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Effect of influent load fluctuation on the efficiency of vertical constructed wetlands treating dairy farm wastewater

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ABSTRACT

Three vertical sub-surface flow (VSSF) constructed wetland (CW) systems (CW-1, CW-2 and CW-3) filled with different filter media, each 4 m^2 in area, planted with *Arundo donax* was operated for 4 years for treating dairy farm wastewater. The vertical CW systems received high fluctuations in influent concentrations and loads i.e., BOD (26 to 619 mg L^{-1} and 1.5 to 34 g m^{-2} d^{-1}), TSS (165 to 643 mg L^{-1} and 9.1 to 24 g m^{-2} d^{-1}), TP (16 to 49.9 mg L^{-1} and 1.2 to 2.7 g m^{-2} d^{-1}) and NH_4-N (24.5 to 76.2 mg L^{-1} and 1.3 to 4.2 g m^{-2} d^{-1}) during the assessment period. Average annual removal rates showed fluctuations in removal of BOD (70.5 to 92.9%), TSS (82.5 to 97.5%), TP (51.1 to 91.9%) and NH_4-N (34.6 to 69%). This shows that the removal of BOD is very sensitive to inlet load fluctuations in CWs. High inlet loads may confine good nitrification that affects ammonium-nitrogen removal while TP removal rate reduced when inlet TP loads reduced. The average concentration of the pollutants (BOD, TSS, TP and NH_4-N) in the treated effluent showed noticeable decrease: 43.4 to 16.1 mg L^{-1} for BOD; 43.3 to 11.7 mg L^{-1} for TSS; 17.9 to 3.1 mg L^{-1} for TP and 33.2 to 22.7 mg L^{-1} for NH_4-N. Thus, from the outcomes of the current study, it can be concluded that the VSSF CW system may provide promising outcomes despite there is fluctuations in the influent loads.

1. Introduction

Wastewater discharged from a dairy parlor consists of various components such as animal excreta, floor washings, waste milk, and cleaning water containing detergents, sanitizers, acid, and alkaline agents [1]. Due to the presence of these components, dairy wastewaters are nutrient-rich (N and P) and pose a potential risk of contaminating ground and surface water [1]. Commonly, dairy wastewater is either stored or used for irrigation [2]. Alternatively, conventional treatment methods like trickling filters, activated sludge technology, and anaerobic lagoons are employed for purification [3]. However, these

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methods are often costly, require skilled manpower, and are less favored by small-scale dairy owners. Constructed wetland (CW) systems have proven to be effective in treating wastewater from various sources, including dairy farms, domestic settings, acid mine drainage, and agricultural runoff [4-10]. They are considered suitable alternatives to conventional treatment technologies due to their simple design, easy operation, cost-effectiveness, and eco-friendly nature [11-15]. CWs can be categorized as Free Water Surface (FWS) and Sub-Surface Flow (SSF) systems based on the flow and direction of wastewater. Among the SSF CW designs, Vertical Flow Sub-Surface (VSSF) CWs exhibit efficient nitrogen removal and require smaller footprints compared to other designs [14,16]. The vertical flow configuration provides sufficient oxygen for the nitrification process [17-19]. The pollutant removal efficiency of VSSF CWs is influenced by several design parameters, including wetland configuration, filling media, operational mode (batch or continuous dosing), influent load fluctuations and environmental conditions [20-21]. Lower loading rates generally lead to better pollutant removal, as reported by Metcalf and Eddy [22]. Although pollutant loads in wastewater flow often fluctuate during operation, lower loading rates offer a buffer to improve treatment performance without compromising the desired level of treatment efficiency. The effect of load fluctuation on vertical flow constructed wetland (VFCW) systems has been a subject of interest in wastewater treatment research. Load fluctuation refers to variations in the quantity and composition of wastewater entering the system over time. These fluctuations can have both positive and negative effects on the performance and efficiency of VFCW systems [23]. One potential positive effect is that load fluctuation can create intermittent aeration within the wetland, which promotes the development of aerobic and anaerobic zones [24]. This can enhance the treatment processes by facilitating a wider range of microbial activities and promoting the degradation of organic matter and pollutants. Furthermore, intermittent loading can increase the oxygen transfer rate, resulting in improved nitrification and denitrification processes. However, load fluctuation can also have negative implications for VFCW systems. Rapid and significant changes in influent characteristics can disrupt the biological activity and microbial communities within the wetland. This disruption may lead to temporary decreases in treatment efficiency and instability in pollutant removal processes. Moreover, if the fluctuations exceed the system's capacity to adapt, it may result in system overload, decreased overall treatment performance, and increased risk of effluent non-compliance. Therefore, this study investigates the influence of influent load fluctuation on the treatment efficiency of a VSSF CW system.

2. Methodology

2.1. Site description

Three VSSF CWs (CW-1 to CW-3) were constructed and operated near Graphic Era dairy farm, Dehradun, Uttarakhand, India (Latitude 30.3165° N, Longitude 78.0322° E) for treatment of dairy farm wastewater. The VSSF beds were constructed in December 2015 as per the design recommendations given by Cooper [26].

2.2. Design parameters: Filter media, bed dimensions and vegetation

All CW units, namely CW-1, CW-2, and CW-3, were structured with two vertical flow beds (VF-1 and VF-2) interconnected in series. Each CW unit had a total area of $4m^2$, where VF-1 covered approximately 2.5 m^2 (2.5m x 1m) and VF-2 covered approximately 1.5 m^2 (1.5m x 1m). The depth of all the beds was 0.7m. In the CW-1, CW-2, and CW-3 systems, both beds were filled with filtering materials from top to bottom: 10 mm gravels for CW-1, 20 mm gravels for CW-2, and washed sand (0.25 mm) for CW-3 (Figure 1). *Arundo donax*, also known as giant reed, served as the surface vegetation for all the VF beds. PVC drainage pipes were placed at the bottom of the beds, and the bed bottoms were lined with concrete material to prevent wastewater seepage. The concrete lining had a slope of 1% from the inlet to the outlet, ensuring efficient water movement from the inlet to the outlet point (Figure 1). Each of the three constructed wetland (CW) systems in the study was operated at three distinct inlet loading ranges: 0-10 g BOD m^{-2} day^{-1}, 11-20 g BOD m^{-2} day^{-1}, and 21-

30 g BOD m^{-2} day^{-1}. To maintain the specified ranges, the wastewater was diluted with tap water. 30 samples were collected for each loading range (operating period 45 days) in each wetland unit (CW1, CW2, and CW3).

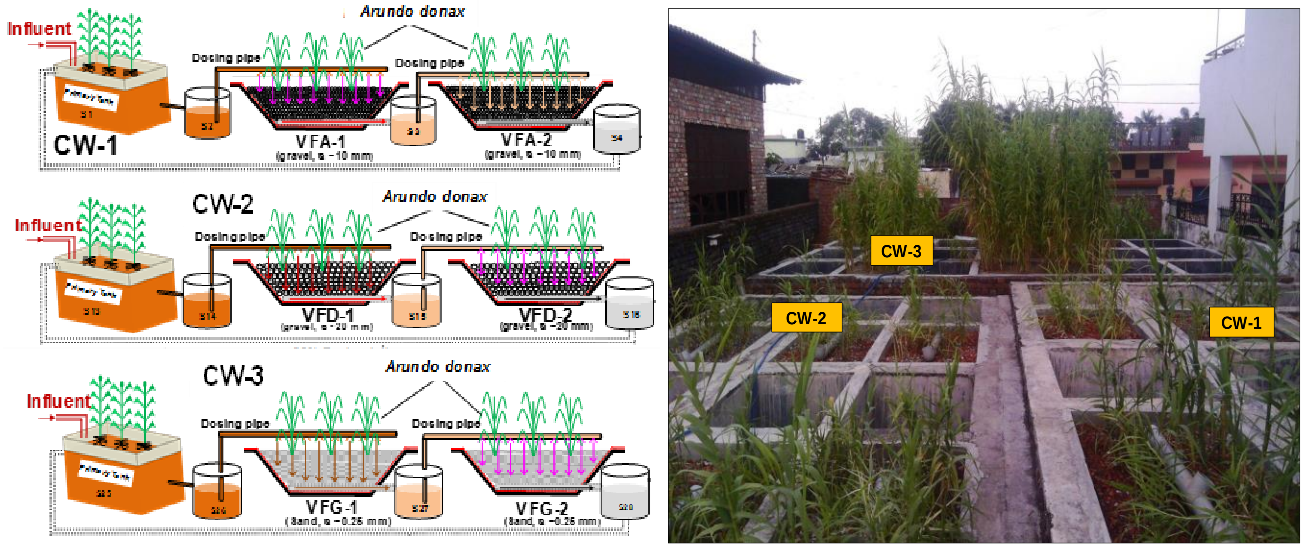

Fig. 1. Left: Schematic diagram of VSSF CW units; Right: Picture of CW-1, CW-2 and CW-3 near Graphic Era dairy farm.

2.3. Wastewater sampling and laboratory analysis

Wastewater from dairy farm was collected in a collection tank and was dosed every day using an electric pump. A total of 220 L was loaded vertically on the first bed of each CW system (Hydraulic loading rate: 55.0 mm day^{-1}) intermittently. Partially treated wastewater from outlet of VF-1 beds was dosed to VF-2 beds. The Hydraulic Retention Time (HRT) of VF-1 and VF-2 beds was set at 24 hrs and 20 min., respectively. Finally, treated water was drained out of VF-2 beds and utilized in dairy farm operations.

The hydraulic loading rate (HLR) was calculated using the following formula:

$$\text{HLR (mm day}^{-1}) = [\text{ Q (m}^3\text{ day}^{-1}) / \text{A (m}^2)] \times 1000 \quad (1)$$

Where:

- HLR represents the hydraulic loading rate in mm day^{-1}
- Q denotes the flow rate of wastewater in m^3 day^{-1}, and
- A represents the effective area of the treatment system bed in m^2.

The hydraulic loading rates (HLRs) of VF-1, VF-2, and the entire system were measured to be 88 mm day^{-1}, 128 mm day^{-1}, and 55 mm day^{-1}, respectively. The hydraulic retention time (HRT) is the total time wastewater stays in a wetland bed. The HRT was maintained using a stopper in the drainage pipes to retain wastewater in the respective wetland bed (VF-1 and VF-2). After the water drained from the outlet of the VF-1 bed, it was loaded on to the VF-2 bed and allowed to stay in it for 20 minutes. Sampling was done once a week from the outlets of each bed. Approximately 1/8th of the total dosed wastewater volume was reduced in the VF-1 bed due to various processes, including evaporation over the bed surface, absorption by surface vegetation, and filtration through the filter material. Similarly, approximately 1/5th of the total volume of wastewater dosed over the VF-2 bed was retained within this bed. The average volume of treated water at the final outlet was measured to be 155 L. Water samples, after collection, were brought to the research facility and preserved for further analysis. The collected samples were preserved at 4 °C and analyzed for total suspended solids (TSS), biochemical oxygen demand (BOD_3), total phosphorous (TP), total nitrogen (TN), ammonium-nitrogen (NH_4-N) and nitrate-nitrogen (NO_3-N) [27]. pH, electrical conductivity (EC), water temperature was measured in the field during sampling by multiparameter system (Hach SensION + MM150). The dissolved oxygen (DO) was measured by DO meter (Hach SensION). The untreated and treated samples were analyzed for TSS (colorimetric method), BOD_3 (3-days incubation method) [28], TP (molybdovanadate method), TN (persulfate digestion method), NH_4-N (salicylate method) and NO_3-N (cadmium reduction method).

2.4. Pollutant removal efficiency of VSSF CWs

The treatment performance of VSSF CW was calculated in terms of removal rates for all the wastewater quality indicators. The performance was determined using the following equations [26,28-30].

$$\text{Removal Rate (\%)} = (C_i - C_o) * 100 / C_i \quad (2)$$

$$\text{Load (g m}^{-2}\text{ day}^{-1}) = [\text{Flow Rate (L day}^{-1})* \text{Conc. (mg/L)}/1000]/\text{A (m}^2) \quad (3)$$

3. Results and discussion

3.1. Dairy influent composition

Dairy influent was discharged from a dairy farm associated with the university. The influent was cattle urine mixed with sanitizers, detergent washings, spilled milk, cow dung, and floor washings.

3.2. pH, EC and DO

During the assessment period, the pH of the dairy influent ranged between 6.7 and 8.6. It was noted that there were slight variations in the pH of the influent and effluent at different organic matter loads in the influent. However, when studied at an inlet load of 0-10 g BOD m^{-2} day^{-1} (Table 1), the three filter materials exhibited fluctuations of 0.2, 0.3, and 0.4 units in pH During the treatment process, even at inlet loads ranging from 0 to 10 g BOD m^{-2} day^{-1}, the mean pH of the dairy influent exhibited very minimal variation. This slight variation in pH persisted even at higher inlet loads of 11 to 20 g BOD m^{-2} day^{-1} and 21 to 30 g BOD m^{-2} day^{-1}. The vertical flow subsurface constructed wetland (VSSF CW) beds promoted nitrification, which resulted in the production of acids and consequently contributed to the slight variations observed in the effluent pH[29]. Average influent DO during the treatment period was also recorded at all the three inlet loads. The average concentration of dissolved oxygen in the influent ranged from 1.65 mg L^{-1} to 3.35 mg L^{-1} across all loading ranges throughout the entire study period. The sand-filled beds demonstrated the highest increase in dissolved oxygen (DO) for three loading ranges. Specifically, during the loading range of 21-30 g BOD m^{-2} day^{-1}, the maximum DO increase of 5.35 mg L^{-1} was recorded corresponding to influent in the sand-filled bed. The gravel bed filled with 10 mm sized gravels exhibited the lowest increase in dissolved oxygen (DO) (1.65 mg L^{-1}) when the influent loading was set to 0-10 g BOD m^{-2} day^{-1}. All of the beds exhibited an increase in dissolved oxygen (DO) across all ranges of inlet loading rates, providing evidence of an aerobic environment within the wetland beds. During the initial days of CW system operation, filter materials occupied more atmospheric oxygen which may have resulted in increased oxygen concentration of the influent [31] during the treatment process. The average electrical conductivity (EC) concentration in the influent varied as follows: 1777 ± 135 micro S cm^{-1} for the 0-10 g BOD m^{-2} day^{-1} loading rate, 2016 ± 178 micro S cm^{-1} for the 11-20 g BOD m^{-2} day^{-1} loading rate, and 2215 ± 205 micro S cm^{-1} for the 21-30 g BOD m^{-2} day^{-1} loading rate. There was a clear increase in electrical conductivity (EC) with higher inlet loading rates, indicating a significant relationship between EC and the dissolved BOD load. The sand-filled bed exhibited a maximum decrease of 54.9% in electrical conductivity (EC) when operated within the inlet loading range of 11-20 g BOD m^{-2} day^{-1} during the assessment period. On the other hand, both the 10 mm gravel-filled and sand-filled beds recorded the minimum decrease of 37% in EC when operated at a loading rate of 21-30 g BOD m^{-2} day^{-1}. Sand, being the finest among all the filter materials used, exhibited superior removal of electrical conductivity (EC) compared to 10 mm and 20 mm gravels across all ranges of inlet loading rates.

Table 1. Physico chemical characteristics of dairy wastewater at fluctuating inlet loads.

Parameters	**Influent**	**0 - 10 g BOD m^{-2} d^{-1}**			**Influent**	**11 - 20 g BOD m^{-2} d^{-1}**			**Influent**	**21 - 30 g BOD m^{-2} d^{-1}**		
		CW-1_{Out}	**CW-2_{Out}**	**CW-3_{Out}**		**CW-1_{Out}**	**CW-2_{Out}**	**CW-3_{Out}**		**CW-1_{Out}**	CW-2_{Out}	CW-3_{Out}
pH	7.5±1.1	8.1±0.3	8.2 ± 0.4	8.1 ± 0.2	7.3±0.4	8.2 ± 0.7	8.3 ± 0.9	8.2±0.5	6.9±0.4	8 ± 0.5	8.1 ± 0.4	8.2±0.3
EC (micro S cm^{-1})	1777±135	974 ± 381.7	946±400.1	1013.8±5 28.2	2016 ± 178	912.9 ± 207.7	888.7 ± 191.4	801.8 ± 144.6	2215±205	1118.7± 421.5	1084.5±401.9	1120.2 ± 493.8
DO (mg L^{-1})	3.35±0.9	5±1.4	5.5 ± 1.6	7.9 ± 1.2	2.15 ± 1.1	6.8 ± 1.1	7.3 ± 1.1	7.2 ± 0.9	1.65 ± 0.5	5.3±1.1	4.9± 1.6	7±0.8
TSS (mg L^{-1})	320±59	46.8 ± 41.6	40.5 ± 33.8	10 ± 8.8	280±45	33.1 ± 13.2	34 ± 14.9	18.8 ± 6.4	299.7±52	47.6±17.2	49.7± 12.9	7.6 ± 3.7
BOD (mg L^{-1})	197±23	25.2 ± 13.8	24.4 ± 11.1	10.3 ± 6.2	385.7 ±36	44.5 ± 14.7	55.1 ± 21.7	22 ± 4.1	633.6 ±69.6	62.4 ± 52.9	75.2 ± 42.5	28 ± 1.6
TP (mg L^{-1})	32.3±3.5	11.5 ± 7.1	12 ± 7.3	3 ± 3.1	35.2±3.8	16.7 ± 9.1	16.5 ± 10.3	3.2 ± 2	43.4±4.5	22.6 ± 7	22.2 ± 6.6	3.1 ± 2.6
NH_4-N (mg L^{-1})	48.2±6.9	19 ± 7.8	20.8 ± 2.8	26.3 ± 14.3	54.1	25± 3.7	30 ± 7.1	35.4 ± 6.1	89.3±11.3	29 ± 10.1	35 ± 4.1	40 ± 8.5
NO_3-N (mg L^{-1})	6.4±0.9	11.3 ± 1.7	12.1 ± 0.7	6.1 ± 2	2.3±0.3	12.6 ± 0.6	14.9 ± 2.5	9.4 ± 2.4	0.9±0.2	10.3 ± 1.7	10.1 ± 2.7	6 ± 1.2

3.3. Inlet and outlet concentrations, load and removal rates

Load and removal rates are precise methods to study the treatment effectiveness of CWs due to the variations in the concentration and removal rates. These variations may be due to some treatment processes such as precipitation, evaporation and evapo-transpiration. During the entire assessment period, the average influent concentration of total suspended solids (TSS) was observed to be 320 ± 59 mg L^{-1}, 280 ± 45 mg L^{-1}, and 299.7 ± 52 mg L^{-1} when the CW units were operated with inlet loading ranges of 0-10 g BOD g BOD m^{-2} day^{-1}, 11-20 g BOD m^{-2} day^{-1}, and 21-30 g BOD m^{-2} day^{-1}, respectively. The average removal rate of total suspended solids (TSS) varied across all beds, ranging from 85.4% to 96.9% when operated with an inlet loading rate of 0-10 g BOD m^{-2} day^{-1}, 88.2% to 93.3% when operated with an inlet loading rate of 11-20 g BOD m^{-2} day^{-1}, and 84.1% to 97.5% when operated with an inlet loading rate of 21-30 g BOD m^{-2} day^{-1}. TSS removal was maximized in the sand-filled beds for all loading ranges, and there was minimal variation observed with an increase in loading rate throughout the study period (Table 1 and Figure 2). TSS removal of approximately 80-90% was observed irrespective of fluctuating inlet load as observed in similar experiments conducted by [32]. The major mechanisms involved in the removal of total suspended solids (TSS) in constructed wetlands include physical processes such as sedimentation, filtration, and adsorption. Sedimentation occurs when the TSS particles settle down due to gravity, while filtration involves trapping and retaining TSS particles within the wetland media. Adsorption refers to the attachment of TSS particles onto the surfaces of the wetland media or plant roots. Additionally, biological processes, such as microbial activity and decomposition of organic matter, can also contribute to TSS removal in constructed wetlands. The average influent BOD concentration varied from 197 mg L^{-1} to 633.6 mg L^{-1} across all ranges of inlet loading rates. During the study period, in CW1, CW2, and CW3 units, the average BOD removal rates were observed as 87.2%, 87.6%, and 94.8% respectively when operated at the loading range of 0-10 g BOD m^{-2} day^{-1}. For the loading range of 11-20 g BOD m^{-2} day^{-1}, the average BOD removal rates were 88.5%, 85.7%, and 94.3% for CW1, CW2, and CW3 units respectively. Similarly, when operated at the loading range of 21-30 g BOD m^{-2} day^{-1}, the average BOD removal rates were 90.2%, 88.1%, and 95.6% for CW1, CW2, and CW3 units respectively. The sand-filled beds demonstrated the maximum BOD removal, with the highest removal rate observed when operated within the loading range of 21-30 g BOD m^{-2} day^{-1}. The BOD removal in constructed wetlands involves various mechanisms, including physical, chemical, and biological processes. In physical processes Sedimentation and filtration play a significant role in BOD removal. As the wastewater flows through the wetland, larger organic particles and suspended solids settle due to gravity (sedimentation). Filtration occurs as the wastewater passes through the wetland media, where organic matter is trapped and retained. BOD removal in constructed wetlands can also be attributed to chemical reactions. Oxygen transfer and diffusion into the wetland media provide aerobic conditions, enabling microbial activity to break down organic matter. In addition, adsorption onto the surfaces of wetland media or plant roots can contribute to the removal of BOD. Microorganisms, including bacteria and fungi, present in the wetland media and plant root zones, are responsible for the biological degradation of organic matter. Through processes like aerobic respiration, they metabolize and convert the organic pollutants into carbon dioxide, water, and microbial biomass. Overall, the combination of physical, chemical, and biological processes in constructed wetlands leads to effective BOD removal and helps in the treatment of wastewater. The results obtained in this study reveal that the BOD removal rates exhibited minimal fluctuations in response to changes in the inlet loading rate, primarily due to the buffering behavior of the constructed wetland system, which effectively mitigated the impact of inlet load fluctuations. The utilization of a 24-hour hydraulic retention time (HRT) in the study facilitated a longer contact period between the wastewater and the microbial community. Consequently, this extended contact time led to more effective and efficient removal of organic matter from the wastewater. [33]. In VSSF CW system, oxygen got diffused into the gravels whereas the wastewater flow and resting phase dispensed oxygen within the bed [31]. Total P removal in the VSSF CWs is mainly dependent on P adsorption by the filter materials [34]. Higher P removal may be ascribed to P binding properties of the applied gravels and sand, since they are rich in Ca/Al/Fe constituents [35-36]. Average TP concentration in the influent fluctuated between 32.3 mg L^{-1} to 43.4 mg L^{-1} for all three inlet BOD loading rates. The total P removal fluctuated between 64.4 to 90.7% at inlet load of 0 - 10 g BOD m^{-2} day^{-1}; 52.6 to 90.9% at inlet load of 11 - 20 g BOD m^{-2} day^{-1} and 47.9 to 92.9% at inlet load of 21 - 30 g BOD m^{-2} day^{-1} (Figure 2). The variation in inlet BOD loading rate influenced the total phosphorus (P) removal efficiencies in CW-1 and CW-2, which are gravel-filled units. However, no significant change in total P removal efficiency was observed in the sand-filled beds when the inlet BOD loading rates were altered. Highest removal (92.9%) of total P was recorded from the sand filled bed when operated under inlet BOD loading range of 21-30 g BOD m^{-2} day^{-1}. In VSSF CW system, intermittent feeding of wastewater was effective due to high oxygen transfer inside the bed [29]. The process related to be conversion of ammonia to nitrite and further to nitrate, is carried out by chemoautotrophic processes under aerobic conditions. The bed depth of the vertical CW system also affects nitrification process. According to studies by Cooper et al. [37], nitrate removal occurred in the anoxic regions in the VSSF CW bed. Ammonium nitrogen volatilization was found to be significant due to the fact that pH of the water was greater than 7.7 [33]. Average NH_4-N removal was observed between 45.4 to 60.6% at inlet load of 0 - 10 g BOD m^{-2} day^{-1}; 44.5 to 53.8% at inlet load of 11 - 20 g BOD m^{-2} day^{-1} while 53.7 to 59% at inlet load of 21 - 30 g BOD m^{-2} day^{-1} (Figure 2). The CW2 unit, which was filled with the largest gravel size of 20 mm, exhibited the highest removal of NH_4-N for all inlet loading rates.

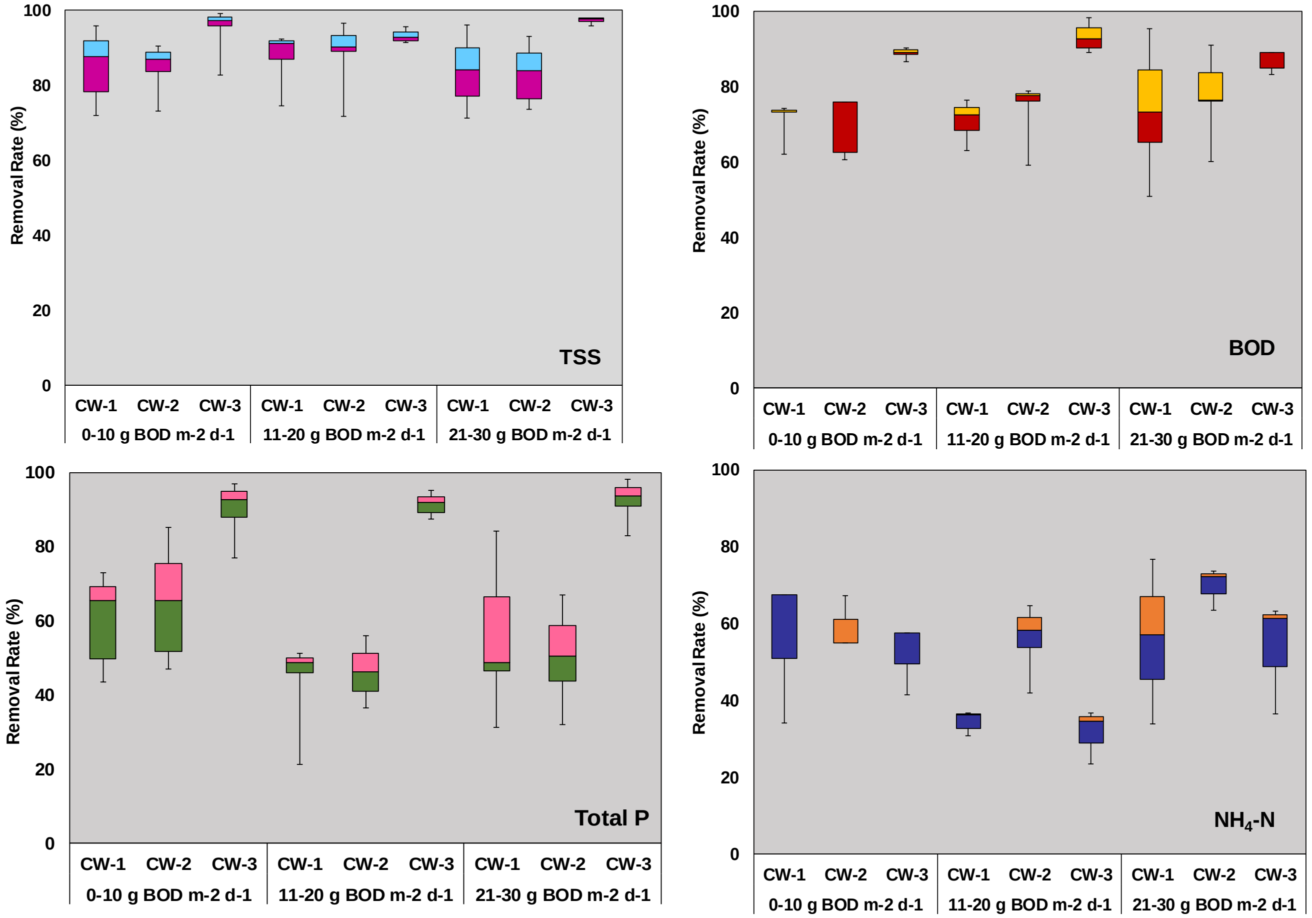

Fig. 2. Removal rates of wastewater pollutants studied at fluctuating inlet loads.

3.4. Correlation between wastewater parameters at fluctuating influent loads

The correlation index measures the relationship between two variables by assessing the extent to which one variable is associated with another. High correlation coefficient values indicate a positive relationship, while lower values suggest a weaker or negative relationship. Correlation analysis was conducted to assess the relationship between water quality parameters at the inlet and outlet points. Based on the correlation data obtained from the current study, the electrical conductivity (EC) showed positive correlations with BOD, Total P (TP), Total N (TN), and NH_4-N in the influent (with R^2 values ranging from 0.166 to 0.551). The influent temperature exhibited insignificant correlations with the pH and dissolved oxygen (DO) of the influent (with R^2 values ranging from -0.365 to -0.480) (Table 2). However, temperature demonstrated a significant correlation with the EC value of the influent, with an R^2 value of 0.184. Furthermore, the influent pH showed negative correlations with the concentrations of BOD, TP, TN, and NH_4-N (with R^2 values varying from -0.052 to 0.537). Additionally, the lack of significant relationships between NH_4-N and the concentrations of BOD, TP, TN, and NH_4-N in the influent indicated a significant positive correlation among the NH_4-N concentrations themselves (with R^2 values ranging from 0.086 to 0.910). Correlation was done for all the wastewater parameters of all the three CW units and their relationship with each other was deduced. Effluent TP concentration was found to be slightly positively correlated with the influent temperature the R^2 values of all the three CWs was recorded as 0.118, 0.192 and 0.166 in CW-1, CW-2 and CW-3 respectively. The concentrations of TP in the effluent decreased as compared to influent, which may be due to the precipitation on the substrates as well as evaporation rates at the CW beds. Influent DO was found to be negatively correlated with the effluent temperature in all the three CW systems with R^2 values of -0.378, -0.478 and -0.352 in CW-1, CW-2 and CW-3 respectively. BOD in the influent had negative correlation with effluent pH with R^2 values of -0.401 (CW-1), -0.365 (CW-2) and -0.323 (CW-3). This may be related to the acid formation due to degradation of organic matter that results in decrease in the wastewater pH [30]. Effluent DO also showed negative correlation (R^2 values of -0.605, -0.586 and -0.066 in CW-1, CW-2 and CW-3 respectively) to the effluent temperature, similar to that of the influent DO. EC is directly correlated with the dissolved solids present in the wastewater and this lead to a positive correlation between EC with TP, TN and NH_4-N in the effluent of CW-1, CW-2 and CW-3 outlet (Table 2, 3, 4). In CW-1 outlet, the effluent BOD also showed positive correlation with TN, NH_4-N concentrations (R^2 values varied from 0.907 to 0.506) and TP concentration (R^2 value 0.298). the R^2 values of correlation of BOD with TN, NH_4-N and TP has been given in table 2, 3 and 4. TN concentration in the effluent also positively correlated with NH_4-N concentration (R value 0.991, 0.99 and 0.84 in CW-1, CW-2 and CW-3 outlets respectively). The data obtained from the current study was more or less in accordance with the correlation data that was obtained in a study conducted by Sharma et al. [30].

Table 2. Correlation values between water quality parameters in the inlet and outlet of CW-1.

	pH (in)	Temp (in)	EC (in)	TDS (In)	TSS (In)	DO (In)	BOD (In)	NO_3-N (In)	NH_4-N (In)	TN (In)	TP (In)	pH (Out)	Temp (Out)	EC (Out)	TDS (Out)	TSS (Out)	DO (Out)	BOD (Out)	NO_3-N (Out)	NH_4-N (Out)	TN (Out)	TP (Out)
pH (in)	**1.00**																					
Temp (in)	-0.37	**1.00**																				
EC (in)	0.13	0.18	**1.00**																			
TDS (In)	0.19	-0.39	**0.83**	**1.00**																		
TSS (In)	-0.31	0.04	-0.41	-0.41	**1.00**																	
DO (In)	0.31	-0.48	0.10	0.19	-0.09	**1.00**																
BOD (In)	-0.54	-0.41	-0.19	-0.06	-0.01	0.44	**1.00**															
NO_3-N (In)	0.05	-0.32	-0.01	-0.06	0.18	0.23	0.57	**1.00**														
NH_4-N (In)	0.27	0.39	-0.57	-0.5	0.16	0.06	0.37	-0.33	**1.00**													
TN (In)	-0.19	0.67	0.13	0.23	-0.57	-0.29	**0.91**	**-0.97**	**0.98**	**1.00**												
TP (In)	-0.05	-0.26	0.06	-0.06	0.21	0.07	0.09	0.02	0.13	0.24	**1.00**											
pH (Out)	0.63	-0.35	-0.06	0.11	0.02	0.32	0.40	0.41	0.14	-0.30	-0.15	**1.00**										
Temp (Out)	-0.46	0.59	-0.33	-0.39	0.09	-0.38	-0.44	-0.1	0.42	0.60	0.04	-0.10	**1.00**									
EC (Out)	0.24	-0.26	**0.89**	0.70	-0.40	0.13	-0.17	-0.01	0.61	0.17	0.11	0.06	-0.32	**1.00**								
TDS (Out)	0.31	-0.36	0.79	**0.9**	-0.49	0.14	-0.06	0.02	-0.60	-0.1	0.11	0.18	-0.29	**0.83**	**1.00**							
TSS (Out)	-0.6	0.32	0.23	0.10	0.52	-0.06	-0.34	0.02	-0.42	0.19	0.21	-0.30	0.28	0.14	0.08	**1.00**						
DO (Out)	0.35	-0.43	-0.17	-0.06	0.27	0.35	0.60	-0.04	0.67	0.00	0.12	0.03	**-0.61**	-0.17	-0.17	-0.29	**1.00**					
BOD (Out)	0.54	-0.37	0.17	-0.06	-0.05	0.40	**0.98**	0.46	0.44	**0.8**	0.08	0.32	-0.48	-0.16	-0.06	-0.34	0.64	**1.00**				
NO_3-N (Out)	-0.05	-0.08	-0.13	-0.17	0.14	0.35	0.67	0.37	0.62	-0.6	-0.10	0.06	-0.22	-0.16	-0.23	-0.02	0.44	0.68	**1.00**			
NH_4-N (Out)	0.45	0.23	0.55	-0.50	0.12	0.15	0.51	-0.19	**0.96**	**0.9**	-0.2	0.30	0.25	-0.59	-0.58	-0.52	0.67	0.56	0.67	**1.00**		
TN (Out)	-0.04	0.43	0.33	0.40	-0.45	-0.17	**0.9**	**-0.85**	**0.93**	**0.9**	-0.4	-0.1	0.40	-0.05	-0.07	-0.08	-0.17	**-0.9**	-0.5	**0.99**	**1.00**	
TP (Out)	-0.19	-0.12	0.43	0.30	0.08	-0.30	0.30	-0.24	-0.23	0.21	0.68	-0.3	0.12	0.39	0.36	0.40	-0.05	-0.27	-0.19	-0.29	0.06	**1.00**

Table 3. Correlation values between water quality parameters in the inlet and outlet of CW-2.

	pH (in)	Temp (in)	EC (in)	TDS (In)	TSS (In)	DO (In)	BOD (In)	NO_3-N (In)	NH_4-N (In)	TN (In)	TP (In)	pH (Out)	Temp (Out)	EC (Out)	TDS (Out)	TSS (Out)	DO (Out)	BOD (Out)	NO_3-N (Out)	NH_4-N (Out)	TN (Out)	TP (Out)
pH (in)	**1.00**																					
Temp (in)	-0.37	**1.00**																				
EC (in)	0.13	0.18	**1.00**																			
TDS (In)	0.19	-0.39	**0.83**	**1.00**																		
TSS (In)	-0.31	0.04	-0.41	-0.41	**1.00**																	
DO (In)	0.31	-0.48	0.10	0.19	-0.09	**1.00**																
BOD (In)	-0.54	-0.41	-0.19	-0.06	-0.01	0.44	**1.00**															
NO_3-N (In)	0.05	-0.32	-0.01	-0.06	0.18	0.23	0.57	**1.00**														
NH_4-N (In)	0.27	0.39	-0.57	-0.51	0.16	0.06	0.37	-0.33	**1.00**													
TN (In)	-0.19	0.67	0.13	0.23	-0.57	-0.29	**0.91**	**-0.97**	**0.98**	**1.00**												
TP (In)	-0.05	-0.26	0.06	-0.06	0.21	0.07	0.09	0.02	0.13	0.24	**1.00**											
pH (Out)	0.61	-0.32	0.06	0.18	0.02	0.33	0.37	0.36	0.13	-0.23	-0.14	**1.00**										
Temp (Out)	-0.48	0.61	-0.28	-0.34	0.08	-0.48	-0.49	-0.10	0.25	0.61	0.01	-0.21	**1.00**									
EC (Out)	0.24	-0.25	**0.90**	0.68	-0.42	0.13	-0.18	0.02	**0.61**	0.16	0.10	0.11	-0.30	**1.00**								
TDS (Out)	0.31	-0.37	0.78	**0.88**	-0.50	0.16	-0.07	0.04	-0.62	-0.17	0.09	0.21	-0.24	0.79	**1.00**							
TSS (Out)	-0.46	0.22	0.46	0.24	0.36	-0.12	-0.37	-0.01	-0.57	0.10	0.30	-0.25	0.22	0.36	0.24	**1.00**						
DO (Out)	0.30	-0.31	-0.13	0.01	0.11	0.47	0.60	-0.12	0.76	0.26	0.09	-0.05	-0.59	-0.25	-0.17	-0.24	**1.00**					
BOD (Out)	0.61	-0.39	-0.15	-0.06	-0.04	0.34	**0.93**	0.42	0.44	**0.72**	0.04	0.40	-0.54	-0.14	-0.06	-0.37	0.62	**1.00**				
NO_3-N (Out)	0.34	0.07	-0.09	-0.16	-0.13	-0.18	0.62	0.21	0.38	-0.32	0.18	-0.02	-0.14	-0.19	-0.03	0.02	0.40	0.71	**1.00**			
NH_4-N (Out)	0.17	0.16	-0.38	-0.28	0.18	0.06	0.32	-0.22	**0.88**	0.69	-0.41	0.19	0.11	-0.52	-0.53	-0.55	0.64	0.42	0.20	**1.00**		
TN (Out)	-0.08	0.18	**0.60**	0.69	-0.57	-0.16	0.55	-0.56	**0.69**	**0.69**	-0.68	0.03	0.18	0.03	0.00	-0.19	0.06	-0.33	-0.48	**0.99**	**1.00**	
TP (Out)	-0.10	0.19	0.37	0.27	0.08	-0.19	0.19	-0.18	-0.22	0.06	0.76	-0.12	0.05	0.32	0.30	0.50	0.02	-0.09	0.29	-0.37	-0.25	**1.00**

Table 4. Correlation values between water quality parameters in the inlet and outlet of CW-3.

	pH (in)	Temp (in)	EC (in)	TDS (In)	TSS (In)	DO (In)	BOD (In)	NO_3-N (In)	NH_4-N (In)	TN (In)	TP (In)	pH (Out)	Temp (Out)	EC (Out)	TDS (Out)	TSS (Out)	DO (Out)	BOD (Out)	NO_3-N (Out)	NH_4-N (Out)	TN (Out)	TP (Out)
pH (in)	1.00																					
Temp (in)	-0.37	1.00																				
EC (in)	0.13	0.18	1.00																			
TDS (In)	0.19	-0.39	**0.83**	1.00																		
TSS (In)	-0.31	0.04	-0.41	-0.41	1.00																	
DO (In)	0.31	-0.48	0.10	0.19	-0.09	1.00																
BOD (In)	-0.54	-0.41	-0.19	-0.06	-0.01	0.44	1.00															
NO_3-N (In)	0.05	-0.32	-0.01	-0.06	0.18	0.23	0.57	1.00														
NH_4-N (In)	0.27	0.39	-0.57	-0.51	0.16	0.06	0.37	-0.33	1.00													
TN (In)	-0.19	0.67	0.13	0.23	-0.57	-0.29	**0.91**	**-0.97**	**0.98**	1.00												
TP (In)	-0.05	-0.26	0.06	-0.06	0.21	0.07	0.09	0.02	0.13	0.24	1.00											
pH (Out)	0.53	-0.52	0.18	0.28	-0.08	0.14	0.32	0.44	-0.12	-0.39	-0.09	1.00										
Temp (Out)	-0.46	0.45	-0.31	-0.37	0.30	-0.35	-0.25	0.08	0.43	0.11	0.21	-0.45	1.00									
EC (Out)	0.15	0.24	0.30	0.15	-0.40	-0.23	-0.37	0.01	0.59	0.34	0.20	0.10	-0.12	1.00								
TDS (Out)	0.16	0.17	0.17	0.20	-0.38	-0.22	-0.31	0.02	-0.63	0.32	-0.20	0.14	-0.12	**0.94**	1.00							
TSS (Out)	0.35	0.13	-0.32	-0.14	-0.15	-0.04	0.35	-0.27	0.75	0.52	-0.07	-0.19	0.26	-0.20	-0.11	1.00						
DO (Out)	-0.28	-0.17	0.12	0.06	0.04	0.06	-0.30	-0.21	-0.19	0.24	0.34	-0.46	-0.07	0.12	0.10	-0.16	1.00					
BOD (Out)	0.37	-0.42	-0.18	-0.10	0.04	0.48	**0.88**	0.80	-0.05	**0.93**	0.07	0.30	-0.16	-0.27	-0.22	0.12	-0.21	1.00				
NO_3-N (Out)	0.07	0.23	0.11	0.04	-0.10	-0.36	0.41	0.13	0.40	0.04	0.04	-0.03	0.33	-0.17	-0.19	0.37	-0.30	0.16	1.00			
NH_4-N (Out)	0.40	0.21	-0.47	-0.40	0.10	0.11	0.48	-0.20	**0.96**	**0.84**	-0.25	0.06	0.30	-0.57	-0.62	0.67	-0.35	0.03	0.38	1.00		
TN (Out)	0.01	0.28	0.56	0.63	-0.62	-0.23	**0.74**	-0.74	**0.84**	**0.84**	-0.51	-0.04	-0.17	0.40	0.33	0.19	-0.05	**-0.88**	-0.03	**0.84**	1.00	
TP (Out)	0.50	0.17	0.31	-0.22	-0.13	0.26	0.49	0.24	0.14	-0.68	0.32	-0.03	0.33	-0.33	-0.27	0.61	-0.23	0.54	0.11	0.17	-0.79	1.00

3.5. Correlation between pollutant removal rates and fluctuating influent loads.

Figure 2 illustrates BOD, TSS and TP removal rates of the three CW beds over the entire study period. Corresponding loading rates have also been depicted in the same plot. The outcomes showed that all the three CW beds followed more or less similar removal trend; i.e., decreased removal rates at higher loading rates. Furthermore, the outcomes point out that all the three CWs showed approximately above 90% BOD, 90% TSS and 85% TP removal rates. The results suggested that even at higher influent loading rates, the CWs showed good pollutant removal efficiencies. Besides, the statistical analysis was carried out to investigate the treatment efficiencies by using MS-Excel 2016 and it suggested that the three CW systems had a significant treatment difference. Primary BOD removal mechanisms in a CW system comprise adsorption, sedimentation and microbial interactions [38]. Along with this, rhizospheric zone also provide additional adsorption as well as favorable environmental conditions for microbial growth and metabolism for enhanced removal. This may lead to enhanced aerobic conditions in the rhizospheric zone and positively affect BOD as well as other pollutants. A slight decrease in BOD removal rates at higher loading rates may be due to inadequate contact time within the system. As per study conducted by Reed and Brown [39], the BOD removal in a CW is inefficient with HRT <1 day and improves with an HRT > 7.5 days. According to the findings of the current study, a strong linear correlation was observed between the loading rates and removal rates for all the wastewater parameters in the three constructed wetland (CW) systems. The influent loading rates were determined to be medium to high, ranging from 1.6 to 34 g m^{-2} day^{-1}. These values are consistent with those reported in previous studies, such as the range of 5.12±2.27 to 20.49±9.08 g m^{-2} day^{-1} observed by Ghosh and Gopal [40] and the range of 0.35±0.04 to 2.34±0.23 g m^{-2} day^{-1} reported by Chang et al. [41]. However, the BOD removal rates showed positive correlation with the influent loads with R^2 values of 0.954, 0.864 and 0.769 in CW-1, CW-2 and CW-3 respectively. TSS decrease in CWs is assisted by physical and biological processes (filtration, sedimentation and microbial uptake) inside the CW bed [31,42]. Additionally, Manios et al. [43] observed that substrate hydraulic and microbiological properties are the other major TSS removal processes in a CW system. There was very slight correlation between TSS removal rates and influent loading rates with R^2 values of 0.148, 0.129 and 0.046 in CW-1, CW-2 and CW-3 respectively (Figure 3); however, the CW system showed good removal rates during its operation. The reason behind less correlation may be the suspension/settlement of solid particles over the filter media substrates before it is subjected to treatment processes inside the CW beds. In other studies, also, it was observed that increased loading rates can have more tendency of rapid percolation through the substrate media with increasing flow velocity. Manios et al. [43] also explained that TSS removal is dependent on the size and type of substrate media as well as HRT.

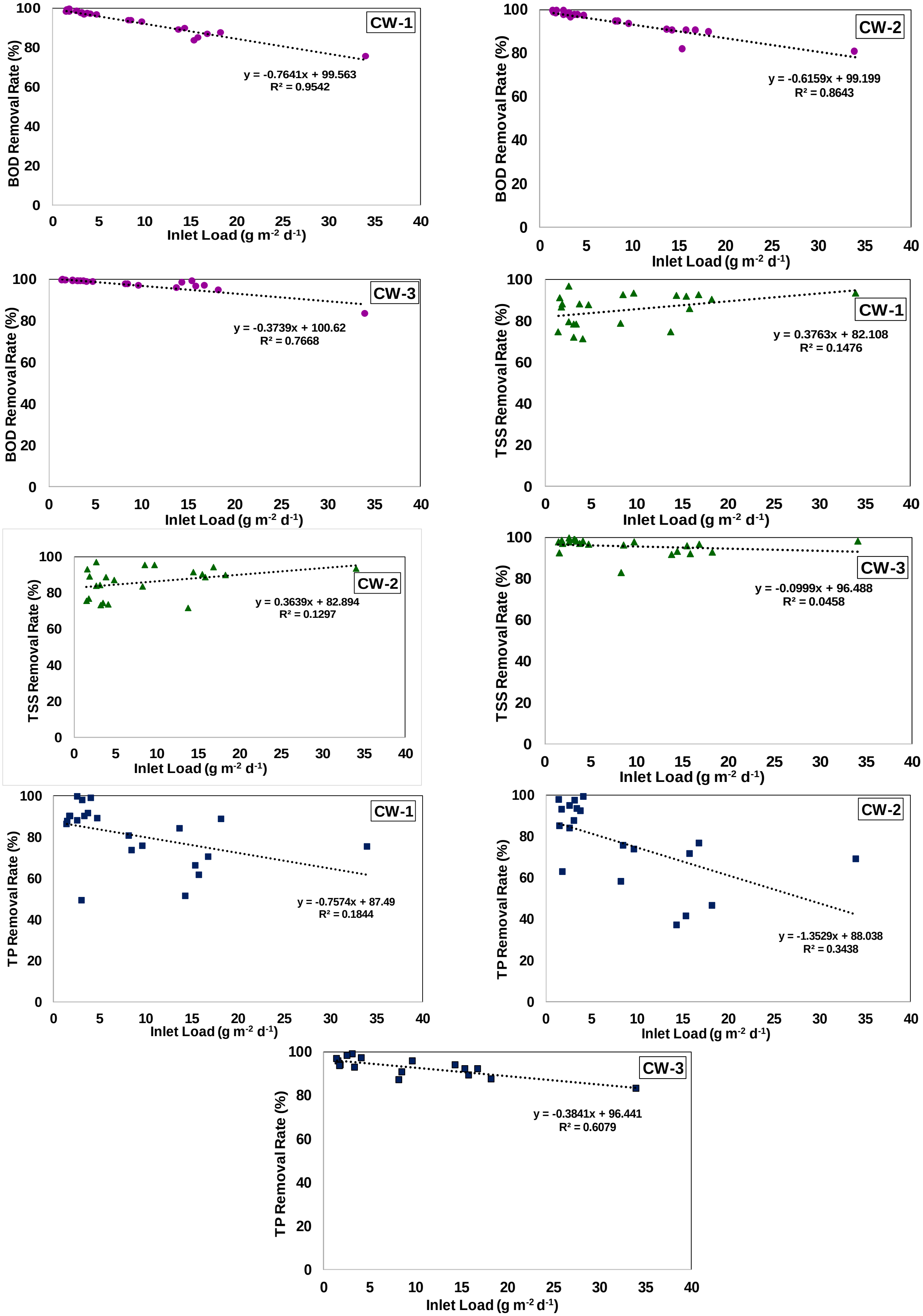

Fig.3. Correlation graphs of BOD, TSS and TP with fluctuating inlet loads in three CWs.

4. Conclusions

The following conclusions can be drawn from the present study.

- The VSSF CW (Vertical Subsurface Flow Constructed Wetland) system proved to be highly efficient in removing pollutants from various types of wastewater, including dairy farm wastewater.
- The average influent concentrations of TSS, BOD_3, TP, and NH_4-N exhibited significant fluctuations. However, despite these fluctuations, the removal rates showed minimal fluctuations for TSS (84.1% to 97.5%), moderate fluctuations for BOD (84.1% to 96.9%), and high fluctuations for TP (47.9% to 92.9%), and NH_4-N (44.5% to 60.6%).
- TSS, BOD, and TP removal were maximized in the sand-filled beds across all loading ranges, with minimal variation observed with an increase in loading rate. However, the maximum removal of NH_4-N was observed in CW units filled with 20 mm-sized gravel for all three ranges of inlet loading rates.
- Organic matter load exhibited slight fluctuations, but the removal rate fluctuations were moderate. This indicates that BOD removal is highly sensitive to fluctuations in inlet load in CWs.
- TSS removal primarily occurs through physical interactions such as filtration and sedimentation, which make these processes more tolerant to load fluctuations compared to the biological and chemical processes in CWs. High inlet loads can limit effective nitrification, thereby affecting ammonium-nitrogen removal.
- The variation in inlet BOD loading rate influenced the total phosphorus (P) removal efficiencies in CW-1 and CW-2, which are gravel-filled units. However, no significant change in total P removal efficiency was observed in the sand-filled beds when the inlet BOD loading rates were altered.
- TP removal rates decrease when inlet TP loads are reduced. This observation suggests that adsorption and precipitation are the major processes for TP removal, allowing phosphorus to remain attached to the CW beds for a longer duration.
- In conclusion, despite the fluctuations in influent loads, the VSSF CW system shows promising outcomes in terms of pollutant removal.

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