Chapter 14
Performance Analysis of Constructed Wetland Treating Secondary Effluent Under Cold Climatic Conditions in Hamirpur (H.P.), India

Adarsh Singh, Akash Rawat, Surjit Singh Katoch, and Mukul Bajpai

14.1 Introduction

Industrial growth and rapid urbanization have resulted in unprecedented water demand and associated wastewater generation (Rashid et al. 2018; Qin et al. 2014). Due to the gap in the installed treatment capacity and the quantity of wastewater generated, a large quantity of untreated wastewater (domestic and industrial) is disposed of directly into water bodies deteriorating the surface water quality (Breida et al. 2020; Chang 2019). The situation is even more critical especially in developing countries where due to financial constraints, wastewater management and treatment are of less priority (Ilyas et al. 2019; Paul 2017; Wang et al. 2014).

The potential solution to the above-stated problem could be the use of sustainable technologies to treat wastewater. In this regard, constructed wetland (CW) is an engineered and ecological technology that simulates the processes of natural wetland for treating domestic and industrial wastewater (Kivaisi 2001; Wu et al. 2015a, b). The conventional wastewater treatment technologies are inefficient in removing heavy metals, nutrients, and emerging contaminants which ultimately enter surface waters contaminating those (Nourmohammadi et al. 2013; Petrović et al. 2003; Yang et al. 2015). Recent researches show that CWs have proven effective in treating effluents enriched with nutrients and other heavy metals (Gill et al. 2017; Jehawi et al. 2020; Tan et al. 2019). The mechanism for pollutant removal in CWs includes a series of physical, chemical, and biological processes (Kadlec and Wallace 2009). The aerobic and anaerobic degradation of organic matter by microbes is mainly accountable for removing organics in CWs, while the conventional nitrification and denitrification route is followed for nitrogen removal (Saeed and Sun 2017). Moreover, phosphorus is removed by getting adsorbed on the surface of substrate media and through plant

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A. Singh (✉) · A. Rawat · S. S. Katoch · M. Bajpai
Department of Civil Engineering, National Institute of Technology Hamirpur, Hamirpur, Himachal Pradesh 177005, India
e-mail: 19m722@nith.ac.in

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uptake (Vymazal 2004). However, treatment efficiency in CWs depends upon several parameters and factors such as hydraulic loading rate (HLR), hydraulic retention time (HRT), mode of feeding (continuous or intermittent), pH, dissolved oxygen (DO), type of macrophytes, and substrate media (Saeed and Sun 2012; Wu et al. 2015a, b).

In addition to the factors influencing CWs, it has also been seen that low temperatures affect the removal efficiency of the CWs significantly (Kadlec and Reddy 2001; Zhu et al. 2018). In general, a feeble microbial activity prevails at lower temperatures resulting in the reduced removal efficiency in CWs (Werker et al. 2002). Moreover, the processes responsible for removing pollutants such as sedimentation, plant uptake, volatilization, filtration, precipitation, and adsorption are largely influenced by low temperatures (Stottmeister et al. 2003). Therefore, it is evident that despite showing satisfactory performance when applied in the warm climatic regions, the implementation of CWs in a cold climate is uncertain. Recent reviews by various researchers present a global view on the application of CWs in cold climatic regions (Ji et al. 2020a, b; Ji et al. 2020a, b; Wang et al. 2017). However, there is limited literature available to support its applicability in the remote and hilly areas in India having mild to cold climatic conditions.

The current study aims to investigate the potential of HSSF-CW to remove the organics and nutrients from secondary effluent under cold climatic conditions in Hamirpur, India. In a cold climate, the sub-surface flow CWs are effective in providing thermal insulation due to the presence of an unsaturated layer at the surface (Varma et al. 2021). To determine the pollutant removal efficiency in the prevailing climatic conditions, a lab-scale horizontal subsurface flow constructed wetland (HSSF-CW) model was designed and tested. Further, the performance of the experimental set-up obtained for chemical oxygen demand (COD), ammonia nitrogen (NH_4^+-N), total nitrogen (TN), and total phosphorus (TP) removal were modelled using the first-order Kinetic plug flow model.

14.2 Materials and Methods

14.2.1 Study Area

The town Hamirpur (31.68°N 76.52°E) is located in the Hamirpur district of Himachal Pradesh, India. In Hamirpur, the temperature could fall to as low as 1 °C between mid-October and April. From the perspective of wastewater treatment and management, Hamirpur has 4 STPs: Hamirpur—Zone I, Zone II, Zone III, and STP at NIT Hamirpur, having the design capacity of 3.13, 1.35, 0.68, and 0.27 MLD respectively. (Ganguly and Dewan 2020) through his case study reported the overall treatment efficiency of the 4 STPs at Hamirpur as 80.67% (Zone I), 73.27% (Zone II), 76.08% (Zone III), and 57.29% (NIT Hamirpur). CW technology could be combined with the existing wastewater treatment plants (WWTPs) to enhance their overall treatment efficiency and can also be implemented independently with a pre-treatment

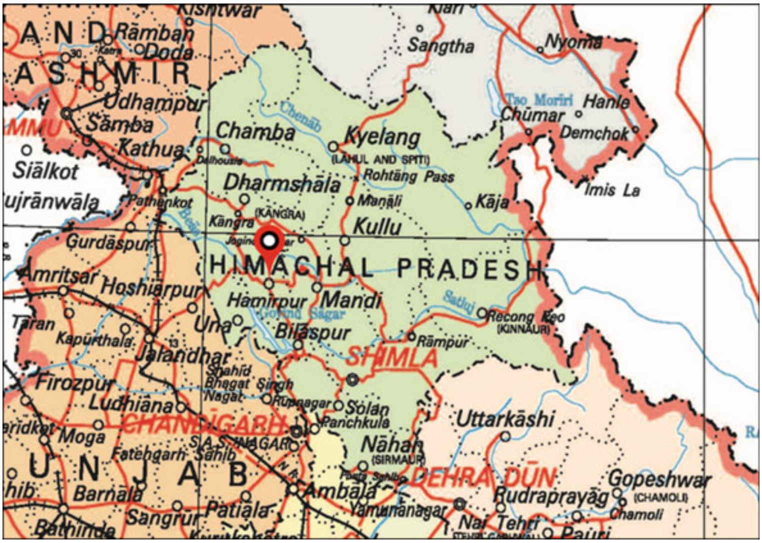

Fig. 14.1 Hamirpur (H.P.), India. (*Source* Survey of India)

facility to treat wastewater from small localities. Figure 14.1 shows the geographical location of Hamirpur.

14.2.2 Selection of Macrophytes

The plant species, namely *Canna indica* was selected for the study. The *Canna indica* plants having an average height of 20 cm were collected from the plant nursery in NIT Hamirpur (H.P.). The previous studies conducted by various researchers explaining the phytoremediation properties of the plant acted as a base for plant selection. These plants have proven effective in remediating heavy metals from the effluents (Solanki et al. 2018; Zhang et al. 2020). Moreover, their efficiency to treat organics and nutrients from wastewater (domestic and industrial) has been investigated by various researchers (Cui et al. 2010; Vankar and Srivastava 2018; Wang et al. 2016).

14.2.3 Selection of Substrate Material

The substrate media selected for the experimental set-up was composed of gravel and sand. Gravel and sand as a substrate have been used in the CWs in previous researches (Anh et al. 2020; Bulc and Ojstršek 2008). The volume of sand and gravel estimated to be used in the experimental set-up was 0.04 m^3 and 0.12 m^3, respectively. Physical properties of the substrate media were tested as per the IS 2386 Part-1 (1963) and were following the code.

14.2.4 Design and Construction of the Experimental Set-Up

The experimental work was conducted in the Environmental Engineering laboratory at the Department of Civil Engineering, NIT Hamirpur (H.P.). The experimental set-up simulates a HSSF-CW under cold climatic conditions. The wetland model consisted of a glass tank having dimensions 100 cm × 40 cm × 60 cm (L × B × H). A tap was provided close to the base of the tank as an outlet to collect the treated effluent for analysis. The tank was filled with the substrate media up to a height of 30 cm; 10 cm thick gravel layer (Ø 5–10 mm) was laid at the bottom and 20 cm of sand layer (Ø 1–2 mm) above it (Wu et al. 2015a, b). Six *Canna indica* plants having an average height of 20 cm were planted spaced equally in the CW model after transplanting it from the NIT Hamirpur plant nursery. The secondary effluent received from the STP at NIT Hamirpur was fed into the experimental system for 2 months until the bio-layer formation and new plant growth were observed. Diagram and image of the experimental set-up along with detailed information is shown in Figs. 14.2 and 14.3, respectively.

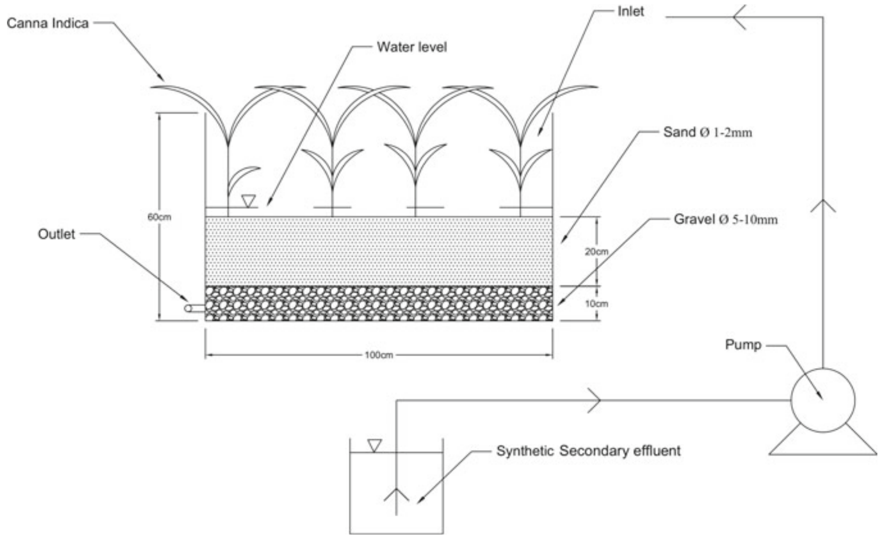

Fig. 14.2 Schematic diagram of the Lab-scale HSSF-CW model

Fig. 14.3 View of the HSSF-CW model at the Env. Eng. Lab, NITH

14.2.5 Operation of the Experimental System

To avoid any disparity in the concentration of the influent, simulated secondary effluent was used. The synthetic wastewater was prepared by dissolving NH_4Cl, $CaCl_2 \cdot 2H_2O$, KH_2PO_4, CH_3COONa, and $MgSO_4 \cdot 7H_2O$ in the tap water (Ge et al. 2018; Liu et al. 2017). This resulted in the COD, NH_4^+-N, TP and TN concentrations being approximately 105 mg/L, 19 mg/L, 2.5 mg/L, and 40 mg/L, respectively. The characteristics of the synthetic secondary effluent have been shown in Table 14.1. The experimental system received wastewater in the intermittent batch mode of 5 L/m^2/day. During the experimental period (seeding and operating) the ambient temperature varied between 8 and 13 °C. The whole experiment lasted from 1 December 2020 to 8 February 2021. Plant growth was carefully monitored and measured in the seeding period, and relative growth rate (RGR) was calculated (Li and Guo 2017).

Table 14.1 Characteristics of the influent (mean ± SD)

COD (mg/L)	NH_4^+-N (mg/L)	TP (mg/L)	TN (mg/L)
104.45 ± 0.32	18.65 ± 0.44	2.32 ± 0.16	39.48 ± 0. 65

14.2.6 Sampling and Analytical Analysis

Water samples were collected at the inlet and outlet of the experimental set-up from February 1 to February 10. Sampling was done every second day up to the tenth day in the operating period, and collected samples were instantly stored at 4 °C for future analysis. For all water samples, COD, NH_4^+-N, TP, and TN were tested as per the APHA (1998), Standard Methods 20th Edition. The test methods adopted for the measurement of the above parameters were the Closed reflex method for COD, Nesslerisation method for NH_4^+-N, Stannous chloride method for TP and UV–Vis spectrophotometer method for TN. Other environmental parameters such as Total dissolved solids (TDS), pH, Temperature (T), and Electrical conductivity (EC) were measured in-situ using Multiparameter Analyzer (Agilent Technologies 3200 M Multi-parameter Analyzer). The DO concentration in the influent and effluent was measured using the DO meter (Agilent technologies 3200D Dissolved Oxygen Meter).

14.2.7 Plant Growth

Height of the plants and relative growth rate (RGR) values have been used to report the growth status of *Canna indica* plants during the seeding period. Equation (14.1) defines the relative growth rate in plants:

$$RGR = \frac{[lnH_2 - lnH_1]}{(t_2 - t_1)} \tag{14.1}$$

where H_1 and H_2 are the average plant heights recorded at time t_1 and t_2.

14.2.8 Modelling and Statistical Analyses

The treatment performance of the lab-scale HSSF-CW for organics and nutrient removal was modelled using the Ist order Kinetic plug flow model (KC*) (Eq. 14.2) to present a correlation between the experimental and simulated results (Kadlec and Wallace 2009).

$$C_o = C_i \times e^{-K_t \times \tau} \tag{14.2}$$

where:

C_o	Effluent concentration (mg/L)
C_i	Influent concentration (mg/L)
K_t	First order reaction coefficient (day^{-1})

τ Theoretical HRT (day)

The R^2, SSE, and RMSE values were also computed to indicate the goodness of fit between the observed and predicted values. All statistical analyses were performed by applying the software R2018a—MATLAB & Simulink—MathWorks.

14.3 Results and Discussion

14.3.1 Plant Growth

The variation in the plants' heights and associated RGR values are shown in Table 14.2. Plants showed rapid growth during the first month of seeding and the RGR value varied between 0.0223 and 0.0357 day^{-1}. This might be due to the excess availability of nutrients at the beginning of the experiment. Lesser plant growth was recorded in the second month with RGR values lying between 0.0131 and 0.0033 day^{-1}. Figure 14.4 shows the growth and development of the *Canna indica* plants in the seeding period. At the end of the seeding period of 2 months, the plants' height was 62 cm. Figure 14.5 shows the height variation recorded in the seeding period (2 months). The experimental set-up was now functional and was filled with synthetic wastewater for final testing.

14.3.2 Measurement of pH, DO, TDS and EC

The pH observed in the HSSF-CW system varied from 6.84 ± 0.26 in the influent to 7.45 ± 0.21 in the effluent. It has been observed that photosynthetically elevated pH affects the treatment performance of CWs (Yin et al. 2016). The influent DO concentration increased from 6.35 ± 0.11 mg/L to 10.84 ± 0.58 mg/L in the effluent. This might indicate the extent of degradation of contaminants that take place in the experimental system. However, DO concentration in the effluent from HSSF-CW could not be straightly related to the removal efficiency of the wetland system

Table 14.2 Plant heights and relative growth rate in HSSF-CW

Time interval (days)	Height variation (cm)	Relative growth rate (day^{-1})
0–10	20 ↔ 25	0.0223
10–20	25 ↔ 35	0.0336
20–30	35 ↔ 50	0.0357
30–40	50 ↔ 57	0.0131
40–50	57 ↔ 60	0.0051
50–60	60 ↔ 62	0.0033

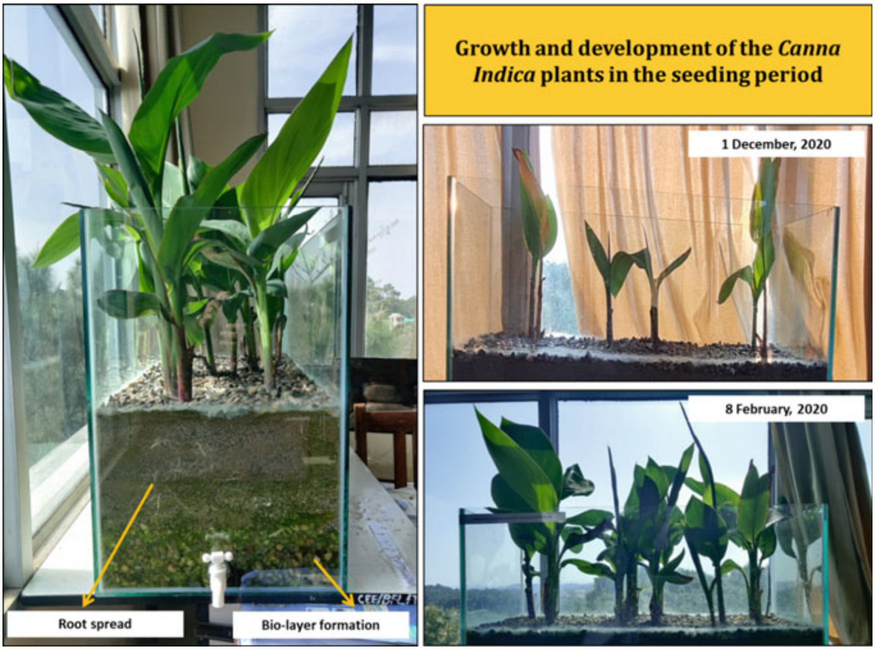

Fig. 14.4 Growth and development of the *Canna indica* plants in the seeding period

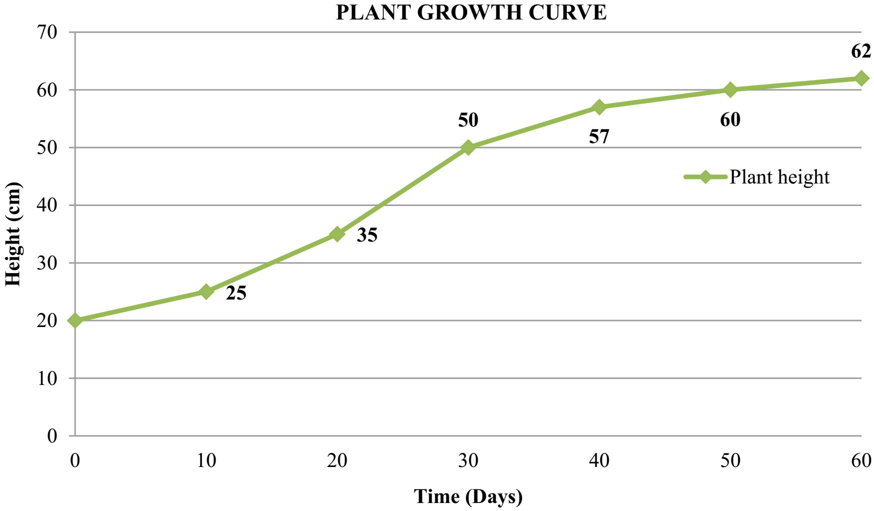

Fig. 14.5 Plant height variation in the seeding period

(Vymazal and Kröpfelová 2008). Figure 14.6 shows the increase in DO concentration and pH with increasing HRT.

The TDS and EC value of the synthetic effluent decreased from 1070.35 mg/L and 1835.428 µS/cm to 359.63 mg/L and 697.43 µS/cm, respectively after being retained for 10 days. In CWs, the main processes responsible for TDS removal are adsorption to the substrate, sedimentation, precipitation, microbial degradation, and plant uptake (Kadlec and Wallace 2009). This might be the reason for the low concentration of TDS in the effluent. Figure 14.7 shows the variation of TDS and EC with increasing HRT. This could be supported by the fact that TDS in water and its EC are correlated (Rusydi 2018).

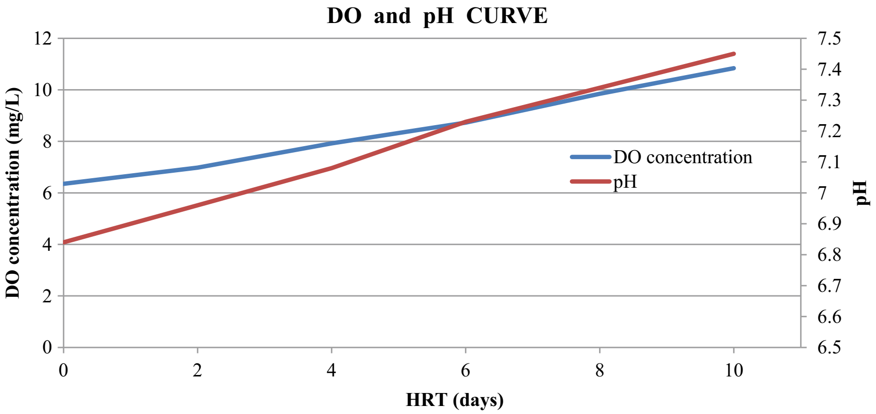

Fig. 14.6 Variation of DO and pH with HRT

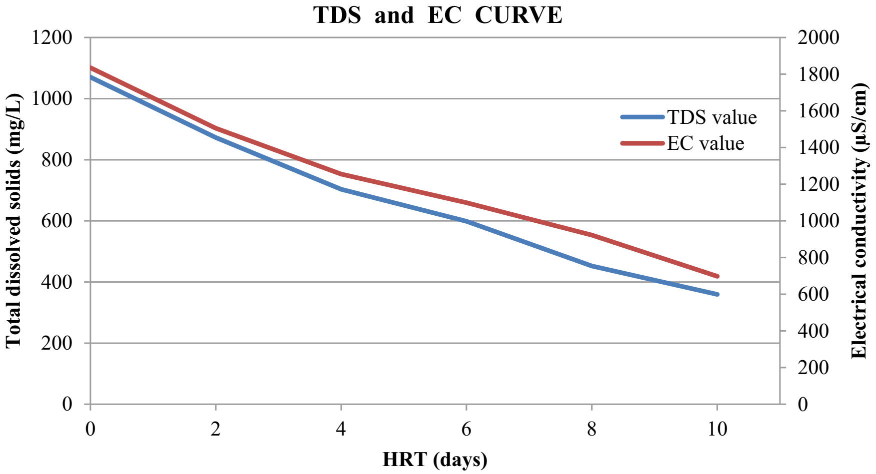

Fig. 14.7 Variation of TDS and EC with HRT

14.3.3 Removal of Pollutants

14.3.3.1 COD Removal

Organics in the HSSF-CWs could primarily be degraded aerobically and anaerobically (Carballeira et al. 2017). The oxygen requirement for aerobic degradation is satisfied by atmospheric diffusion, convection, and plant root transfer. Anaerobic degradation of organic matter takes place in the substrate media where oxygen is deficient. In this study, the average COD concentration in the HSSF-CW declined from 104.45 mg/L to 9.84 mg/L indicating the overall removal efficiency to be 90.58%. This finding could be justified by the presence of high DO concentration in the effluent which was found to be 10.74 mg/L. As shown in Table 14.4, the COD concentration dropped to less than half of its value (<50 mg/L) in 2 to 4 days, signifying organic matter could be removed in a shorter period in the wetland system. COD reduced to about 20 mg/L when HRT reached 8 days and then remained nearly stable up to 10 days. The overall removal efficiency obtained for COD removal is 90.58%. The treatment efficiency obtained is in association with the previous studies in the cold climate using HSSF-CW (Paruch et al. 2016).

14.3.3.2 Nitrogen (NH_4^+ and TN) Removal

The mechanism for nitrogen removal in the sub-surface flow CWs majorly consists of classical nitrification and denitrification path which includes nitrification ($NH_4^+ \rightarrow NO_2^- \rightarrow NO_3^-$) followed by canonical denitrification ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$) processes (Maharjan et al. 2020). In this study, the average concentration of NH_4^+ and TN in the treated effluent was found to be 2.23 mg/L and 39.48 mg/L, respectively.

A rapid decline was observed in the concentration of NH_4^+-N in the initial days where it dropped from 18.65 mg/L to 8.32 mg/L indicating a more than 50% removal of NH_4^+-N in 4 days. This was due to the adequate availability of oxygen in the beginning. However, the removal rate was significantly low at the later stage (8–10 days) of the experiment. The overall removal efficiency obtained for NH_4^+-N removal is 88.04%. The extent of NH_4^+-N removal obtained in this study is supported by the outcomes of the previously published literature (F. Wang et al. 2012).

The TN removal observed in the HSSF-CW decreased gradually. Though, at the initial stage (0–4 days), the concentration of TN reduced from 39.48 mg/L to 21.62 mg/L indicating an initial removal efficiency of less than 50%. However, beyond 4 days, the TN concentration reduced with a decreasing rate and was relatively stable between 8 and 10 days. The insufficient carbon source inhibits the denitrification rate resulting in a lower TN removal. The overall removal efficiency obtained for TN removal is 64.72%. Similar removal efficiency is obtained in other researches as well (Calheiros et al. 2012; Paruch et al. 2016).

The trend obtained in the COD removal justifies the above results. The availability of the carbon source was inadequate to support denitrification in the beginning. Moreover, due to the rapid degradation of organics at shorter HRTs by microbial action makes the carbon source scarcer unable to aid denitrification at longer HRT. A similar emphasis could be drawn from previous studies as well (Zhong et al. 2014; Zhou et al. 2017).

14.3.3.3 TP Removal

TP removal in the HSSF-CWs is primarily attributed to the processes such as adsorption, precipitation, and plant uptake (Vymazal 2004). In the present study, the treatment efficiency for TP in the lab-scale model was found to be low i.e. 52.58%. The major removal of phosphates in the wetland system takes place by getting adsorbed on the substrate media (Ballantine and Tanner 2010). However, in this case, the pH of the influent and effluent was found to be 6.89 and 7.45, respectively implying a relatively neutral environment in the experimental system. This neutrality of the influent and effluent could be associated with the oxidation state of the Fe (Fe^{2+}) in the substrate media (Nandakumar et al. 2019). Therefore, the possibility of phosphate binding to the substrate material was negligible. The TP removal in the experimental system was primarily by plant uptake. The overall removal efficiency obtained for TP removal in the experimental system is 52.58%. The results obtained are supported by the findings of the previously published literature (Rai et al. 2015). Table 14.3 shows the reduction in concentration of organics (COD) and nutrients (NH_4^+-N, TN, and TP) with increasing HRT in the lab-scale HSSF-CW.

14.3.4 Result of Modelling and Statistical Analysis

The Eq. (14.2) representing the first-order Kinetic plug flow model is of the form $f(x) = a \times e^{(b \times x)}$, where f(x) is the function of the independent variable ‘x’ and, ‘a’ and ‘b’ are the constants. Modelling of the lab-scale HSSF-CW yielded reaction rate coefficients (K_t) for COD, NH_4^+-N, TN and TP as 0.31 day^{-1}, 0.22 day^{-1}, 0.12 day^{-1} and 0.09 day^{-1} respectively. The K_t value for COD illustrates that organics could be removed at a higher rate (30% per day) in the HSSF-CW under cold conditions. Moreover, the simulated first-order degradation coefficients (K_t) for NH_4^+-N and TN removal in the experimental system were 0.22 day^{-1} and 0.12 day^{-1}, respectively which shows NH_4^+-N could be removed more effectively than TN at low temperatures. The least value of K_t was obtained for TP removal. To enhance the TP removal, various substrates such as blast furnace slags, activated carbon, marble, etc. could be used (Bachand and Bachand 2020). The coefficients of regression (R^2) obtained are greater than 0.9 indicating the relationship between observed and predicted values to be strong (Dendukuri and Reinhold 2005). The results obtained from modelling and statistical analysis have been shown in Table 14.4. The dynamic transformations

Table 14.3 Reduction in the concentration of organics and nutrients in the effluent (mean ± SD)

Characteristics	Influent (mg/L)	Effluent (mg/L)				
		HRT (days)				
		2	4	6	8	10
COD	104.45 ± 3.16	47.42 ± 2.45	31.56 ± 1.73	21.15 ± 0.86	13.74 ± 0.65	9.84 ± 0.22
NH_4^+-N	18.65 ± 0.44	13.72 ± 0.25	8.42 ± 0.41	4.26 ± 0.57	2.85 ± 0.31	2.23 ± 0.11
TN	39.48 ± 2.16	28.20 ± 0.52	21.62 ± 0. 29	18.42 ± 0.34	14.55 ± 0.02	13.14 ± 0.14
TP	2.32 ± 0.35	1.84 ± 0.15	1.39 ± 0.21	1.22 ± 0.30	1.14 ± 0.18	1.10 ± 0.07

Table 14.4 Details of modelling and statistical analysis

Characteristics	General model $f(x) = a \times e^{(b \times x)}$	Goodness of fit
COD	Coefficients (with 95% confidence bounds): a = 102 (88.77, 115.1) b = – 0.3136 (– 0.3911, – 0.2361)	[a]SSE: 97.73 R-square: 0.9851 Adjusted R-square: 0.9813 [b]RMSE: 4.943
NH_4^+-N	Coefficients (with 95% confidence bounds): a = 19.27 (16.95, 21.59) b = – 0.2179 (– 0.2667, – 0.169)	SSE: 3.277 R-square: 0.9851 Adjusted R-square: 0.9813 RMSE: 0.9051
TN	Coefficients (with 95% confidence bounds): a = 37.92 (33.93, 41.92) b = – 0.1215 (– 0.1495, – 0.09355)	SSE: 11.33 R-square: 0.9768 Adjusted R-square: 0.971 RMSE: 1.683
TP	Coefficients (with 95% confidence bounds): a = 2.214 (1.887, 2.54) b = – 0.0869 (– 0.1206, – 0.05318)	SSE: 0.0815 R-square: 0.9302 Adjusted R-square: 0.9128 RMSE: 0.1427

[a] SSE-Squared sum of errors, [b] RMSE-Root mean square error

of COD, NH_4^+-N, TN, and TP in the HSSF-CW during the experimental period have been shown in Figs. 14.8, 14.9, 14.10, and 14.11 respectively.

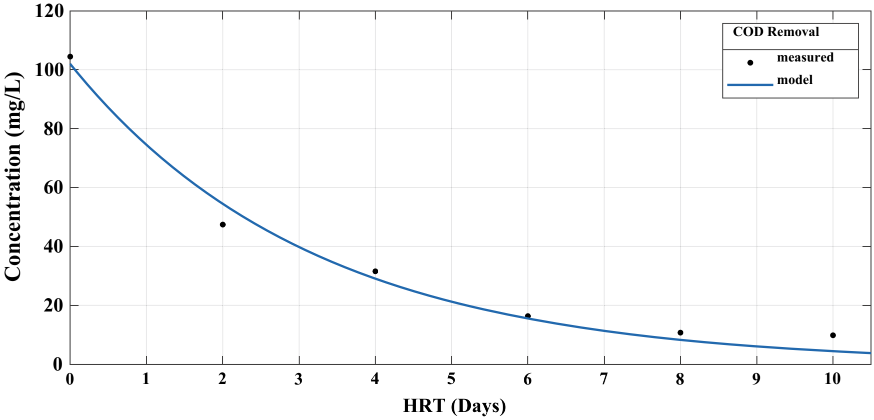

Fig. 14.8 Reduction in the COD concentration with increasing HRT

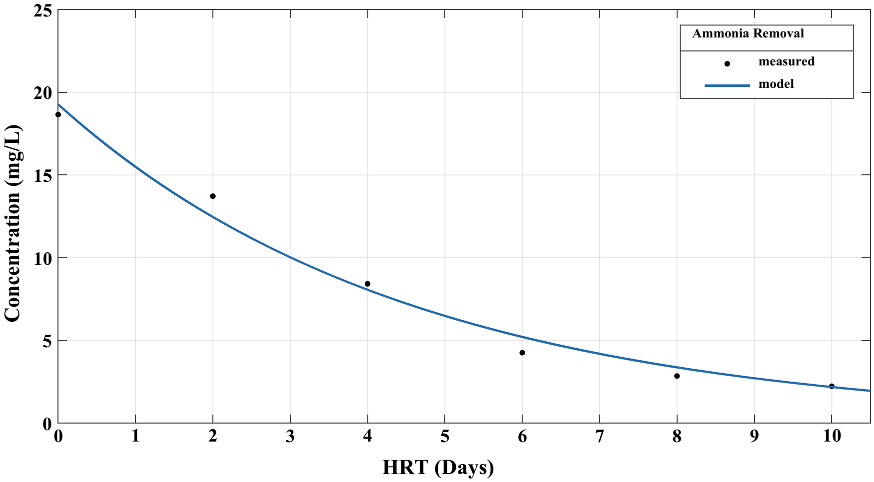

Fig. 14.9 Reduction in the NH_4^+-N concentration with increasing HRT

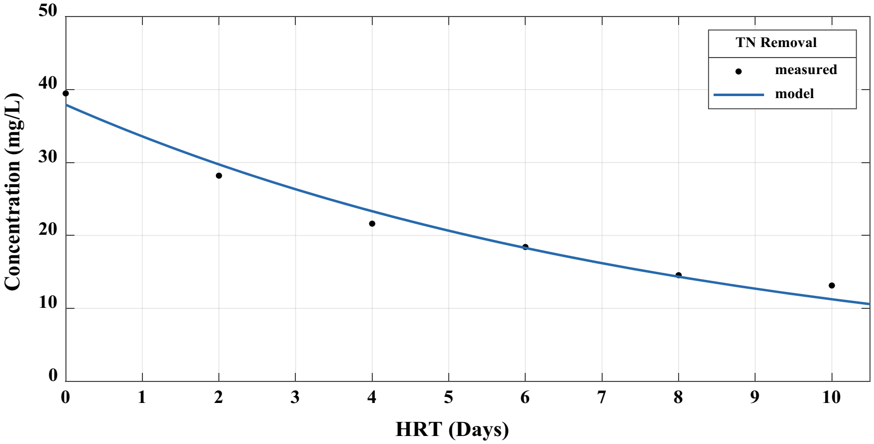

Fig. 14.10 Reduction in the TN concentration with increasing HRT

14.4 Conclusion and Recommendations

- As observed from the experimental and simulation results, the cold climatic conditions had a negligible impact on the efficiency of the HSSF-CW in terms of organics (COD) and ammonia (NH_4^+-N) removal. The results of the first order K-C* model indicated that organics and ammonia were removed quickly because of the presence of adequate DO level in the beginning.

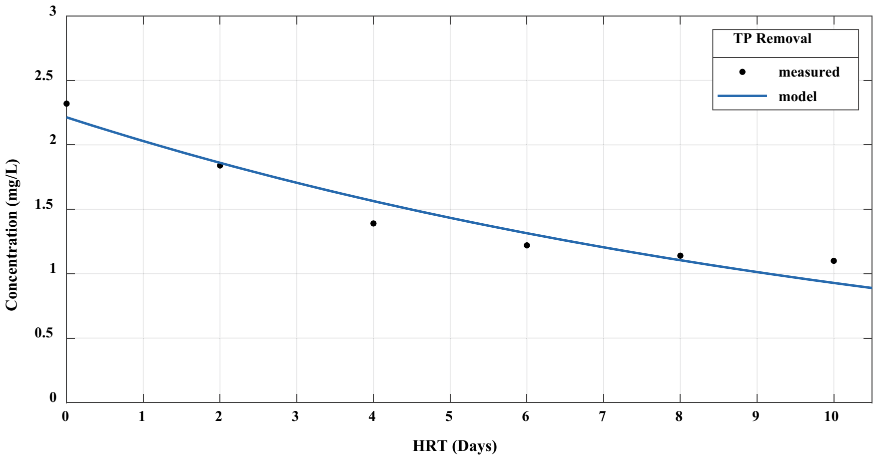

Fig. 14.11 Reduction in the TP concentration with increasing HRT

- It is evident from the results that the efficacy of the experimental system for TN removal was adversely affected under low temperatures. Due to the limited carbon supply, TN removal was hindered requiring a prolonged retention time for its removal.
- The least efficiency was obtained for TP removal which indicates that the capacity of substrate adsorption and plant uptake was exhausted soon.
- The effectiveness of other substrate materials such as activated carbon, steel slag, waste hollow bricks, ceramsite, etc. could be tested to enhance TP removal efficiency. The use of additional carbon sources and artificial aeration could improve nitrogen removal in the HSSF-CWs. Moreover, microbial activity in the HSSF-CW in a cold climate could be enhanced through bio-augmentation. Further, pilot-scale or full-scale studies are required to support the applicability of CWs in cold climates.

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