrid system was operated with high influent loads of BOD_5 (175.2± 87.5 g m^{-2} d^{-1}), COD (544.5±537 g m^{-2} d^{-1}), TSS (363.3±58.6 g m^{-2} d^{-1}), Total N (129.8±50.7 g m^{-2} d^{-1}), NH_4-N (7.8±1.1 g m^{-2} d^{-1}), and Total P (62.1±17.4 g m^{-2} d^{-1}) throughout the study period. The hybrid-CW showed significant removal of BOD_5 (99.1±0.3%), COD (99.7±0.3%), TS (98.2±6.8%), TSS (96.9±4.9%), Total N (98.4±0.4%), NH_4-N (94.8±0.1%), and Total P (99.6±0.1%) from the septage. Finally, the treated septage met effluent discharge standards for all parameters except BOD_5.

1. Introduction

Septage is highly variable in its physico-chemical characteristics and has significantly high levels of organic and inorganic pollutants [1-2]. Septage is anaerobic in nature and has an offensive odour due to the presence of H_2S, mercaptans, and other organic compounds [3]. It contains constituents that may pose risks to public health and cause serious environmental hazards. Disposal of untreated septage into a surface water body may deplete dissolved O_2, cause eutrophication, and endanger aquatic organisms [3]. Septage treatment in India and other developing countries is difficult, as most of the population relies on onsite sanitation systems (OSSs) [4]. Although onsite sanitation systems are governed by the municipalities/local government bodies for the safe

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disposal of septage, the lack of resources, incentives, stringent regulations, and capacities often result in incessant and unrestrained dumping of septage. Furthermore, in India, septage is usually co-treated with domestic sewage at a sewage treatment plant (STP) due to its similar constituents. However, as septage is more concentrated in its strength compared to domestic sewage, it may not be appropriate to treat it with sewage. Common septage treatment methods include lime stabilization, dewatering by sludge drying beds, sludge incineration, waste stabilization ponds, sludge drying ovens, sedimentation ponds, mechanical dewatering, co-treatment anaerobic/aerobic wastewater treatment, co-composting, etc. [5-8]. However, all these methods have some intrinsic drawbacks, such as higher cost, prerequisite of skilled persons, complex processes, etc. [9]. Even the available traditional cost-effective methods are not as effective as required, due to their low treatment efficiencies [10]. In view of this, an alternative viable and cost-effective technology is needed to manage septage. One such technology is constructed wetland (CW) technology, well known for its cost-effectiveness, simple design, and promising results [11-14]. This technology has already been used to treat various kinds of wastewater [1-2]. However, very few studies have been reported on the treatment of septage by CW technology. Moreover, most past studies have used vertical flow CW at a pilot scale or as a pretreatment method for septage treatment [21-23]. In a recent study, a floating wetland with biochar as a substrate was used for septage treatment [24]. In this study, septage treatment was carried out using a lab-scale hybrid CW system to assess the pollutant removal potential of the system. The lab scale hybrid CW consisted of three beds connected in a series, i.e., sludge drying bed (SDB), vertical subsurface flow (VSSF) bed, and horizontal subsurface flow (HSSF) bed. Based on the available data, the treatment of septage by the hybrid design of CW technology was addressed in this study for the first time. The innovativeness of this study was demonstrated through several key aspects. Firstly, it involved implementing a hybrid design (VFFF-HSSF) for the treatment of septage, where the two beds had distinct ratios of their surface areas. Secondly, a sludge drying bed was strategically placed as a preliminary treatment component. The entire constructed wetland system was operated with a consistent hydraulic retention time (HRT) of 24 hours in each component of the CW system. This study aimed to assess the suitability of CW technology for handling septage and evaluate the treatment potential of individual components (sludge drying bed, vertical flow bed, and horizontal flow bed) of the hybrid CW system.

2. Materials and methods

2.1. Design and construction of lab-scale hybrid sub-surface flow CW system

A lab-scale hybrid CW system was constructed at the university research field station. The design layout of the hybrid CW is shown in Figure 1. The system is comprised of three treatment components, i.e., sludge drying bed, vertical flow CW bed, and horizontal flow CW bed. The beds were connected in series with an arrangement of a 1% slope from the inlet to the outlet point. The design specifications of each treatment component are shown in Table 1. Approximately 30 litres of septage were treated daily in the CW system through an intermittent dosing pattern. During the treatment, the oxygen transfer rate (OTR) and limit loading rate were calculated according to the following equations [25].

$$\text{OTR } (\text{g m}^{-2}\text{ d}^{-1}) = \text{Flow Rate}(Q) \times [(\text{BOD}_{in}-\text{BOD}_{out}) + 4.3(\text{NH}_4\text{-N}_{in}-\text{NH}_4\text{-N}_{out})] / \text{ total area} \quad (1)$$

Q: (m^3 d^{-1}): Septage flow rate

Total area (m^2): Total surface area of hybrid CW system, Biochemical Oxygen Demand (BOD_5) and NH_4-N concentrations were measured in mg/L. The total surface area of the hybrid CW system included the sum of the surface area of the sludge drying bed, vertical flow bed, and horizontal flow bed. The surface areas of the wetland components were calculated as follows:

Sludge drying bed:

$$\text{Surface area in m}^2 = \pi r^2 \quad (2)$$

where r is the radius of the circular shaped sludge drying bed in meter.

Vertical flow bed:

Surface area in $m^2 = a^2$ (3)

where a is the length of the side of the VFSSF bed in meter.

Horizontal flow bed:

Surface area in $m^2 = l \times b$ 4)

where l and b are the length and breadth, respectively, of the HFSSF bed in meter.

The limit loading rate (LLR) was calculated using the following equation.

LLR ($g\ m^{-2}\ d^{-1}$) = Flow Rate (Q) x BOD_{in} /total area (5)

The area of the HFSSF bed was 1.6 times the total area of the VFSSF bed. The SDB and VFSSF beds were fixed before the HFSSF bed for the maximum removal of suspended sludge (TSS); therefore, the sequence of septage flow was SDB (inlet) to VFSSF and then VFSSF to HFSSF (final outlet).

2.2. Description of wetland beds used in lab scale hybrid subsurface constructed wetland

First, the bed of the hybrid system was a sludge drying bed. A cylindrical-shaped plastic container with a 41.5 cm. diameter was used as the SDB. Its total surface area and depth were 0.135 m^2 and 50 cm, respectively. The SDB was used at the initial stage of treatment for the efficient dewatering and stabilization of the septage sludge. The hydraulic retention time (HRT) of the SDB was fixed as 24 hrs. The effluent from the SDB was collected through a drainage pipe fixed at its bottom and applied to a VSSF bed connected to it in series. The VSSF bed was prepared using a high-density polyethylene (HDPE) sheet with dimensions of 0.76 m x 0.76 m x 0.53 m and a surface area of 0.58 m^2. The HRT of the VSSF bed was also fixed as 24 hrs. The sludge drying bed differed from the VSSF bed in terms of the shape and the filling of the top layer filter material. The sand on top of the SDB helped in retaining the septage sludge more efficiently, whereas the gravel layer on the top of the VSSF bed maintained the aerobic conditions. The treated water from the outlet point of VSSF was applied to the HSSF bed, prepared with a rectangular shaped HDPE sheet with dimensions of 1.52 m x 0.61 m x 0.30 m and a total surface area of 0.93 m^2. The details of the filter media and surface vegetation of all the beds are shown in Table 1. The total area of the hybrid constructed wetland system was 1.645 m^2.

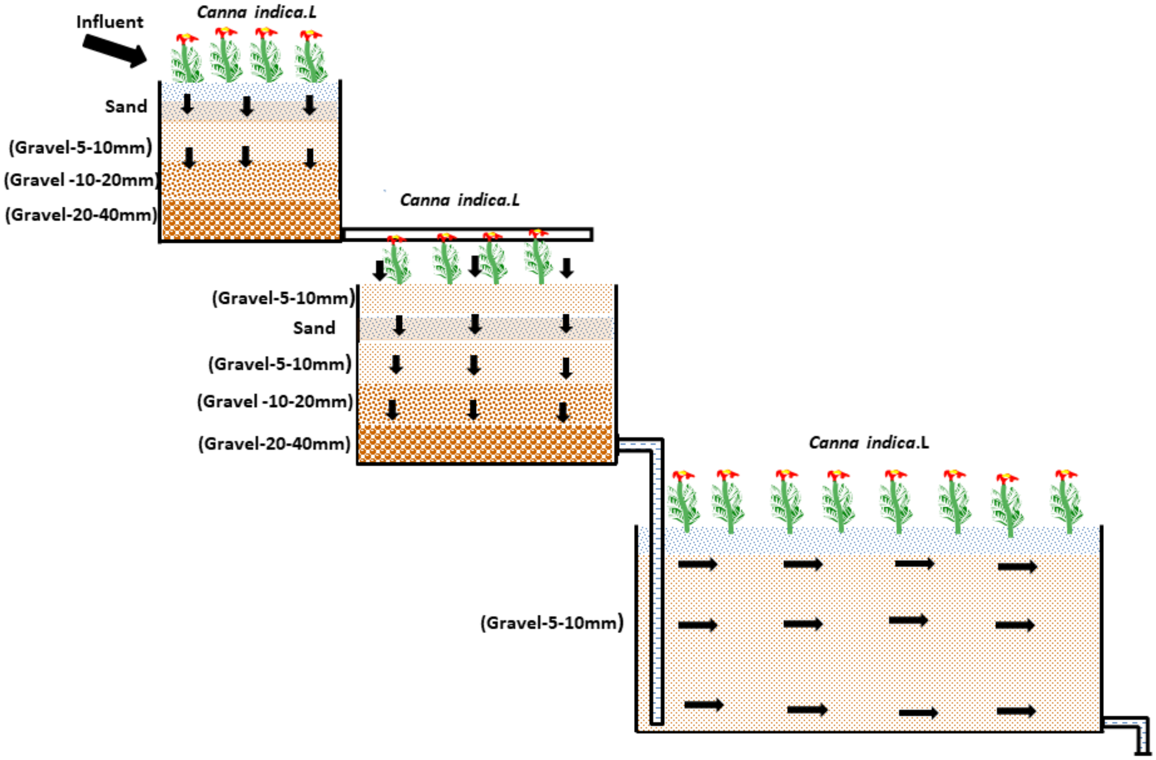


Fig. 1. Schematic layout of hybrid constructed wetland system.

Table 1. Design specifications of different beds used in hybrid sub-surface CWs.

Name of bed	**Type of bed**	**Area of bed (m^2)**	**Filter material type**				**Surface vegetation**
			Layer	**Type**	**Size**	**Thickness**	
SDB	-	0.135 m^2	1st Layer (Top)	Sand	1-2 mm	20 cm	*Canna indica L.,*
			2nd Layer	Gravel	5 mm	10 cm	
			3rd Layer	Gravel	10 mm	10 cm	
			4thLayer (Bottom)	Gravel	20-40 mm	10 cm	
VSSF	Vertical subsurface flow	0.58 m^2	1st Layer (Top)	Gavel	5 mm	20 cm	*Canna indica L.,*
			2nd Layer	Sand	1-2 mm	10 cm	
			3rd Layer	Gravel	10 mm	10 cm	
			4thLayer (Bottom)	Gravel	20-40 mm	10 cm	
HSSF	Horizontal subsurface flow	0.93 m^2		Gravel	5-10 mm	30 cm	*Canna indica L.,*

2.3. Samples collection, measurement, and analysis

Regular samples were collected daily from different sampling points (S1, S2, S3, and S4) to evaluate the performance of the hybrid CW system (Figure 1). The samples were analyzed for different physico-chemical parameters. Analyses of the samples were done in the laboratory of the Environmental Science at Graphic Era (Deemed to be University), Dehradun (30.3165 °N, 78.0322 °E), India. The septage was collected in the collection tank and dosed every day on the SDB. It was retained in this bed for 24 hr, and the partially treated septage was applied to the vertical flow bed. The HRT of the vertical flow bed was also fixed as 24 hrs. After the vertical flow bed, it was finally applied to the horizontal flow bed. The HRT of the horizontal flow bed was also 24 hrs. Finally, the treated septage was collected from the outlet of the horizontal flow bed. The sampling points were fixed at the inlet and outlet of each bed (Fig.1). Sample analysis was performed on alternative days. The samples were analyzed in triplicate for pH, oxidation redox potential (ORP), electrical conductance (EC), BOD_5, chemical oxygen demand (COD), total suspended solids (TSS), total dissolved solids (TDS), total nitrogen (TN), NH_4-N, PO_4-P, and total phosphorus (TP). The measurements of pH, ORP, and DO were carried out using a calibrated digital pH meter (SensION MM150 (Hach)); EC and TDS measurement was done using a calibrated EC-TDS Meter (CON100, Patsio). TN, NH_4-N, and total P (TP) were measured by spectrophotometric methods [26]. TSS was assessed by the colorimetric method [20], BOD_5 by the 5-day incubation method, COD was measured by the reactor digestion method, and NH_4-N and PO_4-P were measured using the salicylate and molybdovanadate method, respectively.

2.4. Measurement of oxygen transfer rate (OTR and OTR′)

The oxygen transfer rate in the hybrid CW is a determining factor for the degradation of organic components and the nitrification process [20]. The Cooper model, as described elsewhere in the literature, was followed to optimize the OTR in the hybrid CW [27]. According to Cooper [27], OTR is calculated by:

$$\text{OTR } (\text{g } O_2 \text{ m}^{-2} \text{ d}^{-1}) = Q*\{(BOD_{In}-BOD_{Out}) + 4.3*(NH_4\text{-}N_{In}-NH_4\text{-}N_{Out})\}/\text{Total area} \quad (6)$$

where the flow rate is measured in $m^3\ d^{-1}$ and the BOD and NH_4-N were measured in mg/L.

The OTR′ was measured as described by Sharma et al. [19]. OTR′ denotes the amount of oxygen required for full degradation of organic materials and nitrification of ammonium nitrogen present in wastewater.

OTR′ (g O_2 m^{-2} d^{-1}) was calculated by the following formula:

$$OTR' = Q *\{BOD\ inlet + 4.3\ (NH_4\text{-}N_{inlet})\}/Total\ area \quad (7)$$

2.5. Statistical analyses of data

Statistical analyses of the obtained results were done using OrginPro 8.5 SR1 (Origin Lab Corporation, Northampton, MA, USA) and Microsoft Excel-2019 for determining the statistically significant differences among the different parameters: BOD_5, COD, TSS, total solids (TS), TN, NH_4-N, and Total P.

2.6. System efficacy for pollutant removal

The assessment of the pollutant removal efficacy of the hybrid CW was estimated based on the purification and removal rates for some selected parameters for six months (July-December 2021). However, other parameters such as pH, ORP, and EC were comparatively analyzed (influent to effluent) to characterize the treatment efficiency of the system. The reduction in pollutant concentration was measured as the purification rate and calculated using the following formula:

$$Purification\ rate\ (\%) = \{(Ci–Co)/Ci)\} *100 \quad (8)$$

where Ci and Co are inlet and outlet concentrations (mg/L)

The removal rate was calculated based on load using the following formula:

$$Removal\ rate\ (\%) = \{(Li–Lo)/Li\} * 100 \quad (9)$$

where Li and Lo are respectively the inlet and outlet loads measured in g m^{-2} d^{-1}.

Load was calculated using the formula below:

$$Load(L) = Q*C/A \quad (10)$$

where Q is a flow rate measured in m^3 d^{-1}, C: concentration measured in mg/L, and A: area in m^2.

3. Results and discussion

3.1. Composition of influent in hybrid CW

Septage was collected from a city sewage treatment plant (STP). The collected septage samples were stored at 4 °C in a refrigerator for further analysis of their physico-chemical characteristics. Based on the source type of the septage, its physico-chemical characteristics significantly varied [28]. The dosing frequency of 30.0 L/d was maintained at a constant level for six months (July to December 2021). The average monthly physico-chemical characteristics of the septage are displayed in Table 2.

Table 2. Average (±SD) monthly physico-chemical characteristics of Septage (n=3).

Month, (2021)	pH	*EC	*ORP	*DO	*TDS	*TSS	*TS
July	7.4±0.15	2252±399	-9.9±2.3	1.12±0.5	8436±1043	4328±787	11492±1334
August	7.4±0.17	2324±418	-9.9±2.2	1.2±0.5	9459±1280	5319±852	12695±1687
September	7.4±0.13	2119±207	-23.0±3.5	1.1±0.2	9183±1115	4891±596	12215±1511
October	7.4±0.14	2123±182	-9.7±2.3	1.2±0.4	8899±1015	5046±1014	8544±1009
November	7.3±0.12	2235±164	-10.2±2.3	1.3±0.5	9154±1318	5076±779	12132±1662
December	7.4±0.14	2171±120	-9.3±2.1	1.1± 0.4	9238±931	5133±474	12244±1130
July-December	7.4±0.1	2213±270	-27.8±3.6	0.5±01	9062±355	4965±341	12119±395

Month, (2021)	*Total N	*NH_4-N	*Total P	*PO_4-P	*COD	*BOD
July	2140±909	99±11	1017±416	606±283	11705±10280	2172±1434
August	1530±854	100±16	890±225	405±307	5076±6618	2377±1511
September	1914±422	108±15	865±181	557±79	10291±7501	2235±428
October	1815±586	114±13	806±133	489±134	6436±7363	2263±1044
November	2092±485	110±15	698±149	531±80	8034±5846	2326±1171
December	1154±234	109±16	815±105	334±81	3108±1213	3000±1370
July-December	1774±374	107±5.7	849±105	487±106	7442±3225	2395±304

*Where, EC measured in Micro S/cm, ORP in; mV and DO, TDS, TSS, TS, total-N, NH_4-N, total P, PO_4-P, COD, and BOD were measured in mg/L. n=total number of replicates per sample.

3.2. pH, EC, DO, ORP

The average pH of the influent was observed as 7.4±0.14, with a range of 7.11 to 7.7 during the study period, showing an almost neutral nature of the septage. The average pH noticed in the effluent from the outlets of the Sludge Drying Bed, Vertical Sub-Surface Flow Constructed wetlands, and Horizontal Sub-Surface Flow Constructed wetlands were 7.3±0.24, 7.3±0.31, and 7.2±0.33, respectively. The maximum pH of 7.4±0.14 was measured in October from the SDB outlet. Overall, no significant change in pH was observed from the influent to effluent during the study period. Similarly, the average electrical conductivity (EC) in the influent was 2213.4±270.6 µS cm^{-1}, ranging from 3323 to 1643 µS cm^{-1}. During the treatment, the average EC was reduced to 1793.9±219.9, 1324.5±239.4, and 930.88±223.70 µS cm^{-1} at the outlets of SDB, VSSF-CW, and HSSF-CW, respectively. The average EC removal in the SDB, VFSSF, and HFSSF beds was recorded as 18.91±11.03%, 29.1±14.9%, and 27.8±9.7%, respectively. High EC reduction in the VFSSF and HFSSF beds was achieved due to the low inlet loading rate of dissolved solids. Routine and accurate monitoring of the dissolved oxygen (DO) level in the filtration beds is essential as the biological degradation of organic sludge mainly depends upon the DO level. The average DO in the influent, SDB outlet, VFSSF outlet, and HFSSF outlet was 0.5±0.1, 2.4±0.1, 2.9±0.2, and 3.3±0.2 mg/L, respectively. The DO level showed an increase from the inlet to the final outlet. The percent increase in the DO concentration at the outlets of the SDB, VFSSF, and HFSSF beds was observed as 25.2±4.2%, 34.7±4.5 %, and 56.3±3.7%, respectively. The average DO increment in the effluents of the VFSSF and HFSSF beds could be attributed to two factors. Firstly, the absorption of atmospheric oxygen trapped in the wetland filter media within the wastewater treatment system contributed to elevated oxygen levels. Additionally, the plant roots in the wetland bed released oxygen, further augmenting the oxygen levels as the wastewater passed through the wetland bed. During the study period, higher average DO levels were observed in November and December in all the beds, suggesting greater diffusion of oxygen at lower temperatures [29]. Overall, the complete CW system significantly contributed to the level of DO (78.45±3.9%) compared to the influent. The oxidation redox potential (ORP) was measured to monitor the presence of oxidizing species in all the beds. The ORP in the influent and the SDB, VFSSF, and HFSSF bed outlets was recorded as -27.8±3.6, 69.8±7.5, 131.8±39.8, and 156.1±30.1 mV, respectively. A sharp increase in the average ORP was observed from the inlet to the final outlet, confirming the progressive stabilization and mineralization of the sludge in all the beds.

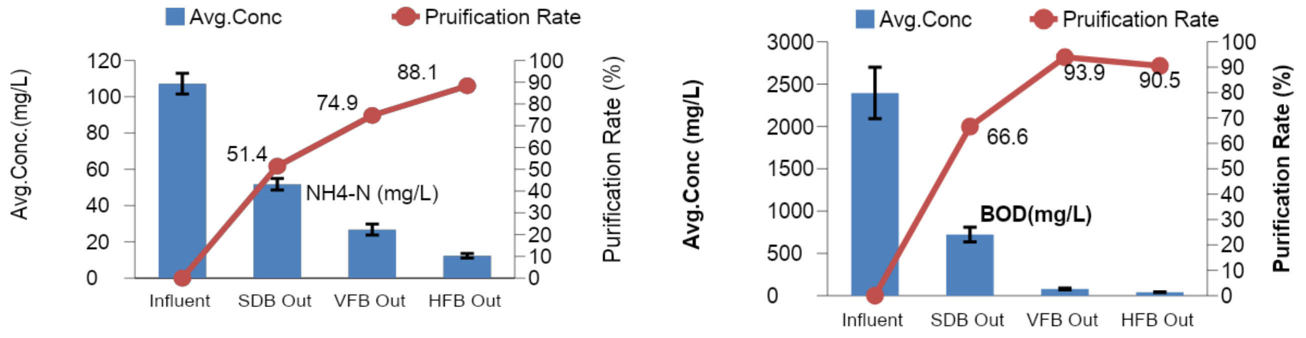
3.3 Septage Concentrations and its purification rates in hybrid CW

3.3.1. BOD and COD

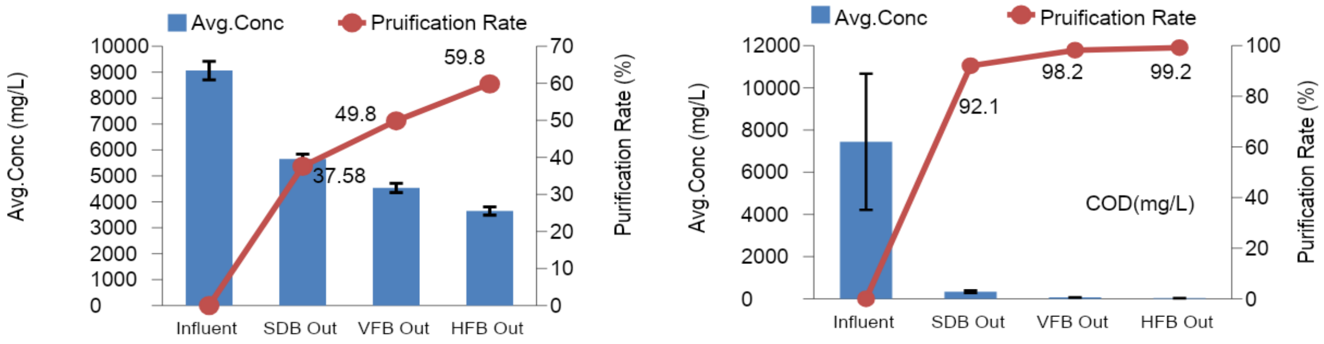
A significant level of fluctuation in the average inlet concentrations of BOD_5 (568-6567 mg/L) and COD (1591-28750 mg/L) was observed during the study period. The average BOD_5 concentration in the influent and outlets of SDB, VFSSF, and HFSSF beds were 2395±1196 mg/L, 722±213 mg/L, 79.4±20.5 mg/L, and 41.8±8.9 mg/L, respectively. The BOD_5 concentration showed a decrease from the inlet to the outlet during the treatment. The average purification rate of BOD_5 at the outlets of the SDB, VFSSF, and HFSSF beds and the whole system was recorded as 66.6±13.8%, 93.9±1.7%, 90.5±0.9%, and 97.9±1.0%, respectively (Figure 2). The maximum purification of BOD_5 was achieved by the sludge drying bed in comparison with the VFSSF and HFSSF beds. This was due to the filtration of the septage sludge at the surface of the sludge drying bed. The top layer of sand in the SDB played an important role in obstructing the suspended sludge from the septage that contributed to high BOD_5 levels in the septage. The placement of the sludge drying bed at the initial place of treatment also helped alleviate the high organic loading shocks in the VFSSF and HFSSF beds, thus achieving a high BOD_5 purification rate by the hybrid CW system. The average concentration of COD in the influent and outlets of the SDB, VFSSF, and HFSSF beds was found to be 7442±7342 mg/L, 337.8±119 mg/L, 67.7±20.6 mg/L, and 29.6±7.6 mg/L, respectively. The average COD purification rates of 92.1±5.1%, 98.2±1.3%, 99.2±0.5, and 99.9±0.5% were observed at the SDB, VFSSF, and HFSSF beds and the whole system, respectively. The ratio of COD to BOD in the influent and outlets of the SDB, VFSSF, and HFSSF beds was observed as 3.1, 0.5, 0.9, and 0.7, respectively. A decrease in the COD/BOD ratio at progressive stages of treatment from the inlet to the final outlet suggested that the hybrid system removed COD more efficiently compared to BOD during treatment. The COD/BOD was more or less similar in the SDB and HFSSF beds and maximum in the VFSSF bed. The BOD and COD inlet concentrations in the present study exceeded those reported by Haydar et al. [30], who conducted experiments on VSSF CW and HSSF CW systems for municipal wastewater treatment. In their research, the average inlet BOD and COD concentrations ranged from 91.4 to 188.6 mg/L and 140 to 500 mg/L, respectively. When utilizing an optimal detention time of eight days, they observed COD and BOD removal rates ranging from 42.9% to 81.4% for BOD and 18.75% to 72% for COD, respectively. The outlet concentrations of BOD and COD in their study ranged from 26.9 to 107.7 mg/L and 110 to 160 mg/L, respectively. Similarly, Torrens et al. [31]employed a hybrid system consisting of a vertical flow constructed wetland followed by a horizontal flow constructed wetland for the treatment of swine slurry. In their study, the hybrid CW system operated with an organic COD load ranging from 3,600 to 14,000 mg/L, achieving a final COD removal rate of 64%. It's worth noting that the inlet COD concentration in the Torrens et al. study fell within the range of the average COD concentration reported in our study. However, the average COD purification rates achieved in our study (99.9±0.5%) significantly exceeded those reported by Torrens et al. The majority of the pollution load consisted of suspended sludge in the septage. Since the sludge drying bed received the untreated septage initially, it retained the highest concentration of sludge, leading to optimal removal of pollutants. However, it was necessary to regularly remove the dried sludge from the upper surface of the sludge drying bed to prevent clogging on the bed surfaces. In a similar study, Kato et al. [15] reported average purification rates of COD between 70 -96% in six real scale hybrid CW systems treating four different types of wastewaters. In another study, Minakshi et al. [17] operated three CW systems at different HRTs and reported the removal of 45.3-63.1% BOD_5, 29.6-56.5% NH4-N, and 20.5-57.8% PO_4-P from dairy farm wastewater.

3.3.2. TDS, TSS and TS

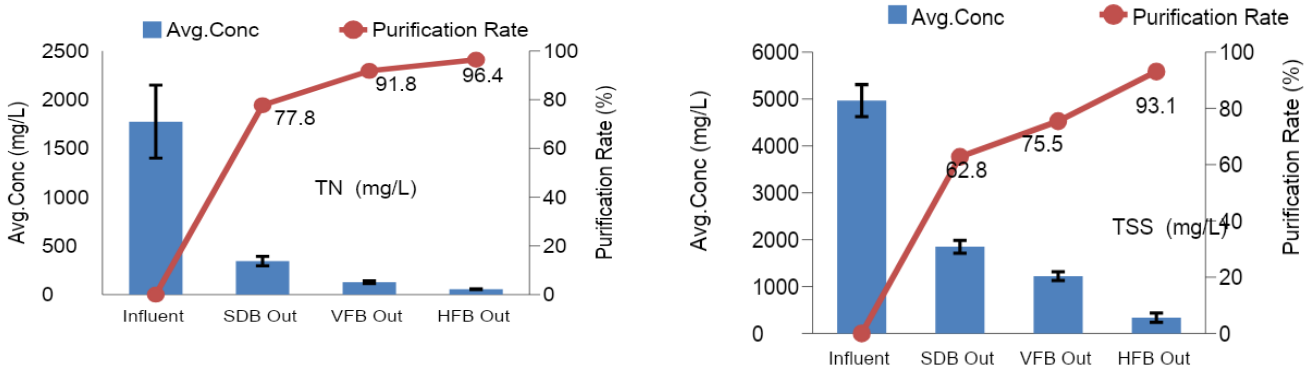
The TDS concentration in the influent ranged from 8436-9459 mg/L with an average value of 9062.1±1125.9 mg/L. The dissolved solids decreased from the inlet to the final outlet during the treatment of the septage. The TDS concentration was reduced to 37.6±2.7% by the sludge drying bed, 49.9±2.9% by the VFSSF bed, and 65.6±13.5% by the HFSSF bed. The TDS purification rate of the total system was observed as 67.2±6.3%. The dissolved solids were removed through processes such as adsorption over the bed filter media, vegetation uptake, microbial uptake, and sedimentation over the bed surfaces. The TDS purification was also affected by design and operating parameters, i.e., size and type of filter media, hydraulic retention time of wastewater in wetland beds, type and density of surface plants, and concentration of dissolved solids in untreated wastewater. The vegetation type and hydraulic retention time (HRT) of this study were similar for all the CW beds; however, the inlet concentration of the dissolved solids varied for each bed, being maximum for the SDB bed and minimum for the HFSSF bed. Moreover, the filter media was also different for all three CW beds, reflecting that the inlet concentration of the dissolved solids and the type of filter media played an important role in its removal from wastewater. The total suspended solids (TSS) were also monitored at each stage of treatment during the entire study period. The average TSS concentration in the influent was recorded as 4965.4±801.7 mg/L. The TSS was mainly present in the form of suspended sludge in the septage. High TSS concentrations may clog the wetland system, thus making it dysfunctional; therefore, a well-designed CW system must consider the average TSS load over the CW beds. Removing the major proportion of the TSS before the wastewater enters the VFSSF and HFSSF beds was important to avoid clogging. In this regard, a sludge drying bed was placed at the first stage of treatment.



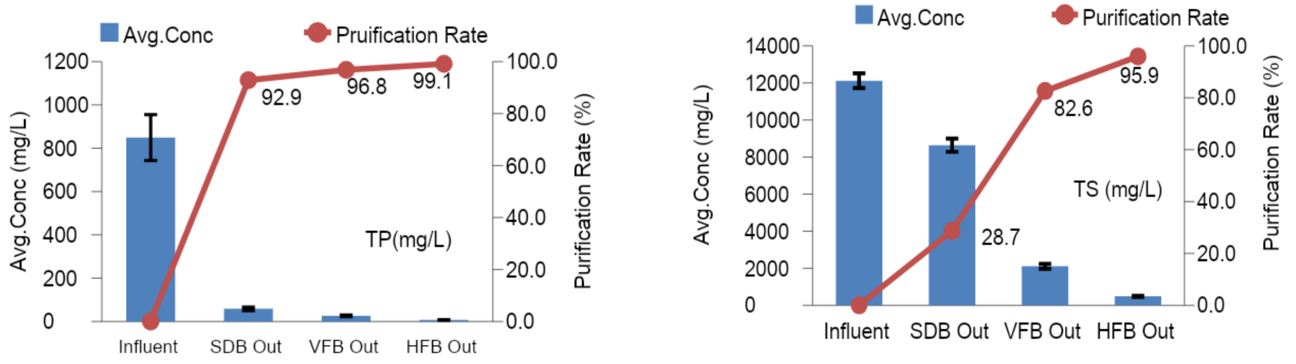
a) NH4-N (mg/L) b) BOD₅ (mg/L)



c) TDS (mg/L) d) COD (mg/L)

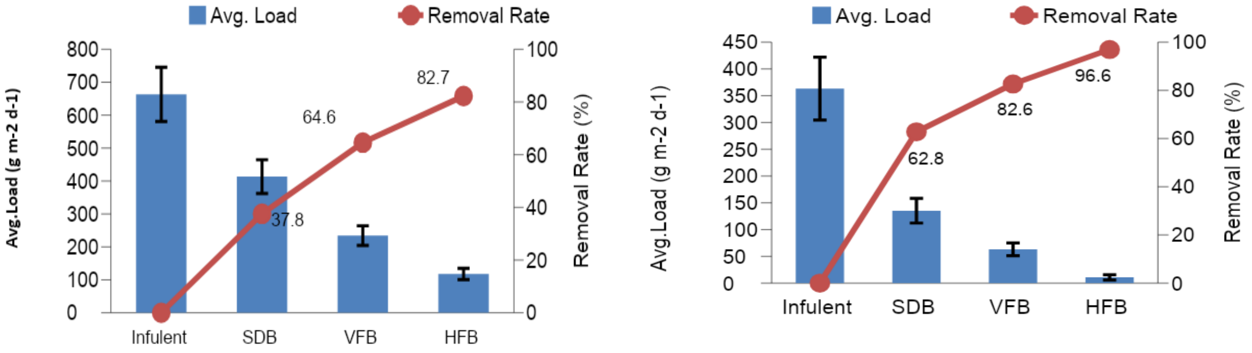


e) TN (mg/L) f) TSS (mg/L)

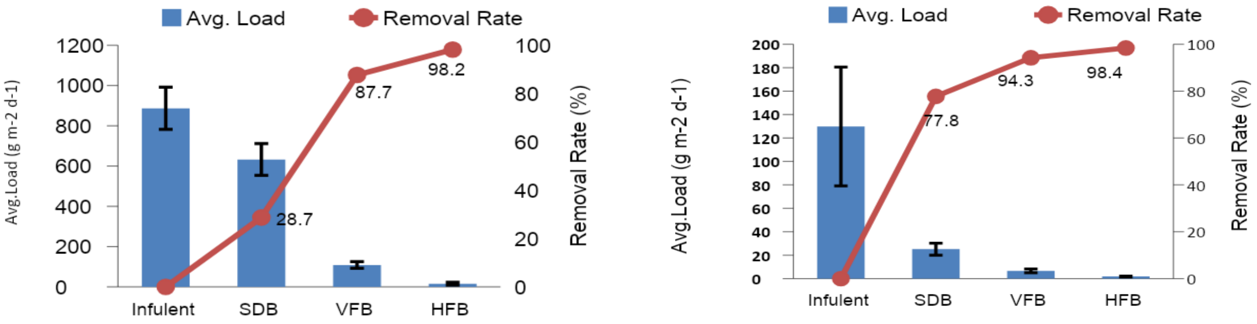


g) TP (mg/L) h) TS (mg/L)

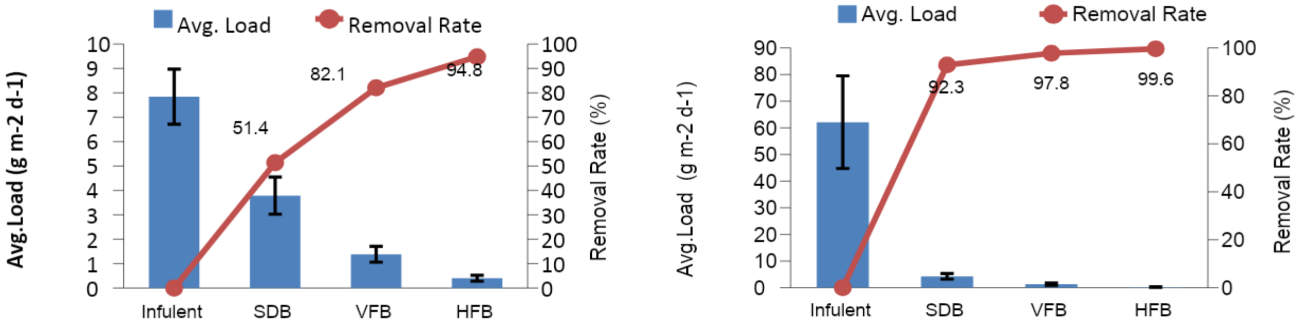
Fig. 2. Average concentrations vs. average purification rates of a) NH4-N, b) BOD5, c) TDS, d) COD, e) TN, f) TSS, g) TP, and h) TS in hybrid CW from septage during the whole study period.



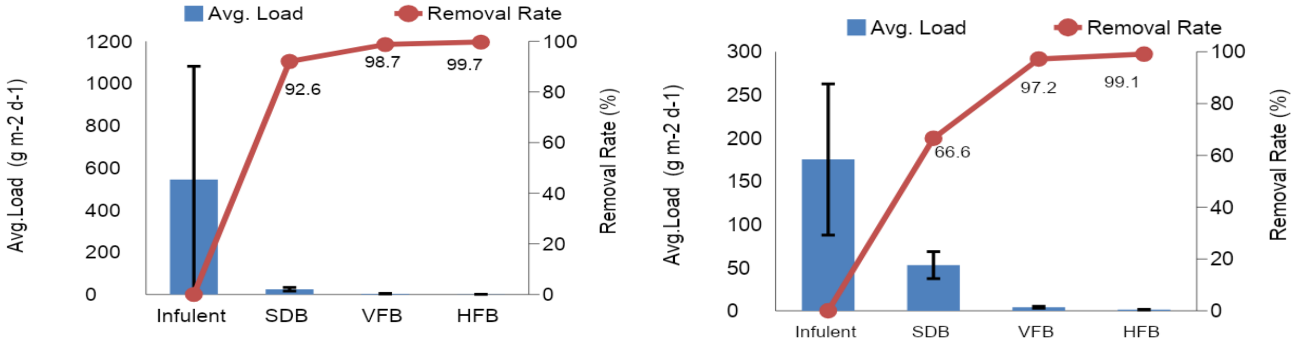
b) TDS a) TSS



c) TS d) TN



e) NH_4-N f) TP



g) COD h) BOD

Fig 3. Average loads vs. average removal rates of a) TDS, b) TSS, c) TS, d) TN, e) NH_4-N, f) TP, g) COD, and h) BOD in hybrid CW from septage during the whole study period.

The top surface of the sludge drying bed was filled with washed sand to retain most of the TSS at the bed surface so that clogging did not happen in this bed. Along with this, the SDB was planted with *Canna indica L.* for smooth percolation of the filtered septage from the top to the bottom of the bed. The average TSS concentration at the outlets of the SDB, VFSSF, and HFSSF beds was found as 1848.0±314.5 mg/L, 1220±228.6 mg/L, and 336.1±152.5 mg/L, respectively. The average purification of TSS in the SDB, VFSSF, and HFSSF beds and the whole system was 62.8±2.0%, 75.5±1.9%, 93.1±3.3%, and 98.6±0.7%, respectively. High levels of purification rate confirmed that the system was able to filter TSS efficiently from the septage. The TSS removal rates observed in this study aligned closely with those found in the Fernandez-Fernandez et al. [32] investigation, where livestock wastewater underwent treatment utilizing a hydrolytic up-flow sludge bed digester combined with a hybrid constructed wetland system. This hybrid system integrated both vertical flow and horizontal flow constructed wetlands in a series configuration. It's worth noting that the TSS input concentration reported by Fernandez et al. [32] was 2000±273 mg/L, which was less than half of the inlet TSS concentration in the present study. Nevertheless, the average TSS removal rate of 98.47±0.53% observed in the Fernandez-Fernandez et al. work was consistent with the TSS purification efficiency achieved in this study. The total solids (TS) reflect the sum of the dissolved and suspended solids in the wastewater. The average TS concentration in the influent and outlets of the sludge drying bed, VFSSF bed, and HFSSF bed showed a decrease from 12120±1431 mg/L to 490±212 mg/L. The TS purification rates of SDB, VFSSF, HFSSF, and the whole system were observed as 28.7±2.4%, 82.6±1.8%, 95.8±1.8%, and 98.2±11.4%, respectively (Figure 3). The system achieved an efficient removal of TS from the septage, and it was below the standard discharge values.

3.3.3. Total Nitrogen (TN), NH_4-N and Total P (TP)

The purification of total nitrogen (TN) and ammonium-nitrogen (NH_4-N) in the hybrid CW mainly depends on redox conditions essential for nitrification and denitrification processes [33]. However, a number of processes are responsible for removing nitrogen in the hybrid CW, such as NH_4-N volatilization, adsorption, plant uptake, ammonification, nitrification, denitrification, anammox, etc. [34]. A significant fluctuation in the average influent concentrations of Total Nitrogen (768-3456 mg/L), Total P (456-2101 mg/L), and NH_4-N (85-143 mg/L) was observed during the study period. The average TN concentration in the influent and outlets of the SDB, VFSSF, and HFSSF beds were 1775±693.5 mg/L, 344±69.8 mg/L, 127.5±31.5 mg/L, and 55.7±13.7 mg/L, respectively. The average purification rate of TN at the outlets of the SDB, VFSSF, and HFSSF beds and the whole system was recorded as 77.8±8.5 %, 91.8±3.2 %, 96.4±1.3 %, and 96.4±1.4 %, respectively. The NH_4-N concentration in the influent and the outlets of the SDB, VFSSF, and HFSSF beds was 107.1±15.4 mg/L, 51.7±10.4 mg/L, 26.8±6.2 mg/L, and 12.3±3.7 mg/L, respectively (Table 3). The average purification rate of NH_4-N by the SDB, VFSSF, and HFSSF beds and the whole system was recorded as 51.4±8.8 %, 74.9±6.0 %, 88.1±3.8 %, and 88.3±3.8, respectively (Figure 3). TN/NH_4-N in the influent and effluents of the SDB, VFSSF, and HFSSF beds was observed as 16.6, 6.6, 4.8, and 4.5, respectively. The total N was mainly constituted by organic nitrogen, NH_4-N, NO_2-N, and NO_3-N in the septage. The decrease in the TN/NH_4-N ratio from the SDB to the HSSF bed indicated a higher removal of organic nitrogen compared to other nitrogen forms present in the septage. The maximum decrease in the TN/NH_4-N ratio was observed in the VSSF bed, which could be attributed to the improved aerobic conditions in that particular bed. Removal of organic N was related to effective sludge filtration over the wetland beds and efficient microbial degradation in the beds. In their 2022 study, Singh et al. [35] employed a laboratory-scale two-stage hybrid CW configuration (VSSF CW-HSSF CW) to treat municipal wastewater. This system was operated with a hydraulic loading rate (HLR) of 5.5 cm/d and a hydraulic retention time of one day. With a notably lower average inlet concentration of 13.5 mg/L, the hybrid system achieved an impressive 99% removal of NH_3-N from the wastewater. In contrast, the inlet NH_4-N concentration in the current study was substantially higher at 107.1±15.4 mg/L when compared to the levels reported by

Singh et al. [35]. However, even with this higher inlet concentration, our investigation still achieved a remarkable average removal rate of 88.3±3.8%. Similarly, in another study by Martel-Rodríguez et al. [36], a hybrid constructed wetland (CW) system featuring a VSSF-HSSF configuration was employed for the treatment of urban wastewater. This system was operated with average inlet concentrations of 107±32 mg/L for total nitrogen (TN) and 84±8 mg/L for ammonium nitrogen (NH_4-N). The CW system achieved a removal efficiency of 48% for total nitrogen and 35% for NH_4-N. The average TP concentration in the influent and the outlets of the SDB, VFSSF, and HFSSF beds was measured as 849.3±237.7 mg/L, 58.2±14.5 mg/L, 25.5±8.8 mg/L, and 7.05±3.5 mg/L, respectively. The average TP purification at the SDB, VFSSF, and HFSSF beds and the whole system was monitored as 92.9±2.1 %, 96.8±1.1%, 99.1±0.4%, and 99.3±0.4 %, respectively. Phosphorus removal primarily takes place through the adsorption and precipitation of dissolved phosphorus on the surface of the wetland filter media. In a newly constructed wetland system, there is a high rate of adsorption and precipitation due to the presence of numerous adsorption sites on the filter media. However, as the wetland system ages, the rate of phosphorus removal gradually decreases until it eventually ceases when the saturation level is reached. In their 2019 study, Minakshi et al. [37] operated VSSF CW systems for treating dairy farm wastewater, which had an average TP concentration of 39.3±9.8 mg/L. They investigated the impact of filter materials, specifically gravel and sand, on the TP removal efficiency of the CW systems. Their findings revealed that the sand filters outperformed the gravel filters, achieving a maximum TP removal rate of 94.1% from the dairy farm wastewater. In contrast, the hybrid CW system in the present study operated with an inlet TP concentration of 849.3±237.7 mg/L, which was approximately 20 times higher than the TP concentration in the Minakshi et al. [37] research. Despite this substantial difference, our investigation achieved an impressive TP removal rate of 99.3±0.4%. Several factors could account for this result, including the enhanced TP sorption capacity of our filter materials, uptake by plants, and longer hydraulic retention time (HRT).

3.4. Loads and removal rates in hybrid CW

The removal of organic and inorganic pollutants can be more accurately measured from the load and removal rates. Also, factors such as precipitation, evaporation, and evapotranspiration may affect the actual concentrations and purification rates. Similar to concentrations, a high level of variability was also observed in the average monthly influent loads for different parameters throughout the study period (Table 4): BOD_5 (41.56-480.51 g m^{-2} d^{-1}), COD (116.41-2103.66 g m^{-2} d^{-1}), TS (708-1152.88 g m^{-2} d^{-1}), TSS (224.02-534.40 g m^{-2} d^{-1}), TDS (516.54-864.66 g m^{-2} d^{-1}), TN (56.20-252.88 g m^{-2} d^{-1}), NH_4-N (6.22-10.46 g m^{-2} d^{-1}), and TP (33.37-153.73 g m^{-2} d^{-1}). Due to variations in the influent loads, the average removal rates of different parameters also fluctuated during the study period, i.e., BOD_5 (65.6 - 99.9%), COD (99.5-99.9%), TS (98.8-99.9%), TSS (95.7-99.9%), TDS (32.5-92.3%), TN (98.9-99.8%), NH_4-N (91.7-98.9%), and TP (99.6-99.9 %). Maximum fluctuation in the removal rates was observed in BOD_5 and TDS, suggesting the high levels of sensitivity of these parameters corresponding to inlet load fluctuations. The average removal rate of BOD_5 was maximum (87.5%) in the VFSSF bed and almost similar (66.0%) in both the SDB and HFSSF beds. BOD removal requires good aeration in the top filter layer of CW beds; therefore, the VFSSF bed achieved the highest removal rate for BOD in this study. The large size gravel in the VFSSF bed provided aerobic conditions over the VFSSF bed, helping in the effective removal of organic pollutants (BOD) from the septage. In a 2020 study by Fernandez-Fernandez et al. [32], a hybrid CW system was operated for the treatment of wastewater originating from small urban agglomerations, agricultural industries, and livestock farms.

Table 3. Month-wise average concentrations (± SD) of water quality parameters in the influent and effluents of all the beds of hybrid CWs, during the whole treatment period.

	BOD, mg/L				COD, mg/L			
Month	Influent	SDB $_{out}$	VSSF-CW $_{out}$	HSSF-CW $_{out}$	Influent	SDB$_{out}$	VSSF-CW$_{out}$	HSSF-CW $_{out}$
July	2172.1 ±1434.3	791.7±291.0	88.5±33.8	40.9±16.04	11705±10280.1	408.4±147.79	77.7±23.87	32.4±11.45
August	2377±1511.2	773.1±191.3	87.4±16.51	38.6±8.54	5076.3±6618.7	274.6±70.09	77.2±17.87	30.3±6.82
September	2235.1±428.6	759.9±159.22	77.7±14.97	43.2±4.37	10291.2±7501.3	388±133.15	72.7±19.04	30.3±5.89
October	2263.4±1044.7	553.4±227.60	62.7±9.41	37.6±5.99	6436.7±7363.2	297.9±81.95	57.6±25.59	25.6±4.60
November	2326±1171.9	739.5±162.04	74.5±12.05	44.6±3.75	8034.7±5846.4	367.5±125.59	62.5±15.33	31.1±6.67
December	3000.2±1371.0	717.5±179.74	85.8±17.88	46.3±7.07	3108.1±1213.0	287.9±88.84	58.3±13.29	28±8.45
July-December	2395.6±1196.4	722.5±213.5	79.4±20.5	41.87±8.9	7442±7342.6	337.8±119.2	67.7±20.6	29.6±7.6
	TN, mg/L				NH_4-N			
Month	Influent	SDB $_{out}$	VSSF-CW $_{out}$	HSSF-CW $_{out}$	Influent	SDB $_{out}$	VSSF-CW $_{out}$	HSSF-CW $_{out}$
July	2140.9±909.9	275.5±24.4	108.6±15.5	50.6±9.12	99.6±11.8	51.1±8.7	25.6±5.2	11.5±2.8
August	1530.8±854.8	289.6±16.9	113.4±20.7	51.2±13.92	100.9±16.4	51.4±8.7	24.5±4.2	11.8±4.8
September	1914.2±422.7	365.6±55.4	128.3±32.6	55.5±11.73	108.9±15.9	47.2±6.1	24.1±3.8	11.9±2.7
October	1815.4±586.1	383.1±79.3	128.5±30.9	56.6±11.60	114.3±13.7	51±9.2	25.7±6.9	11.1±3.3
November	2092.7±485.1	385.5±62.6	145.5±39.5	65.7±19.61	110±15.5	52.7±11.18	29±5.3	14.1±3.1
December	1154.8±234.2	363.8±68.9	140.4±33.	54.4±11.32	109.2±17.0	57±15.9	31.8±8.5	13.7±4.8
July-December	1774.8±693.5	343.8±69.8	127.45±31.5	55.67±13.7	107.15±15.4	51.73±10.4	26.8±6.2	12.35±3.7
	TDS, mg/L				TSS, mg/L			
Month	Influent	SDB $_{out}$	VSSF-CW $_{out}$	HSSF-CW $_{out}$	Influent	SDB $_{out}$	VSSF-CW $_{out}$	HSSF-CW $_{out}$
July	1590.1±275.6	1138.2±244.98	817.7±222.23	561.1±134.42	4328±787.4	1617±317.89	319.1±92.00	112.5±33.75
August	1634.8±205.4	1156±166.06	936±171.47	596.4±121.09	16377.9±25403.9	1010.3±384.71	342.7±118.33	123.5±50.07
September	1486.1±78.7	1062.3±127.61	772±155.55	453.2±62.80	9076.5±2722.5	1069.1±400.11	318±90.53	123.5±44.66
October	1486.1±78.7	1062.3±127.61	772±155.55	453.2±62.80	17013.3±25193.7	999.2±390.51	326±117.52	113.4±40.38
November	1519.7±160.1	1129.9±147.58	821.2±146.53	493.3±90.53	8728.9±2469.3	1192.8±479.65	346.7±111.71	132.5±49.75
December	1629.4±112.8	1175.5±101.52	787.4±60.81	475.5±43.09	8670.7±1324.3	846.2±142.12	307.1±85.54	103.1±28.01
July-December	9062.06±1125.89	5650.51±698.90	4536.04±574.08	3645.81±533.06	4965.93±801.69	1848.03±314.84	1220.97±228.64	336.05±152.94
	TS, mg/L				TP, mg/L			
Month	Influent	SDB$_{out}$	VSSF-CW$_{out}$	HSSF-CW$_{out}$	Influent	SDB$_{out}$	VSSF-CW$_{out}$	HSSF-CW$_{out}$
July	9184.6±1771.2	960.1±188.6	311.1±47.6	112.2±32.8	1017.0±416.2	69.1±15.8	31.70±12.4	5.28±3.62
August	7980.7±866.7	989.3±416.3	322.3±73.4	120.5±46.1	890.0±225.3	64.5±6.4	23.40±7.6	7.00±3.92
September	9195.0±1769.5	939.9±195.8	317.7±56.3	123.5±44.7	865.4±181.8	58.20±14.8	28.80±8.1	8.90±3.48
October	8317.10±1621.7	1011.5±410.2	309.2±67.7	107.3±34.8	806.8±133.9	55.50±10.1	23.80±6.2	6.70±2.63
November	8747.3±1415.1	1049.0±417.3	335.3±68.6	134.4±45.8	698.8±149.9	48.50±18.9	22.40±8.4	6.0±2.2
December	7773.4±839.7	858.9±156.6	296.10±43.7	103.0±21.7	815.4±105.9	53.40±9.6	25.60±7.4	8.4±4.1
July-December	12119.6±1431.2	8642.5±1076.3	2105.30±323.2	489.9±211.8	849.3±237.7	58.2±14.5	25.5±8.8	7.05±3.5

This comprehensive system included a pre-treatment unit, a vertical flow bed, and a horizontal flow bed. Operating with an inlet BOD load of 214 g m^{-2} d^{-1}, this system provided an impressive BOD_5 removal efficiency of 95.2%. Their results closely corresponded to the BOD_5 removal rate observed in the present investigation; however, the hybrid CW system in our study was operated at a low inlet BOD loading rate compared to the system in the Fernandez-Fernandez et al. study [32]. The average removal rates for COD were maximum in the SDB (92%), slightly lower in the VFSSF bed (84%), and minimum (66.6%) in the HFSSF bed. In a 2013 study by Sharma et al., a BOD removal of 86.5-95.7% was achieved with an inlet BOD load of 8.4-14.4 g m^{-2} d^{-1} during the treatment of dairy wastewater. Similarly, the average Total P (TP) removal rates in the SDB, VFSSF, and HFSSF and the total system were observed as 92.9%, 68.1%, 82%, and 99.8%, respectively. Most of the phosphorus was in the form of septage sludge that was separated at the surface of the sludge drying bed; therefore, the SDB showed the maximum removal of total P from the septage, followed by the HSSF and VSSF beds. The average removal rates of NH_4-N in the SDB, VFSSF, and HFSSF were recorded as 51.4±0.8%, 82.1±0.32%, and 94.8±0.12%, respectively. Similarly, the average TN removal rates in the SDB, VFSSF, and HSSF-CW were 77.8%, 94.2%, and 98.4%, respectively. The average removal rates of TSS were observed as 62.8%, 82.7%, and 97.0% in the SDB, HFSSF, and VFSSF beds, respectively.

3.5. OTR and OTR′ in hybrid CW

Dissolved oxygen (DO) signifies its role in the oxygenic degradation of organic matter and NH_4-N nitrification by microorganisms present in each bed of the HCW. Further, the level of DO depends upon the oxygen transfer rate (OTR) in the beds of the CW system. Therefore, OTR′ reflects the total amount of O_2 required in a CW system for complete removal of organic matter and nitrification of NH_4-N present in wastewater. However, the OTR value is an indicator of actual O_2 utilized/absorbed by the CW beds for the degradation of organic matter and nitrification process in CW beds. The OTR value fluctuates with fluctuations in the parameters, such as inlet pollutant load, temperature, aerobic/anaerobic conditions over bed surfaces, design of bed, hydraulic loading rate (HLR), etc. Therefore, using the BOD and NH_4-N values at the inlet and outlet of each CW bed, the OTR and OTR′ values of the VSSF and HSSF beds and the whole system were measured. High fluctuation in the OTR values of the VSSF-CW, HSSF-CW, and total system were observed during the entire study period. The OTR values ranged between 19.2 to 25.4 5 g O_2 m^{-2} d^{-1} in the VSSF bed, 5 g O_2 m^{-2} d^{-1} in the HSSF bed, and 8.8 to 13.5 g O_2 m^{-2} d^{-1} in the whole hybrid CW system (Table 5). The maximum values of OTR in the VSSF bed confirmed the aerobic conditions over the bed surface and high removals of BOD from the septage. The average OTR/OTR′ ranged between 0.8 to 1.1 in the VSSF bed, 0.3 to 0.7 in the HSSF bed, and 0.6 to 0.7 g O_2 m^{-2} d^{-1} in the whole system. The average OTR/OTR′ value was almost twofold (0.9±0.1 g O^2 m^{-2} d^{-1}) in the VSSF bed compared to HFSSF (0.5±0.9 g O_2 m^{-2} d^{-1}), whereas the average OTR/OTR′ value of the whole CW system was observed as 0.6±0.0 g O_2 m^{-2} d^{-1}.

4. Conclusions

The following conclusions are drawn from the present study:

- Septage is highly variable in its physio-chemical parameters as characterized by long ranges of BOD_5, COD, TS, TSS, TDS, TN, NH_4-N, and TP; consequently, inconsistency in the quantitative analysis was observed.
- Overall, the hybrid CW system achieved efficient average removal rates for TSS (96.6%), TN (98.4%), NH_4-N (94.8%), TP (99.6%), COD (99.7%), and BOD_5 (99.1%) during the study period.
- The use of a sludge drying bed (SDB) with VFSSF and HFSSF was justified in a sequence of SDB-VSSF-HSSF, as it effectively removed a significant level of total solids (TS) and decreased the loads for both VFSSF and HSSF-CW.
- Further, an effective level of mineralization and stabilization of sludge in the SDB facilitated VSSF-CW and HFSSF to remove high levels of pollutant loads.
- The OTR/OTR' values of VFSSF and HFSSF confirmed the appropriate level of oxygen transfer in both beds, mainly required for BOD, COD, and NH_4-N removal.

Table 4. Month-wise average loads (± SD) of water quality parameters in the influent and effluents of all the beds of hybrid CWs, during the whole treatment period.

Month	BOD (g m^{-2} d^{-1})				COD (g m^{-2} d^{-1})			
	Influent	SDB out	VSSF out	HSSF out	Influent	SDB out	VSSFout	HSSFout
July	158.9 ±104.9	7.9±21.3	4.6±1.8	1.3±0.5	856.5±752.2	29.9±10.8	4.0±1.2	1.0±0.4
August	173.9±110.6	56.6±14	4.5±0.9	1.2±0.3	371.4±484.3	20.1±5.1	4.0±0.9	1.0±0.2
September	163.5±31.4	55.6±11	4.0±0.8	1.4±0.1	753.0±548.9	28.4±9.7	3.8±1.0	1.0±0.2
October	165.6±76.4	40.5±16	3.2±0.5	1.2±0.2	471.0±538.8	21.8±0.6	3.0 ±1.3	0.8±0.1
November	170.2±85.8	54.1±11	3.8±0.6	1.4±0.1	587.9±427.8	26.9±9.2	3.2±0.8	1.0±0.2
December	219.5±100.1	52.5±13	4.4±0.9	1.5±0.2	227.4±88.8	21.1±6.5	3.0±0.7	0.9±0.3
July-December	175.2±87.5	52.8±15	4.1±1.6	1.3±0.9	544.5±537.3	24.7±8.7	3.5±1.7	0.9±0.2

Month	Total P (g m^{-2} d^{-1})				PO_4-P (g m^{-2} d^{-1})			
	Influent	SDB out	VSSF out	HSSF out	Influent	SDB out	VSSF out	HSSF out
July	74.5±30.5	5.1±1.2	1.6±0.6	0.2±0.1	44.4±20.8	8.3±11.7	1.2±0.3	0.2±0.1
August	65.2±16.5	4.7±0.5	1.2±0.4	0.2±0.1	29.6±22.5	7.7±11.4	1.1±0.3	0.2±0.1
September	63.3±13.3	4.3±1.1	1.5±0.4	0.3±0.1	40.8±5.8	3.6±0.5	1.2±0.4	0.2±0.1
October	59.0±9.8	4.1±0.7	1.2±0.3	0.2±0.1	35.8±9.8	2.9±0.5	1.0±0.5	0.2±0.1
November	51.1±10.9	3.5±1.4	1.2±0.4	0.2±0.1	38.9±5.9	3.4±0.5	1.1±0.5	0.2±0.1
December	59.7±7.8	3.9±0.7	1.3±0.4	0.3±0.1	24.5±5.9	3.2±0.7	1.1±0.4	0.2±0.1
July-December	62.1±17.4	4.2±1.6	1.3±0.4	0.2±0.1	35.6±14.8	4.8±6.7	1.1±0.3	0.2±0.1

Month	NH4-N (g m^{-2} d^{-1})				Total N (g m^{-2} d^{-1})			
	Influent	SDB out	VSSF out	HSSF out	Influent	SDB out	VSSF out	HSSF out
July	7.3±0.9	3.7±0.6	1.3±0.3	0.4±0.1	156.7±66.6	20.2±1.8	5.6±0.8	1.6±0.3
August	7.4±1.2	3.8±0.6	1.3±0.2	0.4±0.2	112.0±62.5	21.2±1.2	5.9±1.1	1.7±0.4
September	8.0±1.2	3.5±0.4	1.2±0.2	0.4±0.1	140.1±30.9	26.8±4.1	6.6±1.7	1.8±0.4
October	8.4±1.0	3.7±0.7	1.3±0.4	0.4±0.1	132.8±42.9	28.0±5.8	6.6±1.6	1.8±0.4
November	8.0±1.1	3.9±0.8	1.5±0.3	0.5±0.1	153.1±35.5	28.2±4.6	7.5±0.2	2.1±0.6
December	8.0±1.2	4.2±1.2	1.6±0.4	0.4±0.2	84.5±17.1	26.6±5.0	7.3±1.7	1.8±0.2
July-December	7.8±1.1	3.7±0.7	1.3±0.3	0.4±0.1	129.8±50.7	25.1±5.1	6.5±1.6	1.8±0.44

Month	TS (g m^{-2} d^{-1})				TSS (g m^{-2} d^{-1})			
	Influent	SDB out	VSSF out	HSSF out	Influent	SDB out	VSSF out	HSSF out
July	840.9±97.6	587.6±63	109.0±14	17.0±6.5	316.7±57.6	118.3±23	54.2±12.1	13.9±4.2
August	928.9±123.5	662.7±100	115.2±17	14.0±7	389.3±62.4	145.3±19	66.4±14.7	12.5±6.4
September	893.8±110.6	626.6±83.5	112.7±20.6	16.3±9.3	357.9±43.6	128.4±16.1	61.1±8.8	14.1±4.6
October	873.5±92.7	625.2±73.9	97.9±10.6	15.3±6.5	369.3±74.2	140.8±32.1	66.0±12.3	6.7±4.3
November	887.7±121.6	641.0±82.3	103.7±17.5	16.4±7.4	371.4±57.1	137.4±22.1	65.3±10.5	7.8±3.6
December	895.9±82.7	651.2±60.3	114.1±15.1	15.9±4.7	375.6±34.7	141.2±14.9	65.5±9.4	10.0±2.8
July-December	886.8±104.7	632.3±78.7	108.77±16.70	15.8±6.8	363.3±58.6	135.2±23.4	63.0±11.8	10.8±4.9

Table 5. The monthly average OTR, *OTR′* and OTR/OTR′ measured from VSSF-CW, HSSF-CW, and whole hybrid CW system

	VSSF-CW			**HSSF-CW**			**Hybrid CW System**		
Month/2021	***OTR***	***OTR′***	***OTR/OTR′***	***OTR***	***OTR′***	**OTR/OTR′**	***OTR***	***OTR′***	**OTR/OTR′**
July	22.7±1.1	24.5±1.8	0.9±0.1	2.2±0.6	3.9±0.7	0.6±0.1	11.1±0.7	17.2±0.9	0.6±0.0
August	22.7±1.4	24.8±2.5	0.9±0.1	2.1±0.5	3.8±0.3	0.6±0.1	11.3±1.1	17.5±1.6	0.6±0.0
September	22.3±0.9	23.5±1.5	1.0±0.0	1.8±0.3	3.6±0.3	0.5±0.1	11.0±0.6	17.2±0.7	0.6±0.0
October	21.5±1.5	23.0±1.8	0.9±0.1	1.8±0.4	3.4±0.6	0.5±0.1	10.3±0.7	15.8±1.0	0.7±0.0
November	22.3±1.7	23.6±1.3	0.9±0.0	1.9±0.5	4.0±0.5	0.5±0.1	10.7±0.9	17.1±1.2	0.6±0.0
December	22.8±1.5	23.6±0.8	1.0±0.1	2.4±0.6	4.4±0.3	0.5±0.1	11.0±0.5	17.4±0.7	0.6±0.0
July-December	22.4±1.4	23.8±1.7	0.9±0.1	2.0±0.5	3.9±0.6	0.5±0.1	10.9±0.8	17.0±1.1	0.6±0.0

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that would influence this paper.

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