Improving the Treatment of Saline Wastewater from Shrimp Farms Using Hybrid Constructed Wetlands Models toward Sustainable Development

Nguyen Trung Hiep[1], Le Huu Quynh Anh[1], Phan Dinh Tuan[1], Dinh Sy Khang[1], Phan Dinh Dong[1], Huynh Thi Ngoc Han[1], Dao Dinh Thuan[2], Dinh Thi Nga[1*]

[1]Ho Chi Minh University of Natural Resources and Environment, 236B Le Van Sy, Tan Binh District, Ho Chi Minh City 700000, Vietnam
[2]Ha Noi University of Mining and Geology, 18 Vien, Bac Tu Liem District, Ha Noi 10000, Vietnam

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*** Corresponding author:**
E-mail: dtnga@hcmunre.edu.vn

ABSTRACT

This study investigated a feasible model for treating actual shrimp farm wastewater at a pilot scale that could be applied to farms in the Mekong Delta area. The research was carried out using a hybrid constructed wetlands (HCWs) model, which included a floating constructed wetland (FCW, total area of 1,500 m^2) and a horizontal sub-surface constructed wetland (HSCW, total area of 400 m^2). The HCWs were cultivated with native plants including: *Scirpus littoralis* Schrab, *Cyperus alternifolius*, and *Paspalum vaginatum*. These plants are all adapted to the high salinity levels of shrimp farm wastewater. The system was operated for 30 days to treat shrimp farm effluent. Results indicated that the model effectively removed organic matter and nitrogen compounds from the wastewater. The treated wastewater had low concentrations of COD (10.0-15.4 mg/L), BOD_5 (7.1-12.5 mg/L), NH_4^+-N (0.04-1.11 mg/L), and TN (0.17-1.83 mg/L), which met the reliable conditions for reuse or safety requirements for discharge to aquatic systems. The findings of this study have significant implications for the sustainable management of shrimp farm wastewater in the Mekong Delta area. The HCWs model is a feasible and effective way to treat this type of wastewater, and it could be adapted to other regions facing similar challenges.

1. INTRODUCTION

Shrimp farming has become an important source of income and food security in many countries around the world, with global production reaching over 9 million tons in 2022 (FAO, 2023). However, the rapid expansion of shrimp farms has also led to significant environmental concerns, particularly with regard to the discharge of wastewater into surrounding ecosystems. Shrimp pond farming wastewater is known to contain high levels of nutrients, organic matter, and potentially harmful substances such as antibiotics and heavy metals (Boopathy et al., 2015; Li et al., 2022), which can lead to water pollution, eutrophication, and other negative impacts on aquatic ecosystems and human health (Iber and Kasan, 2021). In addition, the wastewater has high salinity concentrations, which can further exacerbate the problem of water pollution. The discharge of high-salinity wastewater from shrimp farms can result in soil and water salinization, affecting the growth and productivity of nearby crops and other vegetation (Braaten and Flaherty, 2001; Cardoso-Mohedano et al., 2018). As such, the management of shrimp farming wastewater has become an urgent priority for both environmental and economic reasons.

Various wastewater treatment solutions have been proposed and implemented to mitigate the negative impacts of shrimp farming wastewater. For instance, membrane bioreactors, advanced oxidation processes, integrated recirculating aquaculture systems (RAS), micro and biological treatment methods (Meril et al., 2022; Ng et al., 2018; Visvanathan et al., 2008). These conventional wastewater treatment methods have been found to be

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ineffective for treating shrimp farming wastewater due to their high operating cost and low effectiveness for large-scale farming. As a result, there is a need for new, innovative approaches to shrimp farming wastewater treatment.

One potential solution is the use of salt-tolerant plants for phytoremediation of shrimp farming wastewater. Salt-tolerant plants are able to tolerate the high salinity levels found in shrimp farming wastewater and can effectively remove pollutants through various mechanisms such as uptake, adsorption, and transformation (Lymbery et al., 2013; Szota et al., 2015). Pham et al. (2021) investigated the effectiveness of using the wetland system planted with *Scirpus littoralis* to treat shrimp farming wastewater. The system was operated with the high loading rate (HLR) of 1.54 m/d, the hydraulic retention time (HRT) of 1.31 h, and the salinity of 1.5%. The study found that the system achieved complete removal of nitrite and significant reductions in nitrate and COD, with reductions of 78% and 76%, respectively. In 2018, Trang and co-work studied salt tolerance between the two species: *Scirpus littoralis* and *Typha orientalis* (Trang et al., 2018). A completely randomized factorial design with three replications was used to arrange two plant species and six salinity concentrations (0, 5, 10, 15, 20, 30‰). As a result, *Scirpus littoralis* can be considered the ideal choice for a biofilter in the integration of constructed wetlands and marine shrimp production for sustainable aquaculture.

Another study found that *Juncus maritimus* had a notable horizontal flow floating treatment saltmarsh (FTS) effect on the removal of significant components of aquaculture effluent at low hydraulic retention times (Cicero-Fernandez et al., 2022). As a result, total organic carbon increased by 55%, turbidity by 53%, dissolved oxygen increased by 19%, total phosphorus increased by 86%, total suspended solids increased by 82%, and biochemical oxygen demand increased by 78%. It has been determined that certain characteristics of the native *Juncus maritimus* guarantee a 75-100% survival rate in waters with salinities as high as 38 g/L. Overall, this approach has shown promising results in laboratory and field trials and has the potential to be a cost-effective and environmentally-friendly solution for shrimp farming wastewater treatment.

In this context, the current work explores how hybrid-built wetlands (HCWs) models might be used to treat saline wastewater from shrimp farms in order to promote sustainable development. The use of local salt-tolerant plants in constructed wetlands is a promising solution for the treatment of effluents from a semi-intensive shrimp farm. This research aims to remove organic matter and nitrogen compounds from shrimp farm wastewater by using HCWs models. Out flow wastewater met reliable conditions for reuse or safety requirements when discharged into aquatic systems.

2. METHODOLOGY

2.1 Description of the research area

The experiment was carried out Bac Lieu Province - Mekong Delta which located in southern of Vietnam. The research area has a humid tropical and sub-equatorial climate condition. There are two seasons in a year which are rainy season (May to October) and hot season (November to April). The average temperature varies from 24°C to 34°C. The study was conducted during the duration of March to April, there was almost no rain during the experimental time (the average rain fall was 2 mm/month). Therefore, the salinity and water quality of shrimp farm was not much affected by rain in the experimental time.

2.2 Description of the hybrid constructed wetlands (HCWs)

The HCWs system in this study was established at a shrimp farm in Vinh Hau ward, Hoa Binh District, Bac Lieu Province, Vietnam. The schematic diagram of the system is shown in Figure 1. The HCWs consisted of three parts in sequence: an equalization pond, a floating constructed wetland (FCW), and a horizontal sub-surface constructed wetland (HSCW). The specific parameters of the HCWs were shown in Table 1. Three native plants, including *Scirpus littoralis* Schrab, *Cyperus alternifolius*, and *Paspalum vaginatum* were cultivated in the FCW and HSCW models. Before cultivating, plants were collected from brackish water natural wetland area, then acclimated with actual shrimp farm wastewater for 30 days by stepwise increase the salinity level from 5‰ to 20‰ (actual shrimp farm wastewater was mixed with fresh water). The shrimp farm effluent from the equalization pond was pumped to the FCW pond to operate the system. Afterward, the effluent from the FCW pond was then further treated by the HSCW.

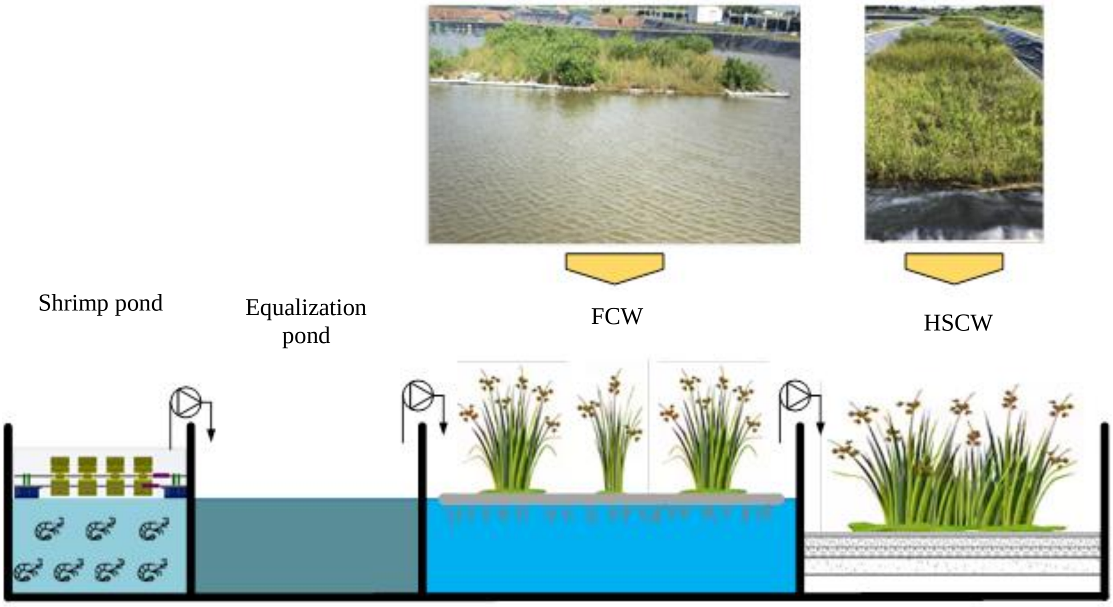

Figure 1. The schematic diagram of the HCWs

Table 1. The specific parameters of the HCWs

Units	Water/media depth (m)	Total area (m^2)	Coverage surface (%)	Substrates	Plant species
Equalization pond	1.0-1.5	1,500	-	-	-
FCW	1.0	1,500	20	-	*Scirpus littoralis* Schrab *Cyperus alternifolius* *Paspalum vaginatum*
HSCW	0.65	400	-	Gravel, sand, soil	*Scirpus littoralis* Schrab *Cyperus alternifolius* *Paspalum vaginatum*

2.3 Wastewater source

The wastewater source was taken from the super-intensive black tiger shrimp farm. On this farm area, each farming cycle lasted between 30 and 120 days, with a density of 120 shrimps/m^2. The water exchange rate varied from 10% to 20%, depending on the quality of the water. The wastewater from the shrimp ponds was collected and stored in an equalization pond and then used as the input for HCWs. The parameters of the shrimp farm wastewater, such as biological oxygen demand (BOD_5, 49.7-64.4 mg/L), chemical oxygen demand (COD, 77.8-89.5 mg/L), ammonium nitrogen (NH_4^+-N, 3.9-5.6 mg/L), total nitrogen (TN, 5.6-8.0 mg/L), and salinity (15.5-21.8‰).

2.4 Data analysis

During the operation, samples were taken from the influent and effluent of each step in the HCWs. The samples were analyzed for pH, temperature, salinity, COD, BOD_5, NH_4^+-N, and TN parameters. A mobile laboratory located at the project site was used for sample analysis. The pH, temperature, and salinity values were determined using a multiparameter water quality meter, HI98194 (Hanna, Romania). The concentrations of TN (detection method: Alkaline persulfate oxidation-UV spectrophotometry), NH_4^+-N (Nessler's reagent spectrophotometry) were determined according to the Standard Methods. The COD and BOD_5 were analyzed following the instructions outlined in Standard Methods for the Examination of Water and Wastewater, 22nd edition (APHA, 2012).

2.5 Nitrogen balance calculation

Nitrogen balance calculation can provide ideas about the pathways of nitrogen conversion in the model. The nitrogen transfer in the HSCW was similar mechanism as in the FCWs models. Because of financial limitation, the FCWs model was chosen to be an example of calculating nitrogen balance.

At the end of the experiment, nitrogen balance in the FCWs was calculated based on the methodology introduced in previous studies (Arslan et al., 2023; Zimmo et al., 2004). In the model, nitrogen from the wastewater was converted by several pathways, including denitrification/evaporation, accumulation by plants and algae, sedimentation, and nitrogen remaining in the effluent. The nitrogen mass balance calculation is illustrated in Equaltion (1).

$$N_d = N_i - (N_p + N_a + N_s + N_e) \quad (1)$$

In Equation (1), the following variables were used:

- N_d: the mass of nitrogen converted by denitrification. This was calculated as the total nitrogen input minus the total nitrogen accumulated by plants, algae, sediment, and nitrogen contained in the wastewater.
- N_i: the amount of nitrogen injected into the model, which was considered to come only from shrimp pond wastewater.
- N_p: the amount of nitrogen accumulated in plants. This was calculated based on the nitrogen concentration and the weight of the plants.
- N_a: the amount of nitrogen accumulated in algae. This was determined based on the algae concentration and the nitrogen content contained in the algae.
- N_s: the amount of nitrogen accumulated in the bottom sediment. This was calculated based on the volume and the concentration of nitrogen in the sediment.
- N_e: the amount of nitrogen contained in the effluent wastewater.

3. RESULTS AND DISCUSSION

3.1 pH and salinity

During the 30-day experimental period, samples of influent, FCW effluent, and HSCW effluent were taken to analyze pH value and salinity (Figure 2). Results showed that the influent shrimp farm wastewater had a pH range of 7.19-8.0 (Figure 2(a)). After treatment in the FCW model, the pH value slightly increased to 7.94-8.48. This increase can be explained by the photosynthesis of algae in the FCW model, which increased OH^- ions in the water, resulting in a higher pH value. The pH of the HSCW effluent varied from 7.19-8.04. These pH values of the models indicated a suitable environment for the metabolism of aquatic organisms.

In addition, salinity concentration is a physicochemical factor strongly affecting the model's growth of microorganisms, plants, and algae. In this study, the average salinity in the influent, FCW effluent, and HSCW effluent was 19.10, 17.14, and 15.35‰, respectively (Figure 2(b)). The salinity levels were within the range suitable for the cultivated plants in the model and did not appear to inhibit the development of the plant system.

(a)

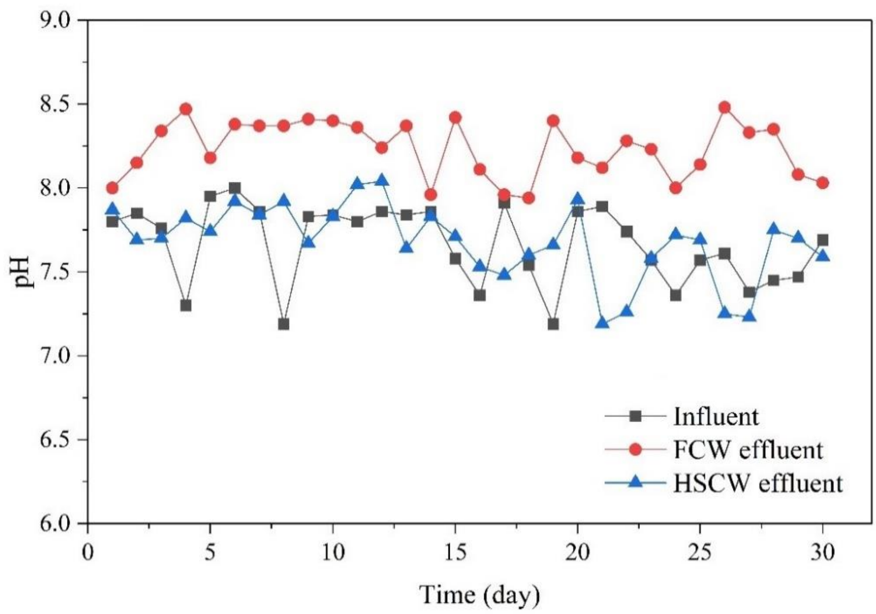

Figure 2. The pH (a) and salinity (b) values during time course

(b)

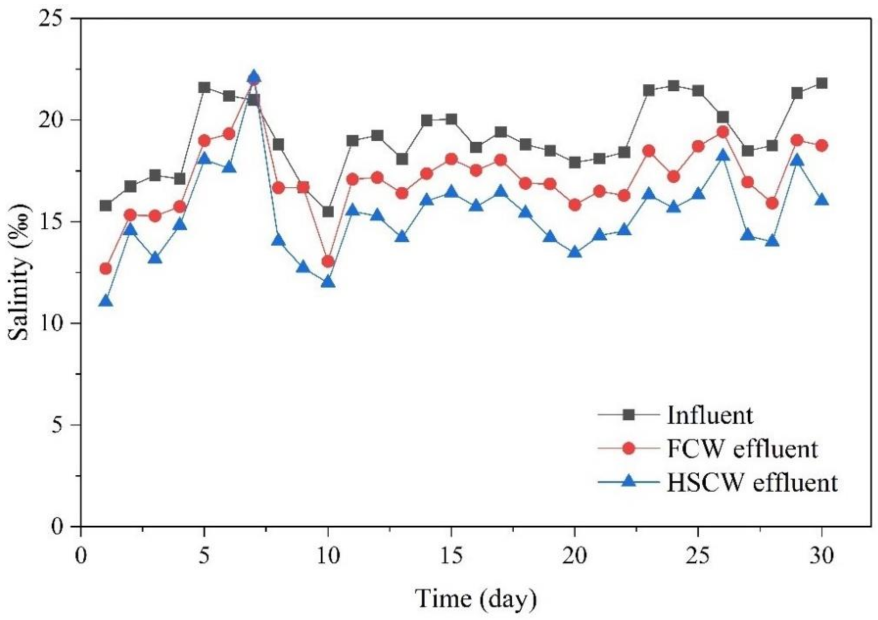

Figure 2. The pH (a) and salinity (b) values during time course (cont.)

3.2 COD and BOD_5 removal

The COD and BOD_5 concentration profile during time course is shown in Figure 3. These parameters in shrimp farm wastewater remained relatively constant over the 30-day operation period, with average influent COD and BOD_5 values of 88.1 and 57.5 mg/L, respectively. This indicates that the oxygen demand was not high. However, the wastewater may contain organic compounds from antibiotics and functional foods found in shrimp feeds, as well as feces and urine from shrimp metabolism. These components need to be treated before being released into the environment. Additionally, shrimp pond wastewater has a high salt concentration, which slows down the conversion of pollutants compared to other common types of sewage.

The results indicated that the average COD removal efficiency was 60.8% for the FCW model and 64.5% for the HSCW model. The total removal rate of the HCWs achieved 88.4% (Figure 3(a)). This result is higher than the study using *Canna indica* to improve pollutant removal efficiency and biomechanics by adding iron ions to aquaculture wastewater in the constructed wetlands of Zhimiao et al. (2019). The average BOD_5 removal rate in these models was 60.5% (FCW) and 59.5% (HSCW), and the maximum BOD_5 removal of the HCWs achieved 87.0% (Figure 3(b)). As a result, the COD and BOD_5 concentration of the effluent was stable in the range of 10.0-15.4 mg/L and 7.0-12.5 mg/L, respectively, which confirmed a safe condition for the receiver source and could be reused for the farm.

A previous study reported that 76% of the COD of White-leg shrimp farm wastewater could be removed by using horizontal subsurface flow constructed wetlands (Pham et al., 2021). In another study, the COD removal level of shrimp farm wastewater by using horizontal subsurface flow constructed wetlands reached 92.7% (Dinh, 2017). Besides, hybrid models have been applied for the treatment of different wastewater (Hu et al., 2022; Maine et al., 2022). It has been shown that the use of rotating biological contactors followed by hybrid constructed wetlands can remove 95.06% of COD in polluted rivers (Hu et al., 2022). Maine and colleagues used a hybrid system involving a free-water surface flow wetland and a horizontal subsurface flow wetland for pet-care center wastewater treatment. The system achieved the removal of 82.8% COD and 88.3% BOD (Maine et al., 2022).

3.3 Nitrogen removal

Nitrogen content is one of the important factors that need special attention for the quality control of shrimp pond water. In the pond, nitrogen compounds can be converted into different forms, of which nitrogen in the form of NH_3 is considered a toxin that affects the growth and metabolism of shrimps. Shrimp farm wastewater contains nitrogen compounds derived from dissolved feed, uneaten food, feces and shrimps' excretory products shrimp. Therefore, it is necessary to eliminate nitrogen to achieve acceptable standards before discharging it into the environment to ensure the receiving source's safety and avoid eutrophication.

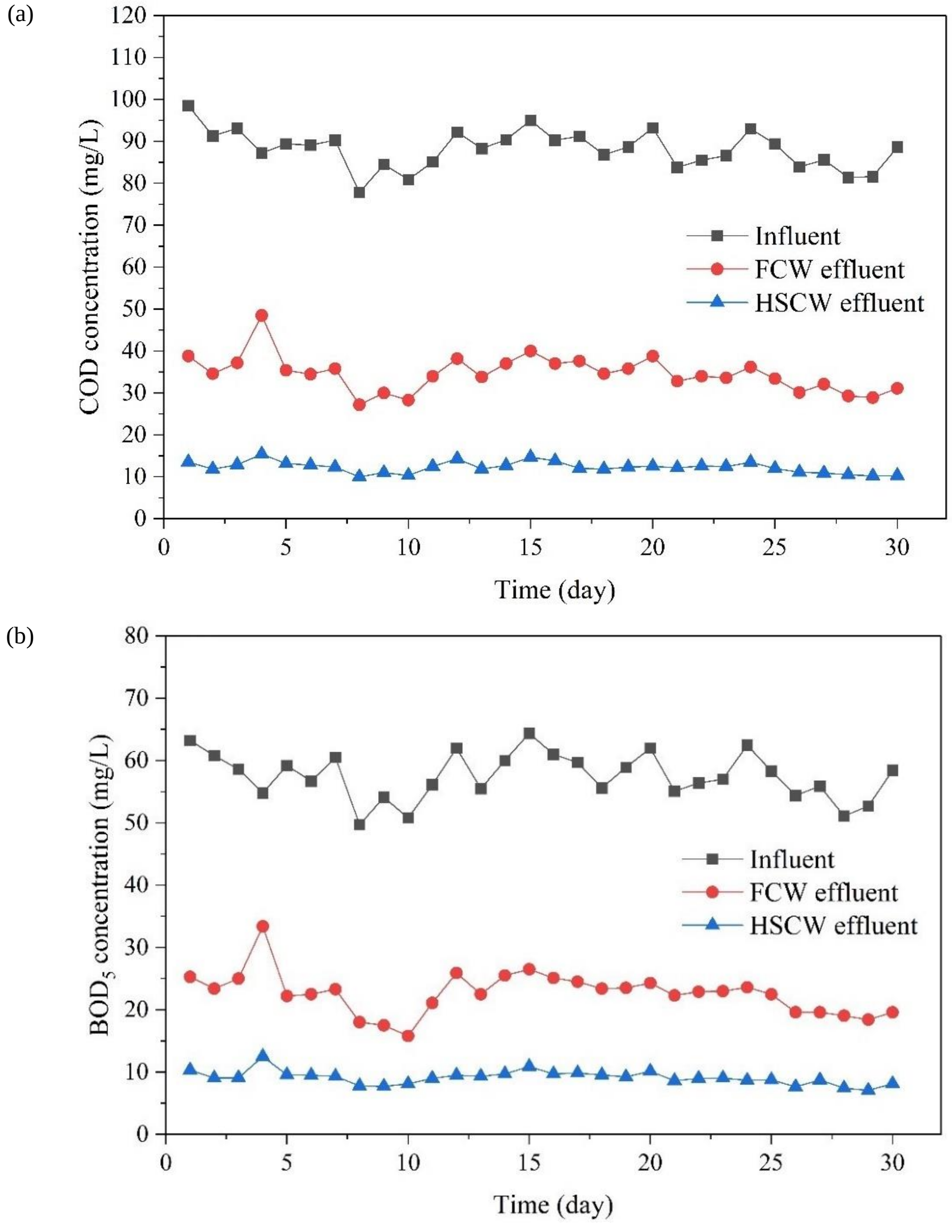

Figure 3. The change in COD (a) and BOD_5 (b) concentration over time

Figure 4 shows the change in nitrogen compounds during the operational time. In the influent wastewater, the concentration of TN varied from 5.62 to 8.02 mg/L, and NH_4^+-N fluctuated from 3.93 to 5.61 mg/L. The maximum removal of TN in the FCW and HSCW models and the total removal efficiency of the systems were 78.71, 90.32, and 97.24%, respectively. The maximum removal rate of NH_4^+-N for those steps was 92.51 and 91.67%; the ultimate removal of NH_4^+-N for all systems achieved 99.09%. According to Nasir et al. (2023), when using green microalgae to treat shrimp aquaculture wastewater, only 90.1% ammonia removal efficiency is achieved. The result illustrated that the applied system was suitable for treating nitrogen-containing shrimp farm wastewater. It was revealed that constructed wetlands and similar models performed well for nitrogen decomposition (Rampuria et al., 2020).

The main mechanisms for nitrogen degradation in constructed wetlands involve microbial conversion, chemical transformation, and physical processes (Li et al., 2021; Lu et al., 2020). Biological pathways utilize several techniques, such as nitrification, denitrification, nitrogen fixation, ammonification, and plant utilization. Nitrogen compounds are also converted through physicochemical processes such as adsorption, sedimentation, gas stripping, ion exchange, and filtration (Dinh, 2017; Dinh et al., 2021; Lee et al., 2009). Previous research has demonstrated the potential of using constructed wetland models to remove nitrogen from wastewater. Hybrid-constructed wetland systems have been shown to remove ammonium, TKN, and nitrate up to 83.0, 83.8, and 20.37%, respectively (Maine et al., 2022). Another study reported the removal of 78% nitrate matter in *Litopenaeus vannamei* farm wastewater using constructed wetlands (Pham et al., 2021). Therefore, constructed wetland models hold great promise for nitrogen treatment, especially in rural areas where land space is appropriate for modeling.

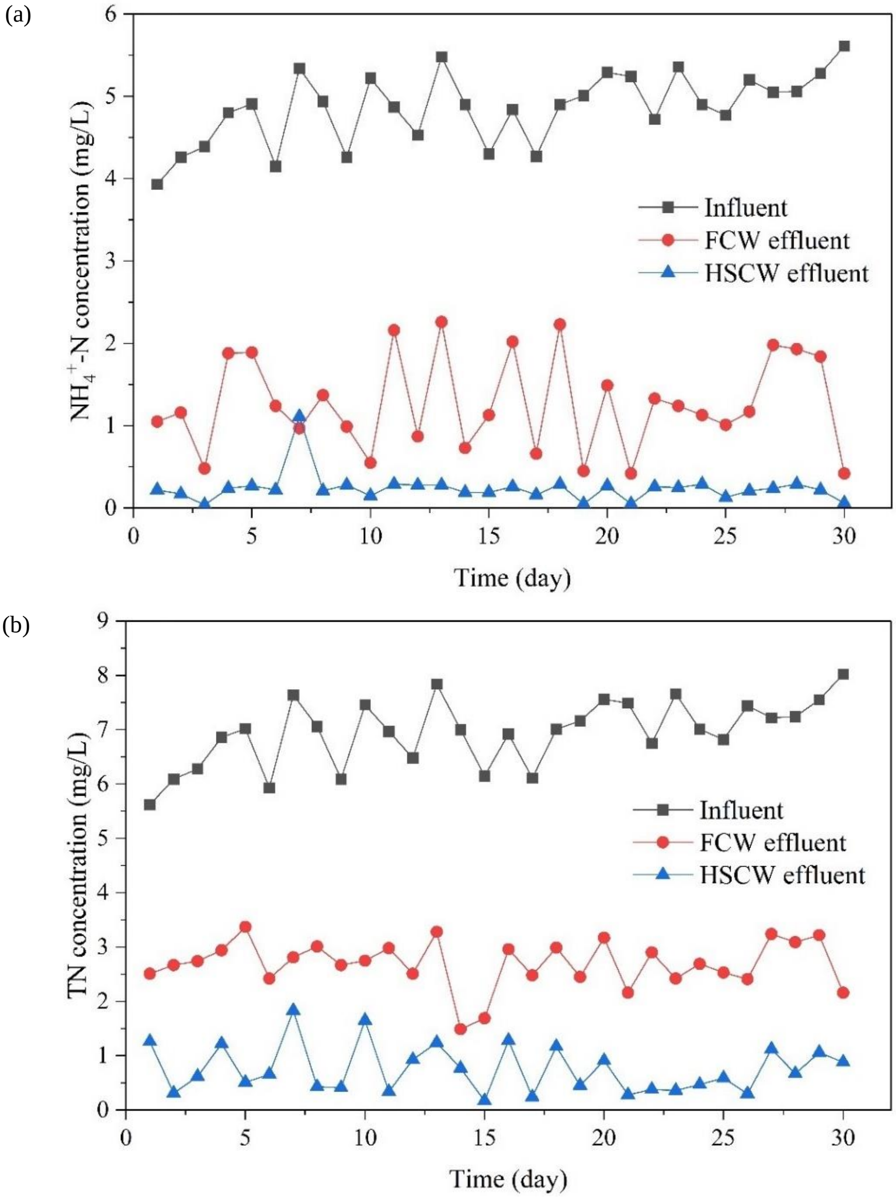

Figure 4. The change in NH_4^+-N (a) and TN (b) concentration during time course

3.4 Nitrogen balance

Nitrogen balance was calculated for the FCWs during operation to evaluate the nitrogen transition in the experimental model (Figure 5). The calculation method for the nitrogen balance considers that the nitrogen added to the model through rainfall is negligible. Towards the end of the operational period, the plants and algae in the pond were harvested, and sediment samples were taken. This work allowed for the determination of the nitrogen balance of the FCW. The findings indicated that a total of 2.272 kg of nitrogen entered the model during the operational period. Most of the nitrogen was converted through denitrification or evaporation processes (59%). In contrast, the amount of nitrogen fixed in plant cells (0.016 kg) and algae cells (0.0018 kg) was relatively small.

The previous study revealed that denitrification in the constructed wetland model was the main route of nitrogen conversion (Lee et al., 2009; Vymazal, 2007). Zimmo and colleagues indicated that the primary nitrogen conversion in the duckweed stabilization ponds was sedimentation and denitrification pathways (Zimmo et al., 2004). This result reveals that the floating constructed wetland is an excellent example of nitrogen transfer in which the dominant portion of nitrogen from the input wastewater was by denitrification and evaporation. The amount of nitrogen fixed in plants and algae cells at a particular time was insignificant because nitrogen was uptake and transferred through the metabolisms.

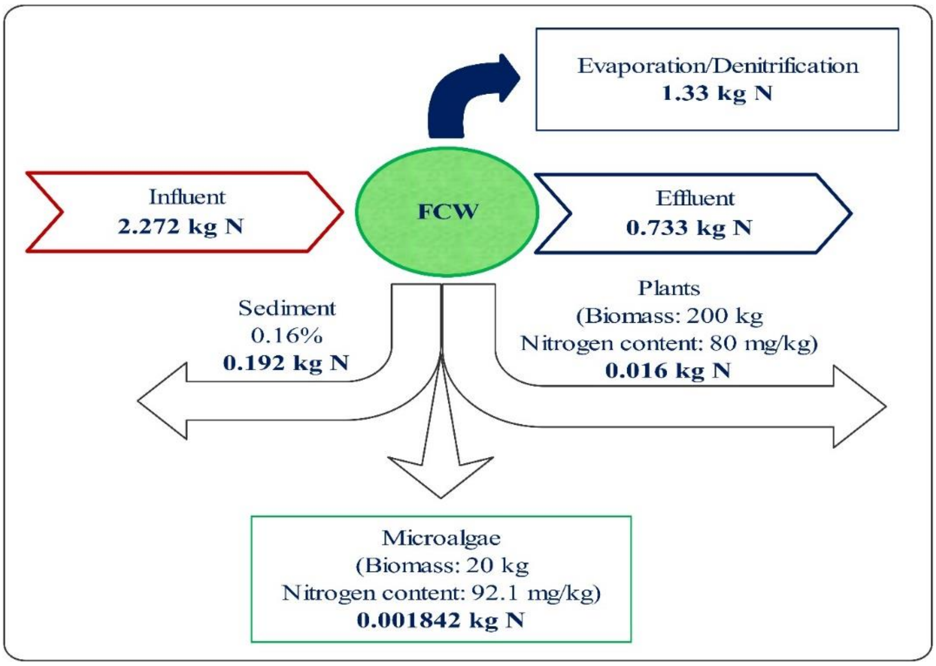

Figure 5. Nitrogen balance of the floating constructed wetland system

4. CONCLUSION

In the present study, the HCWs involve a floating constructed wetland followed by a horizontal sub-surface constructed wetland system designed at a pilot scale to treat actual shrimp farm wastewater. The findings of this study affirm the robust performance of the HCW model in wastewater treatment. Impressively, the model exhibited exceptional removal efficiencies, with values reaching 88.4% for Chemical Oxygen Demand (COD), 87.0% for Biochemical Oxygen Demand (BOD_5), 97.2% for Ammonium-Nitrogen (NH_4^+-N), and a remarkable 99.1% for Total Nitrogen (TN).

A critical aspect of this research lies in elucidating the nitrogen balance within the FCW, revealing that the principal nitrogen transformation pathways predominantly involve denitrification and evaporation processes. These outcomes underscore the potential of constructed wetland models featuring indigenous salt-tolerant flora to mitigate pollutants found in shrimp farm wastewater effectively. Moreover, the scalability of these wetland systems, utilizing pre-existing reservoirs and underutilized agricultural land, emerges as a viable prospect. Consequently, replication of this model on a larger-scale holds promise for widespread adoption, thereby facilitating the sustainable treatment of wastewater from aquaculture facilities. In doing so, it contributes to environmental preservation and bestows the added benefit of creating verdant spaces within shrimp farms in the ecologically sensitive Mekong Delta region.

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