Municipal Wastewater Treatment uses Vertical flow followed by horizontal flow in a two-stage hybrid constructed wetland planted with Calibanus hookeri and Canna indica (Cannaceae)

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Research Article

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Abstract

The utilization of hybrid constructed wetland systems has recently expanded due to more rigorous municipal wastewater discharge and also complex wastewaters treated in hybrid constructed wetlands (HCWs). A lab-scale two-stage Experimental setup of Vertical flow followed by horizontal flow hybrid constructed wetland (VFHCW- HFHCW) configuration was built. First stage vertical flow hybrid constructed wetland reactor with the surface area was 1963.49 cm^2 and second stage horizontal flow hybrid constructed wetland reactor with the surface area was 2025 cm^2. The HCW unit was planted with two type plants: Calibanus hookeri and Canna indica (Cannaceae). Influent Municipal wastewater flow rate 112.32 lit./day, hydraulic loading rate (HLR) 0.55 meter/day, and hydraulic retention time One day. The efficiency was evaluated in municipal wastewater quality improvement and Physico-chemical analysis in our laboratory. The removal rate after the second stage horizontal flow of BOD_3 at 27^oC, COD, TSS, TP, NH_3-N, and NO_3-N reached 92.75%, 89.90%, 85.45%, 88.83%, 99.09%, and 96.05%, respectively. The results shown after both stage hybrid constructed wetland VFHCW- HFHCW, treated effluent of Municipal wastewater produced high-quality effluent which may be reused in gardening, agriculture, and flushing in toilet purpose according to Bureau of Indian Standards (BIS) code for practices. However, in the future, hybrid constructed wetlands could be standards design criteria developing and enhancing the performance standards and economic meets both to make more popular technology of the hybrid constructed wetland (HCW).

1. Introduction

All over the world, many countries face freshwater problems, and even India is not exempted. As per the CPCB (Central Pollution Control Board) study, India's present scenario is approximately 72368 MLD Municipal wastewater generation all over countries, and approximately 40527 MLD untreated Municipal wastewater generation is discharged directly to surface water bodies (CPCB, 2021). It has led to deteriorating aquatic life of surface water quality, threatened human health, environment, and major water-borne diseases. India faces a problem hues gap exists between treated Municipal wastewater and untreated Municipal wastewater because of lack of funding and management create this large gap (CPCB and DST, 2019& ENVIS). In view of capital cost limitation and minimizing large gap can use the less capital cost and less maintenance technique for the treatment of Municipal wastewater.

Various advanced Municipal wastewater treatment technologies are the solution in this context. Some conventional treatment technology such as stabilization pond, anaerobic filter, green filter, septic tank, sand filtration and Activated sludge process are still in use. Now a day's a new low capital cost, less maintenance cost and eco-friendly constructed wetland (CWs) is becoming popular for the Municipal wastewater treatment. (Abidi et. al., 2009; J. Vymazal, 2003;Molle, p., et. al., 2008; Kouki S. et. al., 2009;Brix, H. and Arias, C.A, 2005; Jian Zhang, et. al., 2014). Constructed wetlands (CWs) are the new artificially engineered system that remove the pollutants load from various types of wastewater (Masi, F. et. al., 2002; Brix, H. and Arias, C.A, 2005; J. Vymazal, 2005; Kouki S. et. al., 2009; Dotro G. et. al., 2015). It has been found to effectively remove pollutants like organic and inorganic contamination, nutrients, pathogens as well as transmitted virus in wastewater bodies and pathogens. (Lesage, 2006 & 2007; Keffala C. and Ghrabi A., 2005; Tanner CC, et. al., 2012; Haiming Wu et. al., 2013; Dotro G. et. al., 2015). Now a days mainly horizontal flow or vertical flow hybrid constructed wetlands (HFHCW or VFHCW) are more used individually for the treatment of municipal and industrial wastewaters (Karathanasis, A.D et. al., 2003;J. García, 2005; Wang, R, et. al., 2012;Abou-Elela, S.I. and Hellal, M.S, 2012). Horizontal flow or vertical flow hybrid constructed wetlands (HFHCW or VFHCW) have been successfully used in industries like fertilizer, textile, dairy, tannery, food and beverages and pulp & paper etc. to removes varieties of pollutants (Abou-Elela, S.I. and Hellal, M.S, 2012; Zurita, F, et. al., 2009;D.A. Yaseen and M. Scholz, 2019). The removal mechanism may include ion exchange, soil adsorption and uptake by plants, chemical precipitation, and anaerobic or aerobic microbial growth or decomposed activity (Karathanasis, A.D et. al., 2003; Keffala C. and Ghrabi A., 2005; Klomjek, P. and Nitisoravut, S, 2005;Molle, p., et. al., 2008;Lesage E, 2006; Zhang, D, et. al.,2009). Constructed wetland (CW) treatment performance can be increased using anaerobic and aerobic processes (Lesage E, 2006; Lesage E, et. al., 2007).

In this study, one lab scale at two-stage Vertical flow followed by horizontal flow hybrid constructed wetland (VFHCW- HFHCW) configuration was used to treat municipal wastewater of the Prayagraj city. Two different plant species, such as Calibanus hookeri and Canna indica red color (Cannaceae), were used to treat actual sewage wastewater collected from the outside and Motilal Nehru National Institute of Technology Allahabad, Prayagraj, India, campus.

This study aims to evaluate the pollutants removal, hydraulic retention time, role of flow, and nitrification from two different types’ plant species. At present, there is lack of proper guidelines in our country India for the design criteria, flow regulation, and Hydraulic retention time (HRTs) for the constructed wet land process. If these guidelines are in place then in future more and more ULBs and small town areas can select the most suitable hybrid constructed wetlands configurations with eco-friendly technology for the treatment of sewage and grey wastewater.

2. Materials And Methods

2.1 Experimental Setup

A lab-scale two-stage Experimental setup of Vertical flow followed by horizontal flow hybrid constructed wetland (VFHCW- HFHCW) configuration consisted of one circular and one Square Polycarbonate Compact Transparent 6 mm thickness Sheet (PCTS). PCTS has high impact strength, high-temperature resistance, and ultraviolet (UV) protection. The circular box has an inside diameter of 50 cm and depth of 55 cm, and the Square box has inside dimensions length, width, and depth each of 45 cm. In circular vertical flow and Square horizontal flow hybrid constructed wetland reactor layered with the gavel of size (16–20 mm), 10 mm and 4.75 mm, sand of grade 2.36 mm, 1.18 mm, 600μm, and 300 μm and with soil from the bottom to top in Fig. 1 (CPCB and DB, 2019). Before filling the gravel in both stages of the wetland reactor, gravel is properly washed by de-ionized water. In second stage wetland placed a layered of cold drink plastic bottles chips between 300 μm sand and soil. Flow path from vertical circular to the horizontal square stage to be maintained by gravimetric flow and from vertical circular stage to horizontal square stage connected with polyvinyl chloride pipes (PVC) of diameter 14 mm. The dimensions and operating conditions of hybrid constructed wetland reactors are given in Table 1.

Table 1
Dimensions and operating conditions of hybrid constructed wetland reactors.

Stage	Type	Diameter/ Length × Width of flow (cm)	Depth (cm)	Height of flow (cm)	Surface area (cm^2)	Temperature (^0C)
1st	Circular VFCHCW	50	55	15	1963.49	15–42
2nd	Square HFSHCW	45×45	45	15	2025	15–42

2.2 Effective volume of hybrid constructed wetland bed and plantation

The total volume of the first stage circular VFHCW reactor was 107.99 L and the second stage square HFHCW reactor was 91.125 L. In the hybrid constructed wetland, the actual volume of wastewater was filled in the wetland reactor determined by taking a known volume of wastewater and filling the hybrid constructed wetland bed and knowing the quantity of wastewater filled until the flows first drop through the outlet pipe. The adequate volume in the first stage circular VFHCW reactor was 28.45 L and the second stage square HFHCW reactor was 28.37 L. The two different vegetation plant species used, such as Calibanus hookeri and Canna indica red color (Cannaceae) was available in the Motilal Nehru National Institute of Technology Allahabad (MNNIT), Prayagraj India Campus. The vegetation plant can absorb a high level of pollutant and organic load from municipal wastewater. The vegetation plants roots were washed with the deionized water 2–3 times. Both reactors were planted with 4 Calibanus hookeri and 2 Canna indica red color (Cannaceae), with heights of Calibanus hookeri in between 20 to 35 cm and Canna indica red color (Cannaceae) in between 30 to 45 cm respectively (Brix, H. and Arias, C.A, 2005; Tanveer Saeed, et. al., 2021).

2.3 Sampling and Physico-chemical analysis

Municipal wastewater was collected from prayagraj city, India at latitude 25° 29' 40.8372" N, and longitude 81° 51' 53.2044" E every week and stored in a tank. After that, Municipal wastewater was pumped through Watson Marlow peristaltic pump at the rate of 25–35 rpm 8 hours daily in these reactors. Inlet raw wastewater and treated wastewater samples were collected daily from stage 1 outlet and stage 2 outlet of the hybrid wetland reactor in Fig. 1. The collected samples were analyzed on regular basis for almost Four months in the first Phase from February to May 2021. The samples were examined for inlet raw wastewater and treated wastewater through both stages. The Physico-chemical parameters analysis such as pH, total suspended solids (TSS), Biochemical oxygen demand (BOD_3 at 27°C), Chemical oxygen demand (COD), total phosphate (TP), Nitrate nitrogen (NO_3^--N), and ammonia nitrogen (NH_4-N). The pH value was measured using HI 2210 pH meter. TSS value was calculated using Matrix eco solution-111 Hot air oven followed by Wensar electronic balance, BOD_3 at 27°C was measured using MKSI BOD incubator, COD was measured using HACH company closed reflux COD meter. While TP and NO_3^--N were measured by using LAB INDIA analytical UV/VIS double beam spectrophotometer, and NH_4-N was measured by using universal Kjeldahl digestion and distillation apparatus. All the Physico-chemical parameters analysis procedure was followed by standard methods for examining water and wastewater, 23rd edition (APHA 2017).

All the experimental data analysis was carried using Microsoft Excel 2013 version and Origin Pro 2021b version. The removal efficiency of the pollutant in percentage as calculated by following Eq. (1).

$$\%\ \mathrm{R} = \frac{Ci - Ce}{Ci} \tag{1}$$

Where, C_i initial concentration in mg/l and C_e Effluent concentration in mg/l

3. Results And Discussion

3.1 Influent Municipal wastewater characterization

The minimum, maximum and average characterization of influent Municipal wastewater to the hybrid constructed wetland are shown in the Table 2. The characterization results indicated that the influent Concentration value of BOD_3 at 27°C, COD, TSS, TP, NO_3^--N, and NH_4-N varied during the study period. The pH value and organic loading rate also varied during the study period. The influent concentration value of heavy metals such as Fluoride, Iron, and chromium was measured during the study period but did not exceed 0.01 mg/l.

Table 2
Characteristics of influent Municipal wastewater of four month operation

S.N.	Parameters	unit	Minimum value	Maximum value	Average Value + St. dv.
1	pH	-	7.45	8.3	7.89 ± 0.35
2	BOD_3 at 27^oC	mg/l	49.8	119.2	103.75 ± 29.75
3	COD	mg/l	224	800	546.47 ± 235.71
4	TSS	mg/l	140	597	275.75 ± 191.62
5	TP	mg/l	5.38	30.72	15.138 ± 10.44
6	NO_3^--N	mg/l	3.694	7.573	4.478 ± 3.094
7	NH_4-N	mg/l	2.52	17.96	13.474 ± 3.776

3.2 pH analysis

The observed pH values in the two stage hybrid constructed wetland which VFHCW followed HFHCW are shown in Fig. 2. The results were observed increase pH value of first stage circular vertical flow hybrid constructed wetland as compared to the influent of the Municipal wastewater. It may happen to start the degradation process of Municipal wastewater for that increases alkanity. The pH value while decreases at second stage square horizontal flow hybrid constructed wetland.

3.3 BOD_3 at 27^oC and COD removal study

Figure 3 and Fig. 4 shows the BOD_3 and COD concentrations in two stage VFHCW followed HFHCW effluents. In terms of BOD_3 and COD, the results reveal that lab scale set up units are very effective at removing contaminants. However, the average surface organic loading rate in the two-stage hybrid wetland was 26.35g BOD_3/m^2/day and 144.11g COD/m^2/day respectively while in the second stage, square HFHCW was reached 92.75% and 89.90% with an average treated the effluent value of 3.82 mg/l and 45.62 mg/l respectively. This effective removal depends on the amalgamation of physical and microbial activity. Because in a hybrid constructed wetland, the physical phenomena mechanism allows filtering the water through low porosity of constructed wetland. The solid organic trap through the bed for the long hydraulic retention time, so that these organic in the presence of sunlight and through soil and vegetation plant it allows to biodegradation of the organic matter. These removal rates are high because of the retention of organic and inorganic solid materials on the topsoil bed and rapid decomposition in aerobic conditions (D.A. Yaseen and M. Scholz, 2019; Karathanasis, A.D et. al., 2003). Some organic solid with the wastewater through the low porosity of gravel settles down to the bed of the hybrid constructed wetland, and it decomposes in anaerobic conditions and through the roots of the vegetable plants, in the aerobic and anaerobic both conditions removal of organic matter and reduced by bacteria and microbes

(Karathanasis, A.D et. al., 2003; Jian Zhang, et. al., 2014). From the other studies of wetlands, our two-stage hybrid constructed wetland better BOD and COD removal efficiency was observed.

3.4 Total Suspended Solid (TSS) removal study

Removing suspended solids is a prominent physical phenomenon for treating Municipal wastewater. The concentrations of total suspended solids (TSS) in the two-stage hybrid constructed wetland circular VFHCW followed by square HFHCW effluent and influent of the Municipal wastewater are shown in Fig. 5. The results were observed that the average removal rate in percentage in the first stage circular VFHCW was reached 75.09% with an average treated effluent quality of suspended solid reached 96.47 mg/l while in the second stage, square HFHCW was reached 85.45% with an average treated effluent quality of suspended solid 37.32 mg/l. These effective removals of suspended solids filtered through the surface flow and roots of the Calibanus hookeri and Canna indica red color plants in the hybrid constructed wetland. Moreover, Municipal wastewater filtered through hybrid constructed wetland media of soil sand and gravel bed by gravimetric. The observed high percentage removal rate of the TSS at the second stage might be more settable of the sludge, and the biological decomposition rate could be fast, which is also observed in the BOD_3 and COD removal rate. Suspended solid retention on the bed also observed that more solid retention on top of the layers of the constructed wetland and some small particles could be settled to the bottom of the constructed wetlands (Abou-Elela, S.I. and Hellal, M.S, 2012; Lesage E, et. al., 2007). These results were significant because the physical phenomena for removing solid and small particles settling plants stems and roots play a significant role.

3.5 Removal study of Total Phosphorous (TP)

The physicochemical process associated with phosphorous removal mechanism in a hybrid constructed wetland occurred by precipitation with metals, adsorption from the substrate and vegetable plant roots taken for the growth (Lesage E, et. al., 2007; Molle, p., et. al., 2008). Therefore results shown in Fig. 6 increase the phosphorus removal rate indicate the biological activity as the substrate and algal uptake for the growth. However, decreased phosphorus removal rate indicates that adsorption takes over the sites with an increase in time. The total phosphorous (TP) concentration in a two-stage hybrid constructed wetland circular VFHCW followed by square HFHCW effluent, and influent of the Municipal wastewater are shown in Fig. 6. Moreover, the results were observed that the average removal rate in percentage in the first stage circular VFHCW was reached 80.84% with an average treated effluent quality of suspended solid reached 2.52 mg/l while in the second stage, square HFHCW was reached 88.83% with an average treated effluent quality of suspended solid 1.56 mg/l. These effective removals indicated that total phosphorous uptake the two stages process that through the cell membrane surface absorbed transformation of phosphorous and from the algal surface substrate adsorption. Also, vegetables plant growth via metabolic activity removal of the phosphorous measure and increase the surface of the roots in the water, oxygenation throughout the plant roots and filtration process encouragement (Molle, p., et. al., 2008; Masi, F. et. al., 2002). Thus for the phosphorous removal, the role of vegetation plants and oxygen in a two-stage hybrid constructed wetland circular VFHCW followed by square HFHCW is most appropriate.

3.6 Removal study of Ammonia Nitrogen (NH_3-N) and Nitrate Nitrogen (NO_3^--N)

The sewage wastewater contains one of the significant pollutants, nitrogen which can cause the toxicity effect to the surviving aquatic organism. In sewage wastewater, it exists inorganic and organic both form. Nitrogen in the inorganic forms is Nitrate (NO_3^-), Nitrite (NO_2^-), ammonium (NH_4), and in the gaseous form of nitrous oxide (N_2O), nitrogen gas (N_2), and free ammonia (Masi, F. et. al., 2002; Karathanasis, A.D et. al., 2003). Although in the organic form of nitrogen are urea, peptide in amino acid form. In the hybrid constructed wetland, nitrogen removal by transforming biological processes such as nitrification, denitrification ammonification, reduction of nitrate, assimilation of biomass matter, and uptake by plant roots (Karathanasis, A.D et. al., 2003;Wang, R, et. al., 2012; Haiming Wu et. al., 2013). The transformation of nitrogen is shown in the schematic diagram Fig. 9.

The ammonia nitrogen and Nitrate Nitrogen concentration variation of effluent and influent of the sewage wastewater in the two-stage hybrid constructed wetland circular VFHCW followed by square HFHCW shown in Fig. 7, Fig. 8. The results were observed in the two-stage hybrid wetland with very effective inorganic nitrogen removal in terms of ammonia nitrogen and nitrate nitrogen. The average removal rate of ammonia nitrogen through Kjeldahl nitrogen and nitrate nitrogen through absorption process in percentage in first stage circular VFCHCW was reached 94.64%, and 88.63% with an average treated the effluent value of 0.64 mg/l and 0.613 mg/l, respectively. In contrast, square HFHCW was reached 99.09% and 96.05% in the second stage with an average treated effluent value of 0.105 mg/l and 0.21 mg/l, respectively. The removal performance results were better when treated from both-stage hybrid wetlands. Performance studies on first stage circular VFHCW and second stage square HFHCW planted with two different types of vegetable plants species such as Calibanus hookeri and Canna indica red color.

Organic nitrogen is present in sewage wastewater in a particulate matter like sludge and soluble form. The sludge form in hybrid constructed wetland removal occurs by microbial activity and mix with soil to form fertilizer and exchange nitrate-nitrogen in soil, which is quickly absorbed by plant roots and washed with water and form soluble. The soluble form of organic nitrogen is mainly urea, a peptide in amino acid. Its soluble form in sewage wastewater removal from hybrid constructed wetland by nitrification, denitrification, and ammonification (Wang, R, et. al., 2012; D.A. Yaseen and M. Scholz, 2019). Ammonification releases energy through the biological process, and peptides in an amino acid are oxidative to produce ammonia.

The obtained results showed that square HFHCW removed ammonia nitrogen and nitrate nitrogen at the second stage than the first stage circular VFHCW. It may be organic nitrogen in the soluble form more leached out through the first stage circular VFHCW, and less amount in the form of sludge (Particulate form) to microbial decomposition in aerobic condition and its allow more oxygenation top surface of the first stage. In the first stage, circular VFHCW top surface layer faster ammonification because aerobic condition and bottom of the surface layer slow due to anaerobic condition.

4. Conclusions

From this study, the performance evaluation and assessment of the two-stage Experimental setup of Vertical flow followed by horizontal flow hybrid constructed wetland (VFHCW- HFHCW) were carried out by at same condition. The assessment and evaluation were based on physic-chemical parameters analysis at Influent and treated effluent through the two-stage wetlands and two different types of vegetable plants species such as Calibanus hookeri and Canna indica red color under considerations. The results shown after both stage hybrid constructed wetland VFHCW- HFHCW, treated effluent of Municipal wastewater produced high-quality effluent which may be reused in gardening, agriculture, and flushing in toilet purpose according to Bureau of Indian Standards (BIS) code for practices. Both two-stage vertical circular followed a horizontal square type of hybrid constructed wetland recommended for Municipal wastewater treatment in the rural and small-town areas because it is more diminutive in size, treats high-quality effluent, and maintains a better ecological environment. Moreover, the treatment technology is up-and-coming, and the treated parameters not only pH, BOD_3 at $27^{O}C$, COD, TSS but also removal of TP, **NH_3-N, NO_3-N for nitrification and denitrification.** The removal rate after the second stage horizontal flow of BOD3 at 27oc, COD, TSS, TP, NH3-N, and NO3-N reached 92.75%, 89.90%, 85.45%, 88.83%, 99.09%, and 96.05%, respectively. The wetland plants species such as Calibanus hookeri and Canna indica red color helps in removal by the mechanism of absorption, adsorption, nitrification, denitrification ammonification, reduction of nitrate, assimilation of biomass matter, and uptake by plant root zone. Recent research focuses on the evaluation and assessment of performance-boosting. However, in the future, hybrid constructed wetlands could be standards design criteria developing and enhancing the performance standards and economic meets both to make more popular technology of the hybrid constructed wetland (CW).

Abbreviations

HCW
Hybrid Constructed Wetland
VFHCW
Vertical flow hybrid constructed wetland
HFHCW
Horizontal flow hybrid constructed wetland
HLR
Hydraulic Loading Rate
OLR
Organic Loading Rate

BOD_3
Biochemical Oxygen Demand
COD
Chemical Oxygen Demand
TSS
Total Suspended Solid
TP
Total Phosphate
NH_3-N
Ammonia Nitrogen
$NO_3^{-}N$
Nitrate Nitrogen
PCTS
Polycarbonate Compact Transparent Sheet
EDS
Energy dispersive X-ray spectroscopy

Declarations

Ethical Statement

Hereby, I, Krishna Kumar Singh consciously assure that for the manuscript "**Municipal Wastewater Treatment uses Vertical flow followed by horizontal flow in a two-stage hybrid constructed wetland planted with Calibanus hookeri and Canna indica (Cannaceae)**" the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.

2) The paper is not currently being considered for publication elsewhere.

3) The paper reflects the authors' own research and analysis in a truthful and complete manner.

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The violation of the Ethical Statement rules may result in severe consequences.

I agree with the above statements and declare that this submission follows the policies of Solid State Ionics as outlined in the Guide for Authors and in the Ethical Statement.

Date: 21/06/2022

Corresponding author's signature: Krishna

Consent to Publication

Title of Manuscript: "**Municipal Wastewater Treatment uses Vertical flow followed by horizontal flow in a two-stage hybrid constructed wetland planted with Calibanus hookeri and Canna indica (Cannaceae)**"

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Author Contribution *Krishna Kumar Singh* contributed to the study setup installation, methodology, data collection, data analysis, original manuscript preparation. *Rakesh Chandra Vaishya* Supervision setup installation and manuscript preparation, Resource provided.

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Data availability All data generated and analyzed during this study are included in this published article.

Conflict of interest Not applicable

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Figures

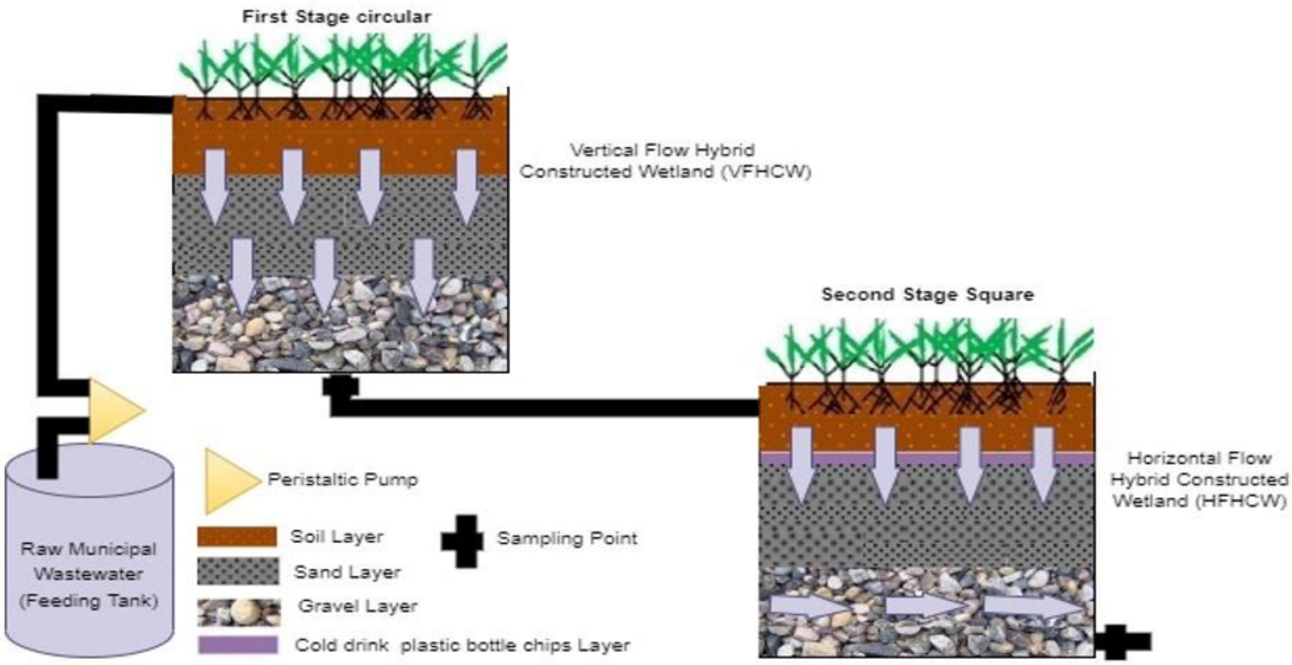

Figure 1

Lab-scale two-stage Experimental setup of Hybrid Constructed Wetland

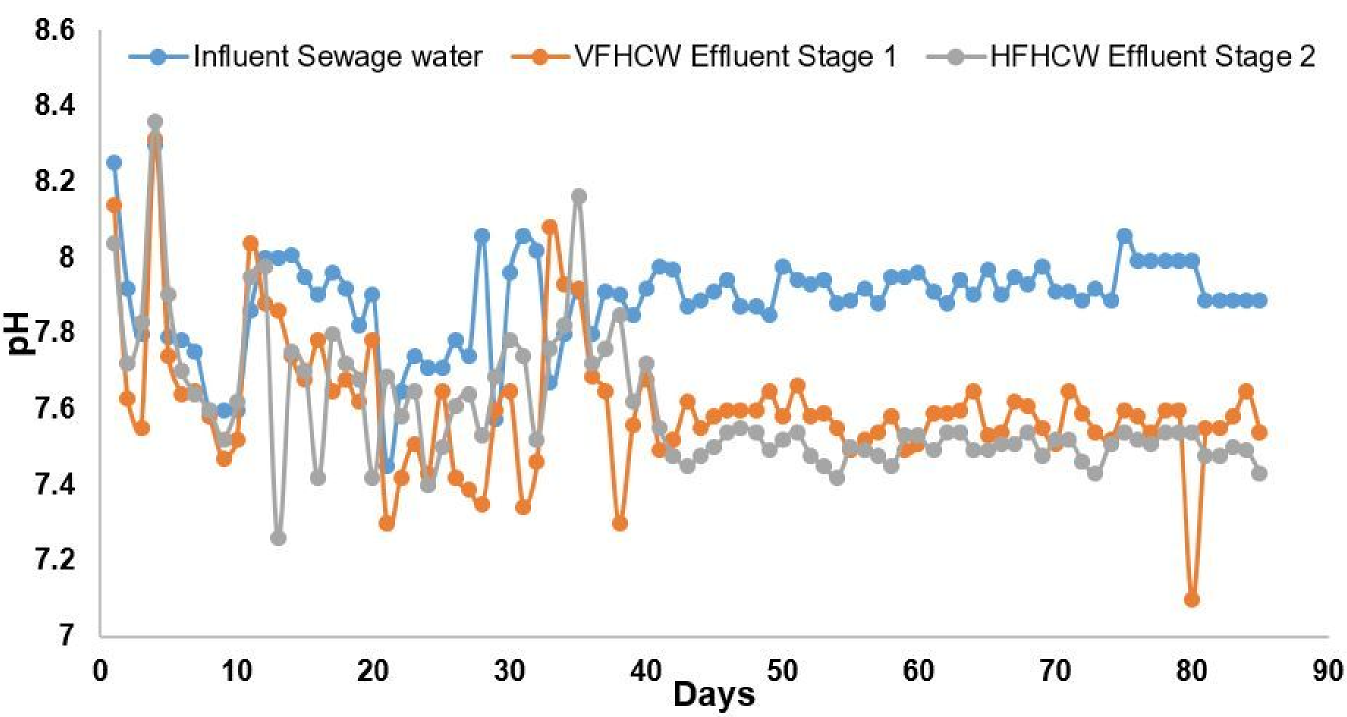

Figure 2

pH value of Influent municipal wastewater and Effluent of VFHCW and HFHCW

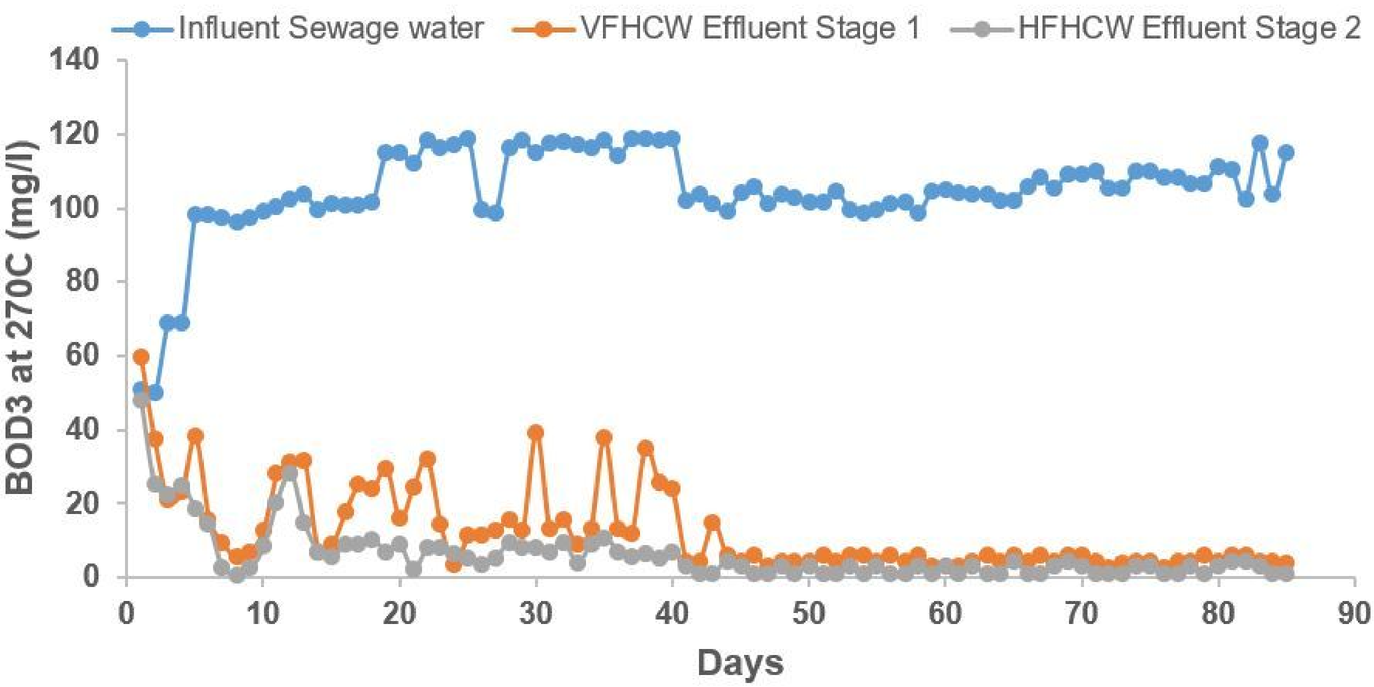

Figure 3

BOD_3 at 27^0C Concentrations in Influent municipal wastewater and Effluent of VFHCW and HFHCW

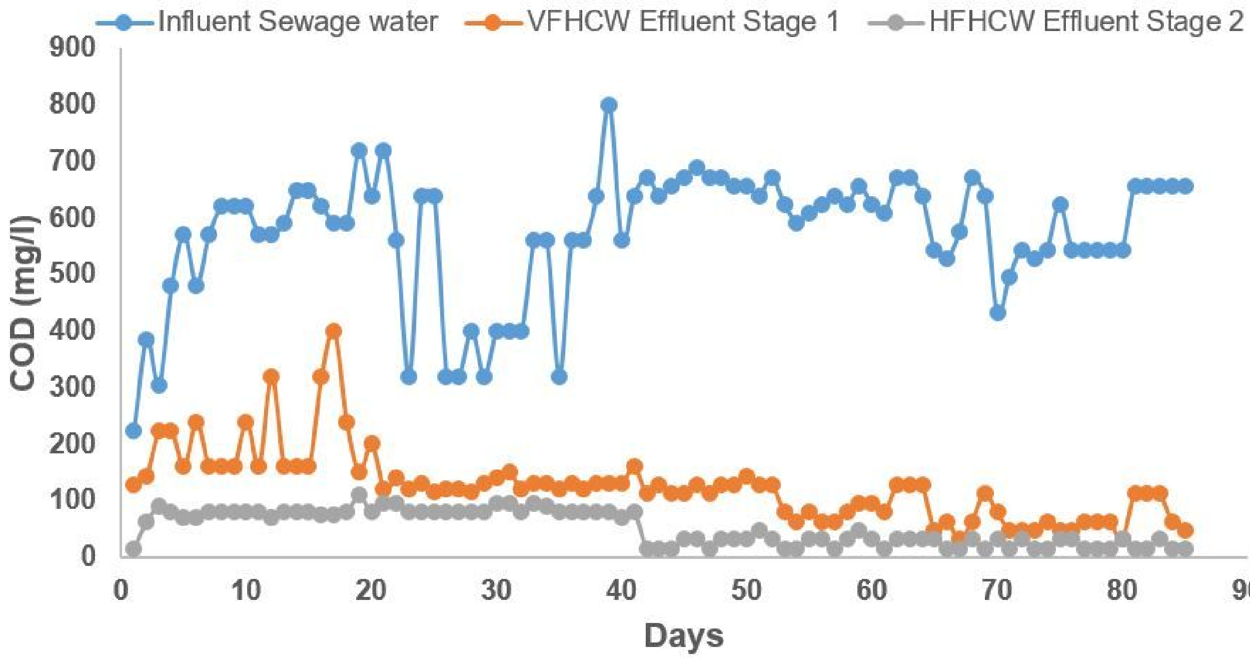

Figure 4

COD Concentrations in Influent municipal wastewater and Effluent of VFHCW and HFHCW

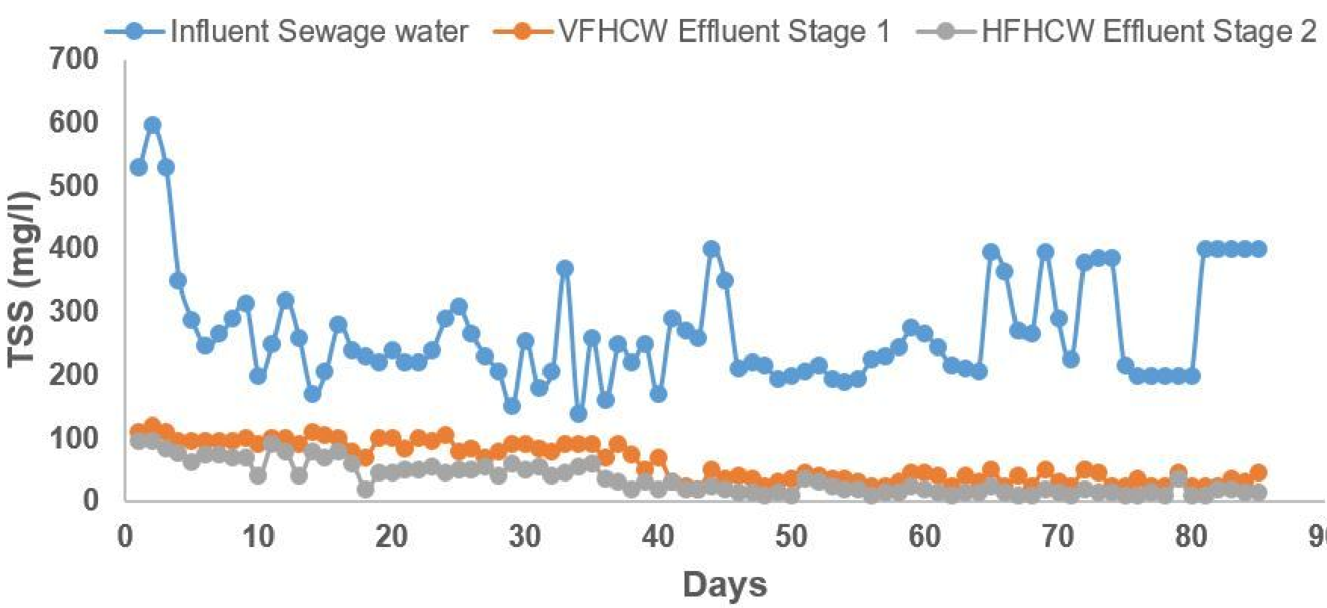

Figure 5

TSS Concentrations in Influent municipal wastewater and Effluent of VFHCW and HFHCW

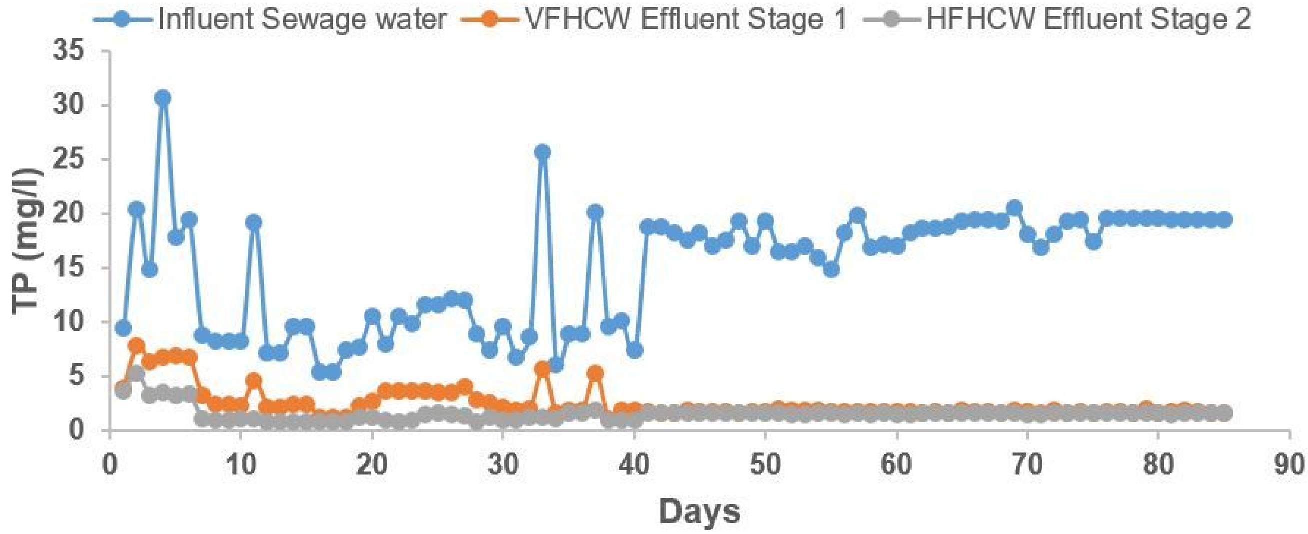

Figure 6

TP Concentrations in Influent municipal wastewater and Effluent of VFHCW and HFHCW

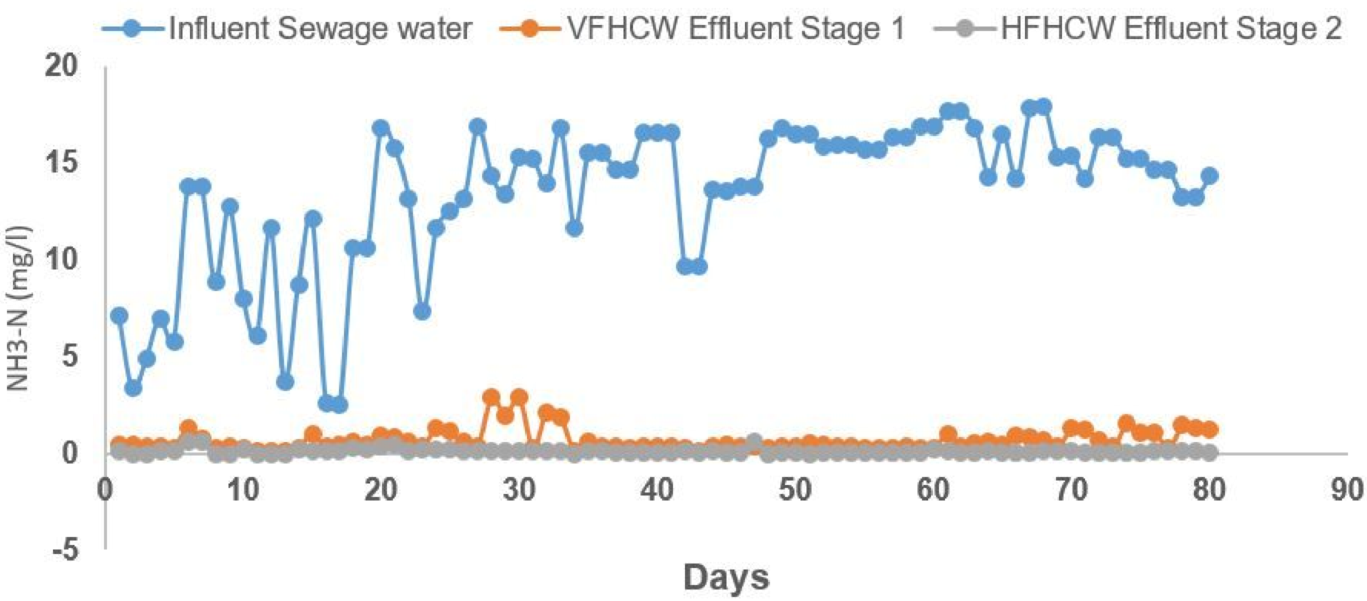

Figure 7

NH_4-N Concentrations in Influent municipal wastewater and Effluent of VFCHCW and HFSHCW

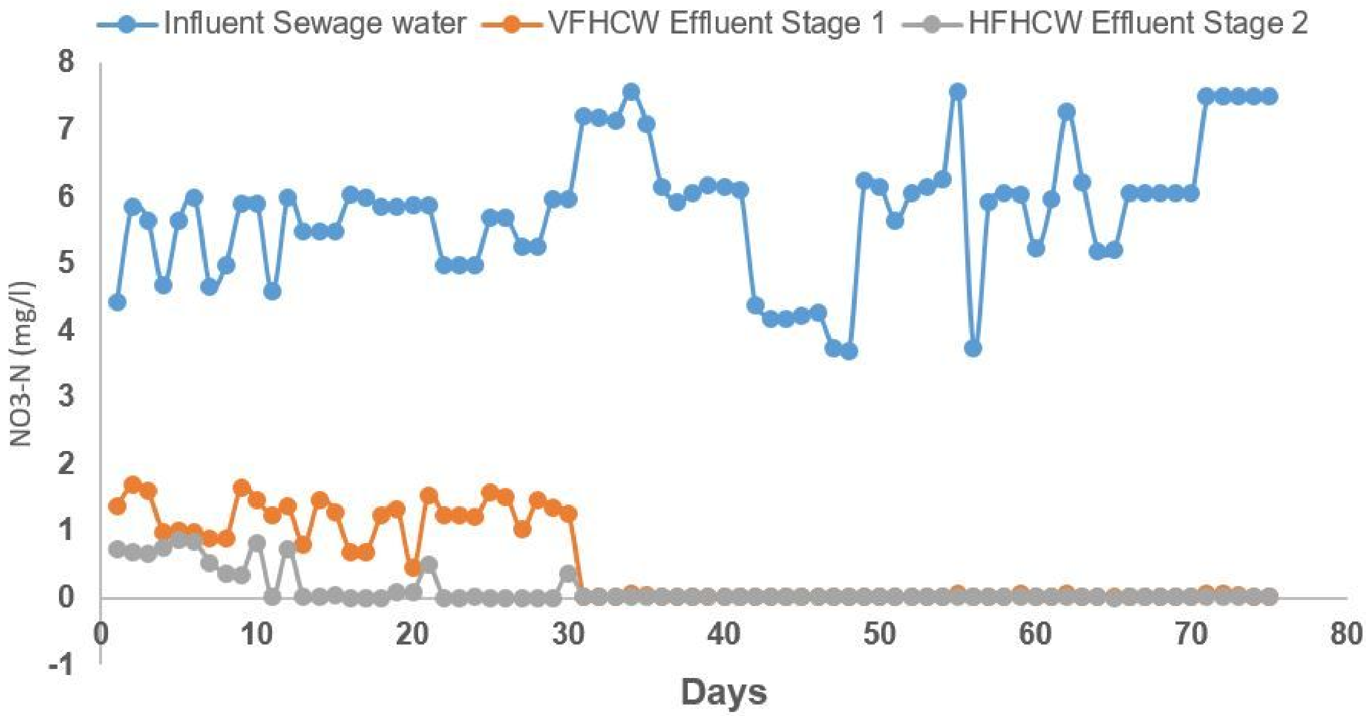

Figure 8

NO_3^-N Concentrations in Influent municipal wastewater and Effluent of VFHCW and HFHCW

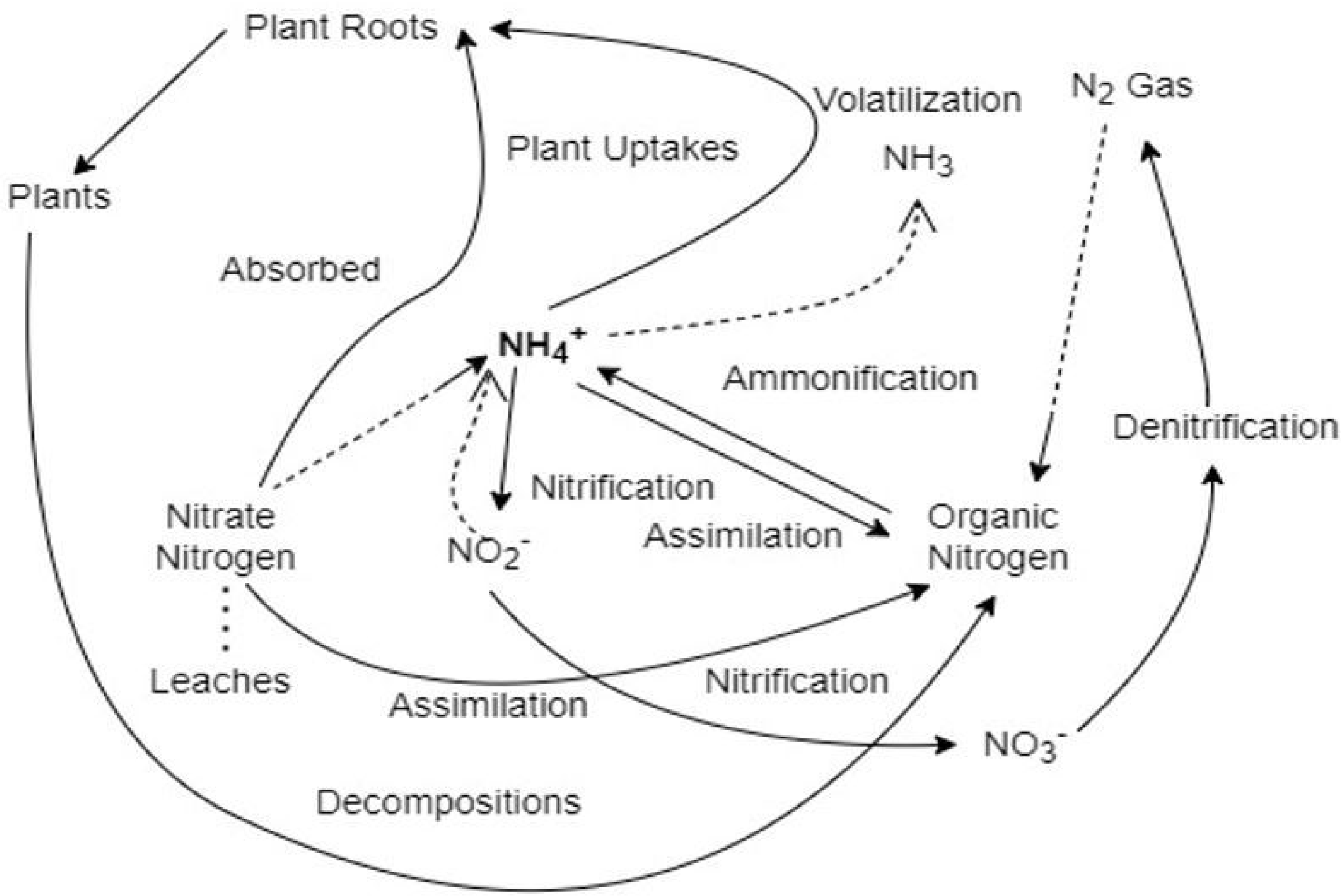

Figure 9

Nitrogen transformation in hybrid constructed wetland