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Highly Efficient Treatment of Shrimp Farm Wastewater by Using the Horizontal Subsurface Flow (HSSF) Constructed Wetlands with *Phragmites australis* Plant

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Aims: This study aimed to investigate the treatment of synthetic wastewater (low salinity) followed by actual shrimp farm wastewater (high salinity) and laboratory scale of constructed wetlands (CWs).

Study Design: A horizontal subsurface flow (HSSF) constructed wetlands, which filled by layers of sand and soil, *Phragmites australis* was grown as wetland vegetation for the model. The dimensions of model is 1.2 m length x 0.4 m width x 0.35 m height, that devised into three zones: inlet zone and outlet zone are 0.15m filled by soil (∅= 10 – 20 mm); the treatment zone is filled by 0.25 m of soils (∅= 5 – 10 mm) at the bottom and 0.1 m of sand at the top.

Place and Duration of Study: Environmental laboratory, Department of Environment, Hochiminh City University of Natural Resources and Environment, from January 2015 to November 2015.

Methodology: The investigation was carried out in two phases: Phase 1 was run by synthetic wastewater at two levels of loading rate; the purpose of this phase is to check the performance of wetland model at low total dissolved solids (TDS) concentration. Phase 2 was run by actual shrimp farm wastewater at low loading rate, this phase aimed to investigate the effect of high TDS

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concentration on the performance of constructed wetland system treating actual shrimp farm wastewater. Samples of influent and effluent were taken and analyzed such parameters of COD, TN, TP, NH4+-N, TDS by following the procedure of APHA to determine the performance of model.

Results: As a result, the average removal efficiency of COD, TN, and TP in constructed wetland model was 92.7; 95.9; and 92.77%, respectively during the phase 1. The removal efficiency of phase 2 for COD, TN, and TP was 89.39; 94.61, and 89.36%, respectively.

Conclusion: The model performed stably for treatment of both types of wastewater. The constructed wetlands model could achieve better removal efficiency in synthetic wastewater than that of shrimp farm wastewater.

Keywords: Wastewater treatment; constructed wetlands; horizontal subsurface flow; Phragmites australis.

1. INTRODUCTION

Aquaculture has been developed in Vietnam for more than three decades and its production has made significant contributing to the national economic development. Mekong Delta areas have many advantages factors for the operation of aquaculture farms such as a complex net of river near the seaport, good weather conditions and near the economic center of Vietnam. Therefore, the fish farms and shrimp farms have been rapidly increased recently, resulted in a high yield; good benefit and contributed to improve the living standard of the residents. However, during the operating time of aquaculture farms a large amount of food to be fed to shrimps and fishes. The shrimp farm wastewater may contains excessive food, excreted waste and other metabolic product of shrimps and other aquatic organisms, therefore there are organic and inorganic compounds in this wastewater which are in the form of BOD, COD, NH_4^+, NO_3^-, PO_4^{3-}.. Therefore, the discharge of untreated wastewater shrimp farm wastewaters into receiving water bodies may destroy the quality of water resources and aquatic ecosystems [1-3].

Natural-like systems are preferably used in wastewater treatment processes because of low requirement for establishing and maintaining, as well as due to high effectiveness and ease of use. One of these treatment systems that have been commonly applied in wastewater treatment is constructed wetlands. Constructed wetlands are models those were designed and constructed to employ the natural processes involving wetland vegetation, soils, and the microbial community to support in treating wastewaters [4]. The main mechanisms of treatment activity in constructed wetland are biotic processes (such as microbial mineralization, transformation and plant uptake) and abiotic processes (such as chemical precipitation, sedimentation, and adsorption). Namely, suspended solids are mainly removed by sedimentation and filtration through the vegetation and media layers. Microbial community in the root zone plays main role for removing of organic matters. Nitrogen is removed through nitrification-denitrification processes, ammonia volatilization and plant uptake during operating. Phosphorus is mainly treated by precipitation and plant utilization [4,5]. The typical constructed wetland systems can be classified according to the wetland hydrology including free water surface and subsurface systems. Free water surface (FWS) wetlands have open water surface and are similar to natural swamps in appearance. Horizontal subsurface flow (HSSF) wetlands are constructed with gravel bed and wetland vegetation. In this model, the influent was kept below the surface of the materials, flows horizontally from the inlet zone to the outlet zone. Vertical flow (VF) wetlands are models in which water is fed in to the surface and permeates down through the medium to the collected zone at the bottom.

In order to achieve good removal efficiency, the hybrid constructed wetlands have been developing in many countries. Hernández-Crespo et al. [6] researched about the performance of surface and subsurface flow constructed wetlands treating eutrophic waters and found out that horizontal subsurface flow CW was much more efficient than free water surface CW in the removal of organic matter, suspended solids and nutrients. HSSF models can self-provide oxic/anoxic/anaerobic conditions because of low oxygen concentration in lower media layers thus high nutrient removal can be achieved from these models. Therefore, HSSF models are commonly applied to treat many types of wastewaters such as agricultural, landfill leachate, shrimp farms wastewater [4,7]. Yang and colleagues [8] studied about the nitrogen removal of constructed wetlands using solid carbon source with limited aeration. The result indicated that higher removal efficiency of ammonia (91.00%) and total nitrogen (97.03%) than non-aerated constructed wetland were achieved in constructed wetland with limited aeration and the COD removal was improved in limited aeration. There have been many authors studied on applying constructed wetland in wastewater treatment. Çakir and colleagues [9] investigated about the effects hydraulic loading rates (HLR) on the treatment of domestic wastewater using subsurface horizontal-flow constructed wetlands used for treatment of domestic wastewaters, they found out that the removal rates of the system were closely depended on the applied hydraulic loading levels: 0.05; 0.075 and 0.125 (m^3 m^{-2} day^{-1}), the highest removal efficiency was 64.9%, 62.5%, 86.3% and 80.34% for BOD5, COD, TSS and Oil & Grease, respectively at OLR 0.05 (m^3 m^{-2} day^{-1}). Tunçsiper et al. [10] operated horizontal subsurface flow constructed wetlands (HSSF-CWs) treating dairy farm wastewater in cold climate and they could achieve good result for the removal of BOD5 and TSS (83 and 90%, respectively). Wu and colleagues [11] investigated nutrient removal and plant uptake by using constructed wetland for remediating a contaminated river in China. As a result, the maximum removal efficiency of this model was TN: 68%; NH_4^+-N: 93%; TP: 67%.

Kirui and colleagues [12] investigated Nitrobenzene removal by horizontal subsurface flow constructed wetlands (HSSF-CWs). As a result, this model could obtain 99% Nitrobenzene removal. In addition , intermittent aeration could not enhance the total removal efficiency however it could improve the buffer capacity of Nitrobenzene removal to shock influent loading.

Vymazal and Kröpfelová [13] operated a hybrid-constructed wetlands that combined of saturated vertical flow, free-drain vertical and horizontal flow units in series a total surface area of 0.101 ha. As a results, the system performed high removal of BOD_5 (92.5%), COD (83.8%), TSS (96.0%), NH_4^+-N (88.8%) and TN (79.9%). Moreover, the aerobic vertical flow stage is performing well in nitrification process whereas the other phase is good in denitrification. There are a great variety of designs and configurations of constructed wetlands such as free water surface flow CWs; subsurface flow CWs; hybrid systems; and floating treatment system [14,15]. In which, horizontal subsurface flow (HSSF) systems are most commonly applied. Because, in this model the wastewater flows horizontally through the granular media and comes into contact with a network of aerobic, anoxic, and anaerobic zones in the subsurface resulting high removal efficiency of organic matter and nutrient [15].

There have been not many researches discussed about the effect of salinity on performance of constructed wetlands model. Camacho and colleagues [16] investigated the effects salinity on the performance of a constructed wetland-microbial fuel cell. The result showed that the increasing salinity first improved the cell voltage, and the resultant maximum voltage (130 mV) under continuous operation corresponded to a salinity concentration between 4 and 5 g L−1, higher salinity levels caused the opposite effect. Phragmites australis plants were damaged at 9.51 g L−1 salinity concentration.

Herein, we have developed a lab scale of horizontal-flow constructed wetland for shrimp farm wastewater treatment. *Phragmites australis* was chosen as vegetation for constructed wetland model because this plant is climatic tolerance, rapid growth and great potential for removing COD thus it is the predominant species commonly used in constructed wetlands around the world [17,18]. In addition, *Phragmites australis* is tolerance with saline wastewater and very popular in natural wetland systems of Vietnam. A horizontal subsurface flow (HSSF) was carried out in 2 phases. The first phase of the experiment was conducted in 18 days in which the model was fed by synthetic wastewater for with high organic loading rate at low TDS concentration. In the second phase, the actual shrimp farm wastewater was fed to the model with lower organic loading rate at higher TDS concentration than those of the first phase. The aim of this study was to investigate the potential of constructed wetland model in treatment of shrimp farm wastewater with high salinity. The performance of constructed wetland model in treatment of wastewater was determined through COD, TN, NH_4^+-N and TP removal.

2. MATERIALS AND METHODS

2.1 Experimental Model

A lab scale of HSSF constructed wetlands was designed by following the method of Robert and Scott [19]. The dimensions of model is 1.2 m long x 0.4 m wide x 0.35 m high that

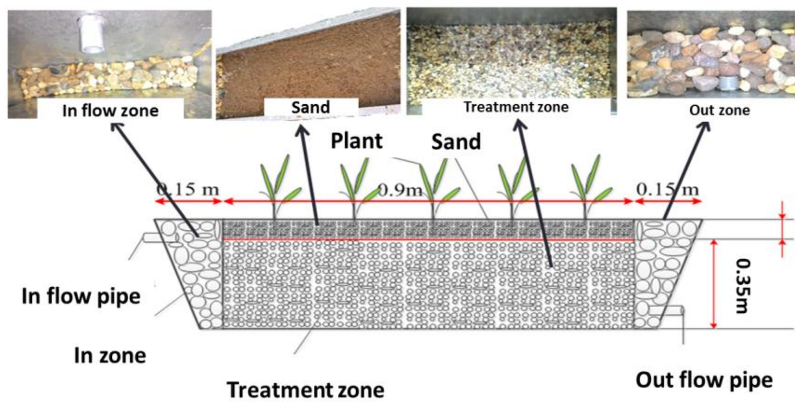

Fig. 1. Schematic of constructed wetland system

devised into three zones: inlet zone and outlet zone are 0.15 m filled by soil (Ø= 10 – 20 mm); the treatment zone is filled by 0.25 m of soils (Ø= 5 – 10 mm) at the bottom and 0.1 m of sand at the top (Fig. 1); *Phragmites australis* was grown as plant for the model. The influent was kept below the surface of the materials, flows horizontally from the inlet to the outlet. Experiment was started after *Phragmites australis* grew stably and achieved the target height about 0.5 m and start to be branched [11].

2.2 Wastewater Sources

During the acclimated period of 20 days duration (Phase 1), synthetic wastewater was fed to the model in which glucose was used as carbon source, the amount of glucose depended on OLR of the phase. The macro nutrient and trace composition of synthetic wastewater was prepared by following Nghiem and Tien [20] as below: $(NH_4)_2SO_4$: 200 mg L^{-1};$(NH_4)_2SO_4$: 80 mg L^{-1}; KH_2PO_4 : 14 mg L^{-1}; $MgSO_4.H_2O$: 15 mg L^{-1}; $MnSO_4$: 2 mg L^{-1}; $CaCl_2$:1,6 mg L^{-1}; $FeCl_3.6\ H_2O$: 0,2 mg L^{-1}; $CuSO_4$: 0,08 mg L^{-1}. In phase 2, the reactor was fed by actual wastewater taken from shrimp farm. The area of shrimp farm pond was 2000 m^2 with was cultivated with 50 shrimps.m^{-2} in density. Wastewater source was taken from the pond during the shrimp cultivation period from 60 days to 80 days. The actual wastewater has range of COD, TN, NH_4^+-N, and TP as 110 – 186; 11.2 – 15.8; 10.5 – 14.9; and 8.2 – 15.2 mg L^{-1}, respectively.

2.3 Experimental Procedure and Analytical Methods

Substrate was injected into the inlet zone through the porous medium of soils and sand under the surface of the wetlands, treatment activities happened in the porous medium and plant roots area; the effluent was collected at the outlet zone. In this study, the investigation was carried out in two phases: Phase 1 was run by synthetic wastewater at two levels of loading rate in which the organic loading rate (OLR- kg COD ha^{-1} day^{-1}), nitrogen loading rate (NLR - kg N ha^{-1} day^{-1}), and phosphorus loading rate (PLR - kg P ha^{-1} day^{-1}) at level 1 was 62.5; 7.88; 1.81, respectively and at level 2 was 100; 10.42; 3.25, respectively, and the TDS was 391 mg L^{-1}, the purpose of this phase is to check the potential of COD, TN,NH_4^+-N,TP of wetland model at low TDS concentration. Phase 2 was run by actual shrimp farm wastewater at low loading rate: OLR (kg COD ha^{-1} day^{-1}): 22.91; 29.79; 38.75; NLR (kg N ha^{-1} day^{-1}): 2.33; 2.54; 3.29, (PLR - kg P ha^{-1} day^{-1}): 1.71; 1.79; 3.17, respectively; TDS was 6,100-10,100 mg L^{-1}, this phase aimed to investigate the effect of high TDS concentration on the performance of constructed wetland system treating actual shrimp farm wastewater. Totally 15 samples were taken during the operational duration. In the first phase, six samples were taken which named S1; S2; S3; S4; S5; S6 on the days operational duration at 3; 6; 9; 12; 15; 18. For phase 2, nine sample were taken and named A1; A2; A3; A4; A5; A6; A7; A8; A9 on the experimental day of 25; 28; 31; 34; 37; 40; 43; 46; 49 in the time course. Samples were analyzed such parameters of COD, TN, TP, NH_4^+-N, TDS by following the procedure of APHA [21].

3. RESULTS AND DISCUSSION

Constructed wetland model was performed stably at the ambient temperature about 29-33°C, with pH values was in neutral range

6.5 – 8.5 (data is not shown here).In addition, the *Phragmites australis* plants were grown stably in the operational period with the average height as at 1m, density at 25 pieces.m^{-2}. During this time, more branches of *Phragmites australis* were sprouted and some old branches were cut out to maintain the density of plant in the model. There was not significantly different of plant characteristics during the experiment of phase I and phase 2. The removal efficiency of COD, TN, TP, NH_4^+-N was high in both phase of the experiment. In addition, it is closed related to TDS concentration in wastewater in which the higher TDS concentration of the influent they lower removal efficiency.

3.1 Chemical Oxygen Demand (COD) Removal

Fig. 2 shows the result of COD removal during the operational period. It was clearly indicated that the constructed wetlands model performed stably throughout the operational period and the removal efficiency of COD was good in both phases. The organic loading rate was much higher during phase 1 (62.6 - 100 kg COD ha^{-1} day^{-1}) than that of phase 2 (22.91 - 38.75 kg COD ha^{-1} day^{-1}) but the average removal efficiency of phase 1 (92.7%) which was higher than that of phase 2 (89.4%). The cause of lower COD removal in phase 2 compare to the acclimation phase can be explained that the actual shrimps farm wastewater has high salinity indicated in high TDS concentration (6,100-10,100 mg L^{-1}) of the phase 2 could inhibit microorganism's activities in decomposition organic matter. In addition, the carbon sources of shrimp farm wastewater are usually from excess food and shrimp's excreted products maybe more complex and recalcitrant than those of synthetic wastewater. However, COD concentration of the effluent was always stable at low value (under 40 mg L^{-1}) thus it is safe for the received environment after treatment. From the previous studies, many authors operated constructed wetland and could achieve high COD removal efficiency. Vymazal and Kröpfelová [22] reviewed about the application of HFCWs in wastewater treatment and summarized the average COD removal efficiencies for different types of wastewater were agriculture (63%), industry (63.1%), landfill leachate (24.9%), municipal secondary (63.2%); the COD removal was closely related to inflow/outflow loadings. Çakir and colleagues [9] used subsurface horizontal-flow constructed wetlands, this model could remove 62% COD from domestic wastewaters. Mantovi et al. [23] applied HSSF for the treatment of wastewater from cheese factory, as a result this model achieved 96% COD removal efficiency. Wu and colleagues [11] investigated nutrient removal and plant uptake by using constructed wetland for remediating a contaminated river in China. As a result, the maximum removal efficiency of this model was TN:68%; NH_4^+-N: 93%; TP: 67%.

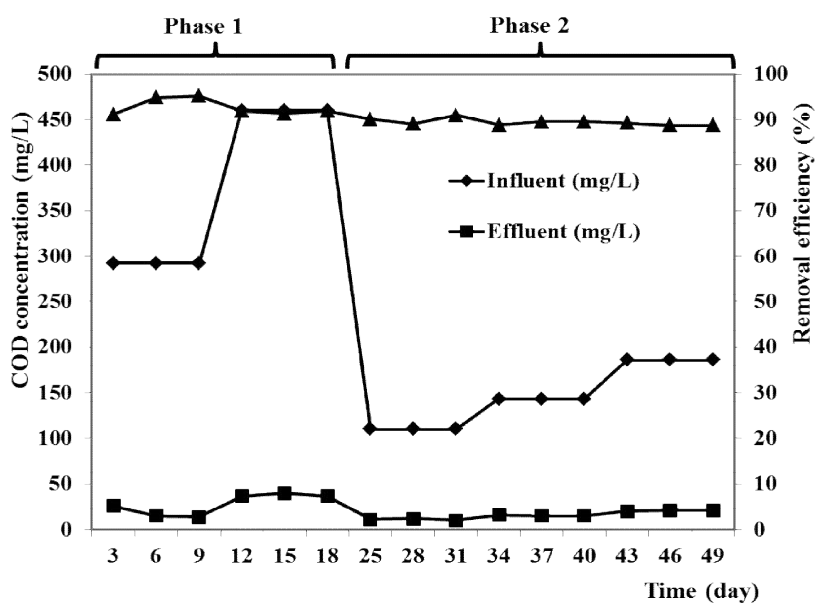

Fig. 2. Chemical oxygen demand removal efficiency of constructed wetland model during time course

3.2 Total Nitrogen (TN) Removal

The total nitrogen concentration in the influent an effluent of synthetic wastewater and actual wastewater is shown in Fig. 3. It is noticed that the removal efficiency of TN was high and stable in the range of 94 -97.9% during the start-up and the removal efficiency was not much change when the NLR increased from 7.88 to 10.42 kg N ha^{-1} day^{-1}. During the treatment of shrimp farm wastewater the removal efficiency was in range 93.92 – 94.06% even NLR value was not high 2.33; 2.54; 3.29 (kg N ha^{-1} day^{-1}). It could be seen that the removal efficiency of wetland models was higher in treating of synthetic wastewater than that of treating actual shrimp farm wastewater. This phenomenon maybe due to two reasons including: (1) actual wastewater had high TDS concentration may inhibited the microorganisms for nitrogen conversion; (2) the nitrogen composition in synthetic wastewater was in the easily biodegradable forms such as NH_4^+, NO_3^- [1,2]. Otherwise nitrogen in actual wastewater was more complex such as protein, antibiotic [1]. Generally, the result of this experiment demonstrated that this constructed wetlands could perform well in nitrogen removal. Many previous researchers also found out the pathways of nitrogen removal in constructed wetlands model including ammonia volatilization, ammonification, nitrification, nitrate-ammonification, denitrification, fixation, plant and microbial uptake, ammonia adsorption, organic nitrogen, burial, and ANAMMOX [1,24]. Wang and colleagues [24] achieved 60.9% TN removal efficiency for the treatment of synthetic wastewater by constructed wetland. Wu et al. [9] operated constructed wetland model for the treatment of simulated polluted river and achieved 68% for total nitrogen removal.

3.3 Nitrogen-ammonium (N-NH_4^+) Removal

The concentration of N-NH_4^+ in the influent, effluent of six samples in acclimated phase, nine samples of the following phase is shown in Fig. 4. It is easy to recognize that this model performed well in both phases, the average removal efficiency for synthetic wastewater phase and actual wastewater phase were 96.3 and 95.4%, respectively. Many researchers also found out that constructed wetlands have high potential for N-NH_4^+ removal [13,15]. The main mechanisms of N-NH_4^+ removal in wetlands model are: (1) plant uptake through metabolism; nitrification process to convert N-NH_4^+ to NO_3^- after that NO_3^- is further converted to N_2 through denitrification process; (3) a part of N-NH_4^+ is evaporated to the air [1,24]. The result of this research for removing of N-NH_4^+ is better than other previous studies. Wang and colleagues [24] achieved 64.3% N-NH_4^+ removal efficiency for the treatment of synthetic wastewater by constructed wetland. Wu et al. [9] used *Typha orientalis, Phragmites australis, Scirpus validus*

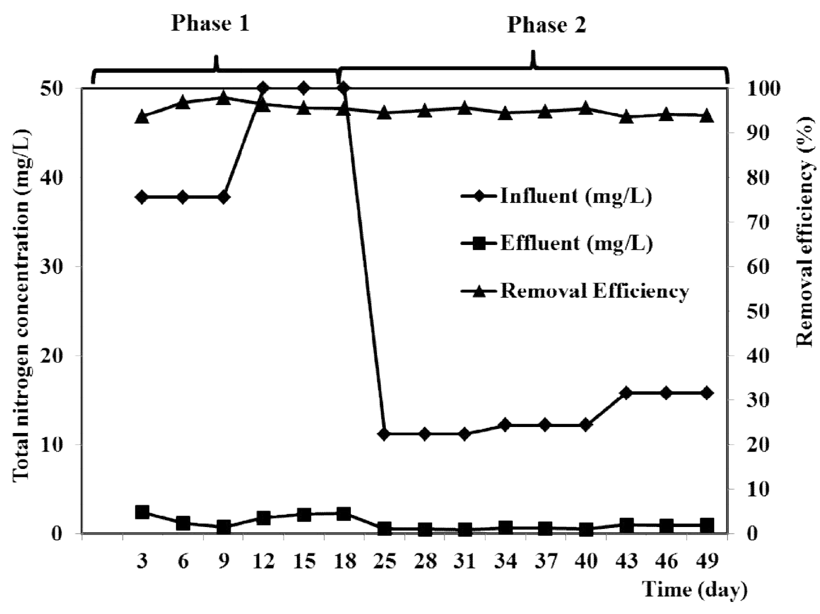

Fig. 3. Total nitrogen removal efficiency of constructed wetland model during time course

and *Iris pseudacorus* for constructed wetland to treat simulated polluted river and the results showed that *Phragmites australis wetland* could decrease N-NH_4^+ from 8.41 ± 0.41 to 0.59 ± 0.46 mg L^{-1} (93% removal efficiency).

3.4 Phosphorus Removal

Fig. 5 illustrates the phosphorus removal profile during the time course. It can be seen that the average of phosphorus removal efficiency was over 92.8% during the treatment of synthetic wastewater and 89.4% during the treatment of actual shrimp farm wastewater. Previous study proved that major processes phosphorus removal in wetland systems are plant assimilation and substrate adsorption. In addition, precipitation reactions of phosphate ion can occur under when aluminum, iron, calcium ions are available in the environment and other

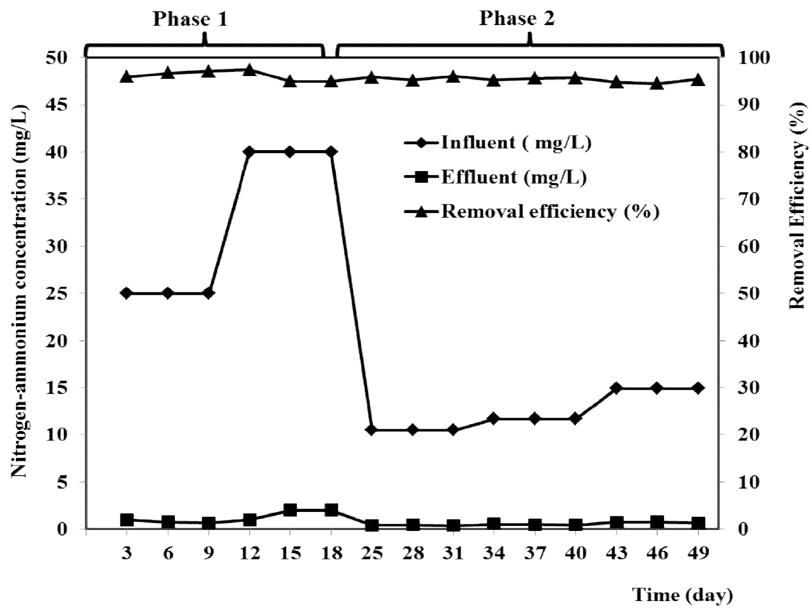

Fig. 4. Nitrogen-ammonium removal efficiency of constructed wetland model during time

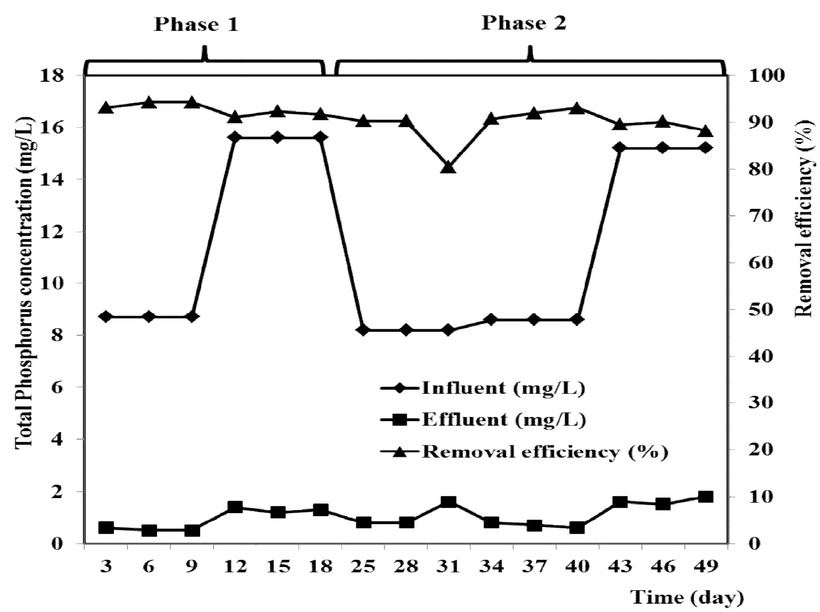

Fig. 5. Total phosphorus removal efficiency of constructed wetland model during time course

clay minerals in the sediment [24,25]. Phosphorus removal efficiency from previous study was lower than that of this study such as about 67% [9] or 32% [23]. These results could achieve the National technical regulation on industry wastewater of Vietnam type A QCVN 24:2009/BTNMT [26].

4. CONCLUSION

In this work, the lab scale of horizontal-flow constructed wetland with *Phragmitesaustralis* plant was applied for shrimp farm wastewater treatment. As a result, the model performed stably with removal efficiency over 90% was achieved for the treatment of COD, N-NH_4^+, TN, and TP in both acclimated phase and actual wastewater treatment phase. The effluent of COD, N-NH_4^+, TN, and TP for the treatment of shrimp farm wastewater was less than 20; 0.72; 0.57; and 1.8 mg L^{-1} respectively. This result could achieve the recycle requirement of the National technical regulation on industry wastewater of Vietnam type A, QCVN 24:2009/BTNMT (COD: 50 mg L^{-1}; TN: 15 mg L^{-1}; NH_4+-N: 5 mg L^{-1}; TP: 4 mg L^{-1}). In conclusion, constructed wetlands model has high potential for removing organic matter and nutrient contained in shrimp farm wastewater. However, in order to make a full conclusion about applying constructed wetland for treating shrimp farm wastewater, it is necessary to study further for other types of wetland vegetation and others constructed wetland models.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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