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TREATMENT EFFICIENCY OF WASTEWATER FROM CATFISH FARMING BY AN ARTIFICIAL SYSTEM: COMBINING CONSTRUCTED WETLAND WITH ADSORPTION MATERIALS AND BIOLOGICAL TANKS PLANTED HYDROPONIC VEGETABLES

The treatment system combines constructed wetland (CW) tanks with adsorption materials and biological tanks planted with hydroponic vegetables to treat wastewater from catfish (*Pangasianodon hypophthalmus*) pond in a production cycle. The CW tanks were completely randomized with two treatments using sand and adsorbent materials as bed media. Adsorbent materials were derived from peat soil and combusted beehive charcoal residues, with a ratio of 70:30 by weight. Wastewater flows continuously in CW tanks at a rate of 0.3 m³/h and then flows through hydroponic vegetable tanks. Treated wastewater was evaluated in accordance with Vietnamese standards, as outlined in Circular 44/2010/TT-BNNPTNT and QCVN 02-20:2014/BNNPTNT, and was found to be suitable for reuse in catfish ponds. The pollutant reduction capacity for BOD₅, COD, total phosphorus (TP), and total Kjeldahl nitrogen (TKN) of the CW with adsorbent was higher than that of the CW with sand. Treatment efficiency for BOD₅, COD, TP, and TKN reached an average rank of 76.97–92.57%. The system's advantages are stable processing of large wastewater from fishponds, low cost and simple operation. This is an effective solution for mitigating pollutant loads from fishponds' effluents in the Mekong Delta, Vietnam.

1. INTRODUCTION

Catfish farming is the spearhead agricultural economic sector in the Mekong Delta, Vietnam. Tra catfish farming has occurred along two main branches, the Tien River and the Hau River, and the associated channels of these main branches. An Giang, Dong Thap, Can Tho, and Vinh Long provinces are the most important farming areas [1]. In recent years, catfish production has statistically increased to 2,251,825 tons/year corresponding to the pond surface area of 808.8 thousand ha. Besides rice cropping, pangasius farming

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has become the main livelihood of people in the Vietnamese Mekong Delta region [2]. Catfish farming activities discharge a huge amount of wastewater into the surrounding canal network due to the need for periodic water replacement. According to Pham Quoc Nguyen et al. [3], in the Vietnamese Mekong Delta, the volume of replaced water could be about $10,000 \text{ m}^3/(\text{day}\cdot\text{ha})$ in a fishpond 3 m deep. The wastewater exhibits a high level of pollution due to the presence of contaminants derived from uneaten feed, fish metabolic waste, pond sanitation chemicals, and nutrient inputs from supplementary water sources [4]. The average load of chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) of intensive pangasius farming ponds increased with farming time; ranging from 1.90–5.37 tons COD/(ha·day), 0.19–1.46 tons N/(ha·day) and 0.01–0.53 tons P/(ha·day) [5]. According to Le Hoang Nam et al. [4], surface water sources in the catfish farming area in Thanh Binh, Dong Thap province have total suspended solids (TSS), COD, and biological oxygen demand (BOD) contents that exceed the allowable limits of Vietnamese standards, from 2.4 to 3.7 times for TSS and from 1.4 to 2.1 times for COD and BOD. When polluted surface water sources exceed the self-purification capacity of the river system, not only the catfish farming industry but also the aquaculture industry in the Vietnamese Mekong Delta will be affected. Therefore, the application of appropriate treatment technologies is essential to ensure adequate treatment of this wastewater before its discharge into receiving water bodies. Several methods can be employed for treating fishpond wastewater, including constructed wetland systems (CWS), adsorption, and floating plant-based treatment systems [6, 7]. However, currently, catfish farms in the Vietnamese Mekong Delta apply settling ponds to treat wastewater. Although this solution can decrease pollutants in wastewater, its efficiency is not high and the wastewater retention time is long.

Adsorption is a well-recognized and effective wastewater treatment method. However, the high cost of most commercial adsorbents limits their practical application at the farm scale. There have been some studies that used peat-derived materials to adsorb heavy metal ions and textile dyes in wastewater with high efficiency [8]. Moreover, peat-derived materials also show good treatment capacity for catfish wastewater [9]. Combusted beehive charcoal residues are solid waste generated in daily life. Beehive charcoal is quite commonly used in cooking in many localities in Vietnam. The main raw materials used to produce beehive charcoal are charcoal (accounting for 20–30%), and the remaining component is clay. According to Kim Lavane et al. [10], the constructed wetlands using combusted beehive charcoal residues as filtration bed media and planted with Napier grass (*Pennisetum purpureum*) have a domestic wastewater treatment efficiency of about 92.6% for BOD and COD, about 47.5% for TKN, and 63.2% for TP. However, the combined application of CWS, adsorbent materials, and floating plants to treat catfish farming wastewater has not been fully researched and published in the Mekong Delta.

Although the CWS provides high treatment efficiency, it requires a long treatment time. Its treatment efficiency is based on the concentration of pollutants in the wastewater and the types of plants used in the system [11, 12]. Hydroponic plants combined in bio-

logical ponds are a simple method for treating wastewater from fishponds. Still, they require a considerable amount of time to process and necessitate a large area for pond installation [13]. In this study, the catfish wastewater treatment efficiencies of the CWS that plants water celery (*Oenanthe javanica*) on a mixture medium of peat soil and combusted beehive charcoal residues, combined with the biological tank that plants hydroponic vegetables, were evaluated. This study aims to identify the optimum method for treating catfish pond wastewater, after which the treated water can be reused as an alternative water source for catfish culture activities.

2. MATERIALS AND METHODS

2.1. EXPERIMENTAL DESIGN AND PREPARATION OF THE TREATMENT SYSTEM

This research was conducted at the Binh Thanh Experimental Site (10°18'12.82"N, 105°47'23.82"E) in Dong Thap province, Vietnam. The experiment was implemented within a complete cycle of catfish (*Pangasianodon hypophthalmus*) production in seven months from November 2021 to May 2022. The fishpond has an area of 200 m², with an approximate water depth of 2 m and a usable volume of 400 m³ for fish cultivation. In our experiment, the farmer stocked fish at a density of 47 fish/m² and an initial weight of 20±2.5 g/individual. After harvesting, the total production was 4.3 tons per pond, and the final weight of the fish ranged from 1 to 1.5 kg. During the farming period, the farmer used commercial pellet feeds, with a total feed input of 8.05 tons and a feed conversion ratio (FCR) of 1.87.

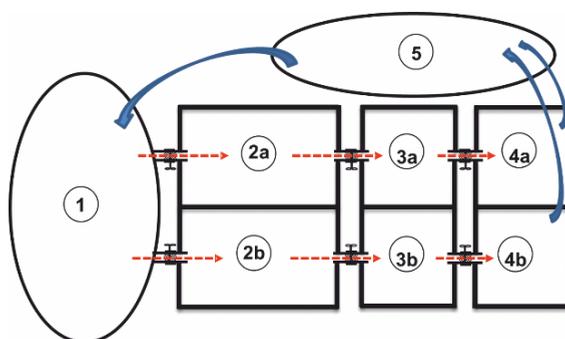


Fig. 1. Constructed wetland systems: 1 – the catfish pond, 2a – the CW used peat soil and combusted beehive charcoal residues as bed medium and planted water celery, 3a and 4a are artificial floating islands planted with hydroponic vegetables, 2b – the CW used sand as a bed medium and planted water celery, 3b and 4b – artificial floating islands planted with hydroponic vegetables, 5 – the pond stored treated wastewater that can be used as a source of water supply to the catfish pond, red arrows – wastewater flow

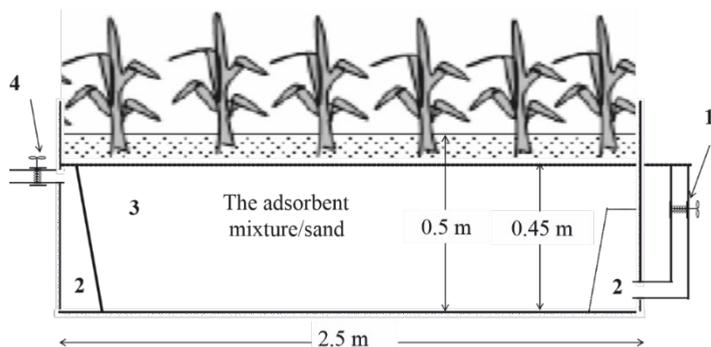


Fig. 2. The constructed wetland system with horizontal subsurface flow (HSF):
 at the tank 2a and 2b: 1 – valve to control wastewater level in tank 2,
 2 – area with gravel (size 1–2 cm) to avoid CWS blockage, 3 – adsorbent mixture in tank 2a
 or sand in tank 2b. The top layer is soil (5 cm thick), ensuring the growth of vegetables,
 4 – valve to discharge wastewater after treatment



Fig. 3. Adsorbent mixture and sand in CWS (a), *Oenanthe javanica* grown in tanks 2a and 2b after 3 weeks (b)

The constructed wetland system employing horizontal subsurface flow (HSF), with dimensions of $1.2 \times 2.5 \times 0.5$ m, was located next to the fishpond. The wastewater from the fishpond was loaded into the CWS using a water pump and controlled at a rate of $0.3 \text{ m}^3/\text{h}$ with a valve. Water in the catfish ponds was changed once per week during the first 16 weeks and twice per week during the subsequent 12 weeks. According to recommended catfish farming practices in Vietnam, the required water-exchange volume in catfish ponds is approximately 20–30% [5]. We followed this recommendation and selected a water-exchange ratio of 20% of the pond volume. The experiment was designed with

two treatments (Fig. 1). Treatment 2a applied CWS using a medium composed of peat soil and combusted beehive charcoal residues, whereas treatment 2b used sand as the medium in CWS (Fig. 2). Water celery (*Oenanthe javanica*) was planted in both CWS to enhance pollutant-removal capacity (Fig. 3b). Both treatments were followed by four biological tanks (3a, 3b, 4a, and 4b) used for growing hydroponic vegetables. Each tank measured $1.2 \times 1.5 \times 1.0$ m with an effective water depth of 0.8 m.



Fig. 4. Artificial floating islands with hydroponically grown vegetables on the water surface of a tank (a), and a 5.0 m^3 pond for collecting treated effluent from tank 4, which could be reused as a water source for farming activities (b)

Artificial floating islands carrying hydroponically grown vegetables, including *Lactuca sativa* var. *crispata*, *Brassica chinensis* L., and *Allium ascalonicum*, were installed on the water surface of each tank (Fig. 4a). Finally, a 5.0 m^3 pond was constructed to collect treated effluent from tank 4, which could be reused as a water source for farming activities (Fig. 4b).

2.2. CWS EXPERIMENT

Adsorbent material. Peat soil and combusted beehive charcoal residues are readily accessible in the Vietnamese Mekong Delta, where both are abundant and possess high adsorption capacity. Peat soil was collected at a depth of 0–50 cm in the U Minh area in Kien Giang province, air-dried at $30 \text{ }^\circ\text{C}$ for 5 days, and sifted through a sieve (mesh size 2 mm, ASTM standard) to remove stone and plant remains. Combusted beehive charcoal residues were dried and crushed. Then they were passed through a 2.0 mm mesh sieve (ASTM standard). Peat soil and combusted beehive charcoal residues were mixed in the 70:30 (w:w) ratio [9]. The mixing of combusted beehive charcoal residues into peat soil increased porosity and limited the blockage when operating the system.

The sand was sieved by a sieve with a 2.0 mm mesh (ASTM standard) to remove organic debris and homogenize the sand material. The layer of adsorbent material was 0.45 m thick, and the top layer was soil 0.05 m thick. The characteristics of the soils are given in Table 1.

Table 1

Characteristics of peat soil and the soil on the surface of CWS

Characteristics	Peat soil	Soil on the surface of CWS
pH	5.40±0.03	6.23±0.01
Carbon, wt %, dry weight	51.02±0.28	1.50±0.01
N _{total} , wt %, dry weight	0.16±0.005	0.03±0.0003
P _{total} (wt %, dry weight)	0.04±0.002	0.04±0.0005
Specific surface area, m ² /g)	10.49	–

Artificial floating islands and hydroponic plants. Artificial floating islands constructed from perforated foam plastic sheets were installed in tanks 3a, 3b, 4a, and 4b. Each foam plastic sheet had a surface area of 0.15 m² and contained 84 holes. Each tank was equipped with nine artificial floating islands. Each island had a surface area of 0.15 m², resulting in a total floating-island area of 1.35 m², which corresponds to approximately 75% of the tank's water surface area. Plants were well nursed and then transplanted into holes with the support of the foam plastic sheet. In the experiments, seedlings were selected 10 days after sowing, separated, and transplanted into holes with growing substrates.

2.3. OPERATION OF CONSTRUCTED WETLAND SYSTEMS

To stabilize the adsorbent materials within the system and to calibrate the flow rate to the required operational level, before the experiments, the treatment system was thoroughly washed three times with clean domestic water. Each washing cycle lasted 5 hours. Two experiments (1 and 2) were carried out during the first 16 weeks, when the water change frequency was once per week. During the final 12 weeks, experiment 3 was carried out, when the water change was increased to twice per week. The hydraulic residence time (HRT) in tanks 2a and 2b was 4.5 hours, in tanks 3a, 3b and 4a, 4b, it was 4.8 hours.

Experiment 1. Evaluation of treatment efficiency of CWS (tanks 2a and 2b) and tanks planted with hydroponic vegetables. Wastewater from the catfish pond was loaded into tanks 2a and 2b with a flow rate controlled by the valve of 0.3 m³/h. After 4.5 hours, the wastewater from tank 2a began to flow into tank 3a, while the wastewater from tank 2b flowed into tank 3b. Continuously, wastewater from tank 3a flowed to tank 4a, and wastewater from tank 3b flowed to tank 4b. Wastewater in tanks 3a, 3b, 4a and 4b was treated using the hydroponic vegetables. Tanks 3a and 3b, as well as tanks 4a and 4b, were identical in terms of species composition and planting density (84 holes/artificial floating

islands). The effective volume of tanks 3a, 3b, 4a, and 4b was 80% of their design capacity. In experiment 1, the wastewater treatment system was operated from week 10 to week 15 of the water-change period for the catfish ponds.

Experiment 2. Evaluation of the treatment efficiency of hydroponic vegetables. The wastewater treatment system was operated in week 16 of the water change time. To ensure relative uniformity in the growth time of *Oenanthe javanica* in CWS, the operating time was shortened (not repeated). For the first batch, the system was operated in the same manner as in experiment 1, with vegetables planted in tanks 3a, 3b, 4a, and 4b. For the subsequent batch, the system was operated without planting vegetables in the tanks.

Experiment 3. Evaluation of the effectiveness of the entire treatment system under continuous and recirculating operation. The treatment system was operated continuously, and all treated wastewater was recycled back into the catfish pond. Wastewater was loaded from the catfish pond through tank 2a at a flow of 0.3 m³/h, then flowed into tanks 3a and 3b. It was retained in tanks 3a and 3b for approximately 4.8 hours before flowing into tanks 4a and 4b at a rate of 0.3 m³/h. Similarly, wastewater was retained in tanks 4a and 4b for about 4.8 hours before flowing into tank 5 at the same flow rate of 0.3 m³/h. Treated wastewater from tank 5 was recycled back into the catfish pond to offset the water lost due to discharge into CWS. In this experiment, the wastewater treatment system was operated for 14 days.

2.4. WATER SAMPLING AND ANALYSIS

In experiments 1 and 2, samples were taken from the catfish pond and tanks 2–4. The sampling locations and sampling time in experiment 3 are given in Table 2.

Table 2

Locations and times of water sample collection in experiment 3

Sampling location		Time		
		Day 1	Day 7	Day 14
Catfish pond	initial (before flow into the system)	×	–	–
	after 7 days of operating the wastewater treatment system	–	×	–
	after 14 days of operating the wastewater treatment system	–	–	×
Tank 5	before reuse in the catfish pond	×	×	×

Fish feeding time was from 6:30 AM to 7 AM. Then, the sampling time in the fish-pond arranged in the period of 8:00 AM to 9 AM also limits the disturbance on the pond water surface when sampling. During the period of 9:00 AM to 10:00 AM, water samples were collected from tanks 2–4. In experiments 1 and 2, water samples were collected once per day during the wastewater treatment system's operation period, totaling five days per

batch. In experiment 3, the water samples were collected at days 1, 7, and 14 after system initiation.

The analyzed pollution parameters included: BOD₅ determined by the improved Winkler method (SMEWW 5210 D:2012), COD by closed reflux, titrimetric method (SMEWW 5220 C:2012); TP using persulfate and ascorbic acid method (SMEWW 4500P E&J:2012), TKN by Kjeldahl method (SMEWW 4500N:2012) [14].

Treatment efficiency (H) was calculated according to the equation:

$$H = \frac{C_0 - C}{C_0} \times 100\% \quad (1)$$

where C_0 , C , mg/dm³, are the influent and effluent pollutant concentrations.

Before being recycled back into the catfish pond, the quality of treated wastewater in tank 5 was compared and evaluated against the permissible limits in Circular 44/2010/TT-BNNPTNT, which regulates the quality of water supplied to *Pangasianodon hypophthalmus* ponds, issued by the Ministry of Agriculture and Rural Development of Vietnam. Additionally, the study also compared and evaluated the permissible limits of pollutants in QCVN 02-20:2014/BNNPTNT, which regulates wastewater from catfish ponds discharged into receiving water sources, as issued by the Ministry of Agriculture and Rural Development of Vietnam.

2.5. DATA ANALYSIS

The data was statistically analyzed using IBM SPSS Statistics for Windows software, Version 22. The study applied ANOVA to analyze variance and used Duncan's test to test the average concentration and treatment efficiency of each pollution parameter at the 5% significance difference level between the catfish pond and treatment tanks in the same experimental treatment, with adsorbent materials (a) or with sand (b). Besides, the average concentration and treatment efficiency of each water quality parameter of the same type of tanks (2, 3 or 4) between the different experimental treatments, with adsorbent materials (a) or with sand (b), were analyzed by the t -test method.

3. RESULTS

3.1. WASTEWATER TREATMENT EFFICIENCY WITH THE USE OF ADSORBENT OR SAND IN CWS

The concentration of pollutants in the entire treatment system is presented in Table 3, which highlights clear differences between the two CWS treatments. When wastewater from the catfish pond flows through the tank 2a, the concentration of BOD₅, COD, TP and TKN was reduced 5.68, 6.23, 3.11, and 6.26 times, respectively ($p < 0.05$). In contrast, in CWS with sand material, organic matter and nutrients slightly decreased in tanks 2b.

BOD₅, COD, TP, and TKN in tank 2b were reduced by approximately 1.07–1.08 times relative to the catfish pond ($p < 0.05$). In the hydroponic vegetable tanks, BOD₅, COD, TP, and TKN did not decrease strongly in tanks 3a and 4a. However, in tanks 3b and 4b, they decreased significantly. These results indicate that CWS that combines adsorbent materials and hydroponic vegetables exhibits strong potential for improving wastewater treatment in catfish aquaculture systems.

Table 3

The concentration of pollutants in the wastewater treatment system with and without adsorbent materials

Sampling point	Concentration [mg/dm ³]	BOD ₅	COD	TP	TKN
		Mean±standard error			
Catfish pond	C ₀	98.04±0.62 a	150.05±1.31 a	10.66±0.05 a	61.73±0.71 a
Tank 2a	C _{2a}	17.27±0.93 bB	24.10±0.13 bB	3.43±0.26 bB	9.86±0.11 bB
Tank 3a	C _{3a}	14.23±0.53 bB	20.27±0.57 bB	2.72±0.32 cB	7.98±0.84 bcB
Tank 4a	C _{4a}	11.76±0.80 bB	16.67±0.92 bB	2.27±0.24 cB	6.54±0.51 cB
Tank 2b	C _{2b}	91.79±2.18 bA	139.53±3.76 bA	9.87±0.15 bA	57.36±0.79 bA
Tank 3b	C _{3b}	71.90±2.10 cA	108.24±3.75 cA	7.35±0.12 cA	44.08±1.04 cA
Tank 4b	C _{4b}	57.10±2.14 dA	86.03±3.45 dA	5.56±0.24 dA	34.36±0.89 dA

In the same column, values followed by different lowercase letters (a, b, c, d) differ significantly among sampling points (catfish pond, tanks 2, 3, 4) within the same treatment (a or b) at $p < 0.05$. Values followed by different uppercase letters (A, B) differ significantly between treatments (with vs. without adsorbent) for the same sampling point at $p < 0.05$.

The result also shows that the treatment efficiency of sand material in tank 2b was lower than that of the adsorbent material in tank 2a (Table 4). In tank 2a, the treatment efficiency reaches 67.84±1.91 (for TP), 82.37±2.37 (for BOD₅), 83.92±2.41 (for COD), and 84.02±2.00 (for TKN). In tank 2b, the treatment efficiency was only from 6.36±0.55% to 7.44±1.31%. Moreover, in the CWS with adsorbent material and hydroponic vegetables, total treatment efficiency (Total H_a) reached 78.72±1.25% (for TP), 87.99±1.68% (for BOD₅), and 88.87±1.92% (for COD). Especially, Total H_a reached the highest value of 89.40±1.41% for TKN. In contrast, in the CWS with sand and hydroponic vegetables, total H_b only reached 41.74±2.36% (BOD₅), 42.65±2.43% (COD), 44.35±1.27% (TKN), and 47.90±2.11% (TP). The adsorbent material played a crucial role in the process of removing BOD₅, COD, and TKN in tank 2a. However, the phosphorus removal effect of the adsorbent material was not high.

The treatment efficiencies for TKN and total phosphorus in tanks 3b and 4b were significantly higher than those in tanks 3a and 4a ($p < 0.05$). This shows that hydroponic vegetables contributed to the removal of nitrogen and phosphorus through nutrient uptake, thereby reducing pollutant concentrations in wastewater. This proves the potential role of hydroponic vegetables in removing pollutants from the wastewater of the catfish pond.

Table 4

Treatment efficiency of the wastewater treatment system with and without adsorbent materials

Sampling point	Treatment efficiency [%]	BOD ₅	COD	TP	TKN
		Mean±standard error			
Tank 2a	<i>H</i> _{2a}	82.37±2.37 bA	83.92±2.41 aA	67.84±1.91 bA	84.02±2.00 bA
Tank 3a	<i>H</i> _{3a}	17.87±1.17 cB	16.16±1.27 bB	20.64±1.12 cB	19.28±0.92 cB
Tank 4a	<i>H</i> _{4a}	17.16±1.16 cA	17.95±2.56 bA	16.57±0.65 cB	17.94±1.46 cB
Total Ha (%)		87.99±1.68 aA	88.87±1.92 aA	78.72±1.25 aA	89.40±1.41 aA
Tank 2b	<i>H</i> _{2b}	6.36±0.55 cB	6.98±0.87 cB	7.44±1.31 cB	7.07±1.33 cB
Tank 3b	<i>H</i> _{3b}	27.68±0.84 bA	22.42±0.92 bA	25.52±0.83 bA	23.17±1.02 bA
Tank 4b	<i>H</i> _{4b}	20.62±0.68 bA	20.54±0.56 bA	24.46±1.06 bA	22.06±0.21 bA
Total Hb (%)		41.74±2.36 aB	42.65±2.43 aB	47.90±2.11 aB	44.35±1.27 aB

In the same column, values followed by different lowercase letters (a, b, c, d) differ significantly among sampling points (catfish pond, tanks 2, 3, 4) within the same treatment (a or b) at $p < 0.05$. Values followed by different uppercase letters (A, B) differ significantly between treatments (with vs. without adsorbent) for the same sampling point at $p < 0.05$.

Discharging and treating wastewater from catfish farming activities is an increasing concern in sustainable agricultural development in the Mekong Delta. Adsorption technology offers many advantages, such as low cost, selectivity, effective removal of substances from water even at low concentrations, ease of operation, simple design, and high capacity [15]. Compared with sand material, the adsorbent mixture is related to the deposition and accumulation of contaminant atoms or molecules on the surface of the material. This adsorption occurs at the surface of the adsorbent. This depends on the properties of the adsorbent, such as surface charge, surface area, and surface function [16]. In CWS, the functions of substrate materials mainly focus on filtration and adsorption functions for different contaminants, electron donor function for metabolism and denitrification, carrier function for microorganisms, and physical support function for wetland plants. These functions are inextricably linked in the CWs and determine the contaminant's removal effectiveness [17].

The use of peat in wastewater remediation has become the most promising solution due to its high porosity and adsorptive capacity, which have a higher efficacy in treating wastewater. Unprocessed peat contains many integral constituents such as lignin, cellulose, fulvic and humic acids [16] and polar functional groups such as alcohols, aldehydes, ketones, carboxylic acids, and phenol hydroxides [17]. Peat is highly organic, providing a substantial absorptive and strong cation exchange capacity. Moreover, it also has fibrous material for filtration, a high-water retention capacity, and media for microorganisms [18]. Based on specific chemical and physical reactions among contaminants and peat functional groups, reactions such as chelation, complexation, and adsorption enable peat to act as an adsorbent or filter for removing heavy metals, hydrocarbons, as well as reducing organic and suspended matter in contaminated water [19]. However, applying only peat

in wastewater and water treatment is not as effective as combining peat with other materials [17, 18].

It was observed that, in the Mekong Delta, combusted beehive charcoal is often discarded into the environment without collection, treatment, or reuse. Beehive charcoal, also referred to as beehive briquettes, is a widely used domestic fuel. This type of briquette derives its name from its characteristic honeycomb-like structure. Combusted beehive charcoal residues contain aluminum oxide and iron oxide because the clay is used to produce them to increase adhesion and shaping. Materials containing metal oxides can adsorb nutrients such as PO_4^{3-} relatively effectively [20]. Combusted beehive charcoal residues can be reused as a substrate in artificial wetlands alongside other materials such as sand, gravel, etc., to reduce water pollution [10]. Moreover, our results show that the adsorbent mixture of peat soil and beehive charcoal residues can treat wastewater more effectively than sand.

3.2. WASTEWATER TREATMENT EFFICIENCY OF BIOLOGICAL TANKS PLANTED WITH HYDROPONIC VEGETABLES

In this experiment, wastewater was first treated in tanks 2a and 2b, then flowed into tanks 3a and 3b, tanks 4a and 4b. Tanks 3a, 3b, 4a, and 4b maintained normal water storage conditions but did not contain any hydroponic plants. After passing through tanks 2a and 2b, substances in the wastewater were naturally decomposed and assimilated by algae. This experiment evaluated the reduction in pollutant concentrations in tanks with and without hydroponic plants. Hydroponic vegetables in the tanks also significantly absorb nutrients in wastewater. In the treatments with hydroponic vegetables, the treatment efficiencies for BOD_5 and COD were 32.76–38.80% and 34.04–39.85%, respectively. In contrast, the treatments without hydroponic plants showed much lower efficiencies, with BOD_5 and COD reductions of only 10.81–14.21% and 9.47–15.17%, respectively (Table 5).

In terms of nutrients, the capacity of hydroponic vegetables to remove nitrogen and phosphorus was very high, reaching 45.54% (for TP) and 41.30% (for TKN) in CWS with sand and hydroponic vegetables. In treatments without hydroponic vegetables, the treatment efficiency was low, 10.81–14.21% for BOD_5 , 9.47–15.17% for COD, 9.94–10.98% for TP and 10.51–12.14% for TKN. This shows the role of hydroponic plants in the system to absorb substances in wastewater significantly. This result is also like the studies using hydroponic plants for wastewater treatment [11, 21]. It is also the reason that in phytoremediation using aquatic plants, emergent, submersed, or floating plants are grown to remove nutrients efficiently [13, 22].

Water from the catfish pond contains high levels of organic matter and nutrients that will cause pollution when discharged into receiving water sources. Hydroponic plant systems have remediation potential that can serve the dual goals of reducing pollution from catfish farming and decreasing the need for commercial fertilizers [23]. In our experiment

2, hydroponic vegetables have absorbed and removed nutrients in wastewater. Especially, the treatment efficiency of hydroponic vegetables in tanks 3b and 4b is the highest (45.54% for TP and 41.30% for TKN). Moreover, hydroponic vegetables in tanks 3b and 4b grow better than in tanks 3a and 4a. This may be due to the higher content of organic compounds N and P in the wastewater of tanks 3b and 4b, providing plants with more nutrients. The contribution of the plants is the direct removal of nutrients through both direct uptake and the creation of a conducive environment for microorganisms that use nitrogen and phosphorus as nutrients [24]. In addition, hydroponic systems also produce considerable biomass of vegetables, which can be utilized for different purposes as food.

Table 5

Efficiency of the treatment system with and without hydroponic vegetables

Treatment	Parameter	BOD ₅	COD	TP	TKN
CWS with adsorbent and hydroponic vegetables	C_{2a}	12.73	17.04	3.02	7.44
	C_{4a}	8.56	11.24	2.01	4.88
	H	32.76	34.04	33.44	34.41
CWS with adsorbent and no hydroponic vegetables	C_{2a}	18.97	25.34	3.22	10.30
	C_{4a}	16.92	22.94	2.90	9.05
	H	10.81	9.47	9.94	12.14
CWS with sand and hydroponic vegetables	C_{2b}	93.81	142.62	9.97	57.38
	C_{4b}	57.41	85.78	5.43	33.68
	H	38.80	39.85	45.54	41.30
CWS with sand and no hydroponic vegetables	C_{2b}	92.71	140.66	9.84	57.64
	C_{4b}	79.54	119.32	8.76	51.58
	H	14.21	15.17	10.98	10.51

C is concentration, mg/dm³, and H is treatment efficiency, %.

3.3. TREATMENT EFFICIENCY OF THE TREATMENT SYSTEM OPERATING CONTINUOUSLY AND CYCLICALLY

Aquaculture is an industry that consumes a lot of water. Therefore, the reuse of water after treatment and recirculation during a pond water change is a cost-effective solution. This is an environmental sustainability criterion that is of interest in aquaculture in the Mekong Delta. The treatment system is operated continuously and cyclically to evaluate its applicability and processing efficiency. Moreover, the experiment was carried out to evaluate the stability of the quality of the treated wastewater to ensure that it can be used as a source of water for the catfish farming process. Concentrations of substances at sampling locations and times are presented in Table 6.

Table 6

Efficiency of continuous recirculating wastewater treatment system [mg/dm³]

Sampling site/regulatory standard	Day	BOD ₅	COD	TP	TKN
Catfish pond	1	98.34	148.72	10.71	62.65
	7	99.32	150.58	10.82	62.92
	14	99.22	150.14	10.73	62.89
Tank 5	1	13.52	16.48	2.34	6.91
	7	12.47	16.83	2.43	7.12
	14	13.82	17.41	2.72	7.16
44/2010/TT-BNNPTNT ^a	–	< 30	–	–	–
QCVN 02-20:2014/BNNPTNT ^b	–	< 5 0	< 1 50	–	–

^aCircular about the quality of water supplied to catfish ponds.

^bRegulationsthe wastewater from catfish pond discharged into receiving water sources.

Table 6 shows that the concentration of substances in the wastewater in the catfish pond (initial wastewater) was high. It may cause many environmental impacts if discharged without treatment. However, wastewater after being treated and collected in tank 5 has BOD₅, COD, TKN, and TP content lower than in the catfish pond. The concentration of substances in tank 5 at 3 sampling times (day 1, 7, and 14) was all very low and did not fluctuate much. This shows the stability and treatment efficiency of the CWS, especially the adsorption capacity of materials from a mixture of peat soil and combusted beehive charcoal residues, and the nutrient absorption capacity of hydroponic vegetables. The quality of treated wastewater that is recycled back to the catfish pond meets permissible limits of BOD in Circular 44/2010/TT-BNNPTNT, regulating the quality of water supplied to pangasius ponds issued by the Ministry of Agriculture and Rural Development of Vietnam [25]. Besides, it also meets permissible limits of BOD and COD in QCVN02-20:2014/BNNPTNT, which regulates the wastewater from catfish ponds discharged into receiving water sources [26].

The advantage of CWS in this study is that the adsorbent is easy to fabricate and has stable processing efficiency. The results of the study demonstrate the effectiveness of a wastewater treatment system that integrates adsorbent materials in CWS with the nutrient-uptake capacity of hydroponic vegetables in biological tanks for treating wastewater from catfish ponds.

4. CONCLUSIONS

The catfish farming development in the Mekong Delta implies low-cost and easy-to-operate effluent treatment methods to treat large wastewater volumes. The use of a wastewater treatment system that combines CWS with adsorbent material and biological tanks with hydroponic vegetables to treat wastewater from catfish ponds is low-cost and eco-

friendly. This is a suitable alternative to reduce the loads of organic matter, nitrogen, and phosphorus from effluents. The average efficiency of the wastewater treatment system, determined as the reduction of BOD₅, COD, TP, and TKN exceeded 78%, with the highest decrease being for TKN. The quality of wastewater after treatment not only meets the discharge standards (QCVN 02-20:2014/BNNPTNT) in Vietnam but is also suitable for reuse and re-supply to catfish fishponds (Circular 44/2010/TT-BNNPTNT) regarding BOD and COD. This is an effective and useful solution for farmers in treating catfish pond wastewater in the Mekong Delta region, in Vietnam.

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