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Comparison of Piggery Wastewater Treatment after the Biogas Process by *Cyperus alternifolius* and *Ipomoea aquatica* in a Vertical Subsurface Flow Constructed Wetland System in Vietnam

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ABSTRACT: Vertical subsurface flow constructed wetlands (VSF CWs) have been widely applied as an eco-friendly solution for treating livestock wastewater. This study compared the treatment performance of *Cyperus alternifolius* and *Ipomoea aquatica* planted in VSF CWs treating piggery wastewater after biogas digestion. Two laboratory-scale VSF CW systems (50 × 50 × 50 cm) with identical media configuration and operational conditions were operated in an intermittent mode with a hydraulic retention time of 3 days over 20 treatment cycles. The VSF CW planted with *C. alternifolius* consistently exhibited higher removal efficiencies for all monitored parameters compared with the system planted with *I. aquatica* ($p < 0.05$). The average removal efficiencies of the papyrus-based system reached 74.2 ± 3.1% for COD, 85.8 ± 3.4% for TSS, 70.9 ± 4.1% for TN, 75.1 ± 5.5% for NH_4^+–N, and 64.7 ± 7.9% for TP, with most effluent concentrations complying with the Vietnamese discharge standard QCVN 62:2025/BTNMT (Column B). In contrast, the VSF CW planted with water spinach achieved lower treatment efficiencies, with average removal rates of 53.9 ± 2.6% for COD, 80.5 ± 5.6% for TSS, 54.6 ± 5.6% for TN, 57.0 ± 8.6% for NH_4^+–N, and 44.5 ± 13.1% for TP, and did not consistently meet discharge limits for nitrogen and phosphorus.

KEYWORDS: Vertical subsurface flow constructed wetlands; *Cyperus alternifolius; Ipomoea aquatica;* piggery wastewater; Vietnam

1. Introduction

Pig farming wastewater has been one of the major sources of serious environmental pollution in rural areas of Vietnam, primarily due to its high concentrations of organic matter, nitrogen, phosphorus, and pathogenic microorganisms [1]. Vietnam is among the leading pig-producing countries in Southeast Asia, with pig farming dominated by small- and medium-scale household farms, where wastewater management remains limited. Although biogas digesters have been widely applied to recover energy and reduce the initial pollution load, biogas effluent still contained high pollutant concentrations exceeding permissible discharge limits [2, 3]. Therefore, further treatment was required before discharge into the environment or reuse.

In recent years, constructed wetlands (CWs) have been considered an environmentally friendly biological treatment solution with low investment and operating costs, well suited to the socio-economic and climatic conditions of developing countries [4, 5]. Among these systems, vertical subsurface flow constructed wetlands (VSF CWs) have been highly regarded for their effective removal of organic pollutants and nutrients [6]. Previous studies demonstrated that VSF CWs were capable of treating domestic, livestock, and craft village wastewater [7–9].

The treatment performance of CW systems largely depended on the plant species employed [10]. Vegetation supplied oxygen to the rhizosphere, absorbed nutrients, created favorable conditions for microbial growth, and stabilized the structure of the filter media. *Cyperus alternifolius* was a commonly used species characterized by fast growth, a well-developed root structure, and strong adaptation to waterlogged conditions [11]. This species had been successfully employed in CW systems treating domestic, industrial, and livestock wastewater [11, 12]. In addition, *Ipomoea aquatica* was a native aquatic plant characterized by ease of cultivation, rapid growth, and high capacity for nitrogen and phosphorus uptake [13]. Earlier studies applied *I. aquatica* in the treatment of domestic wastewater, aquaculture effluents, and swine wastewater [14].

Although many studies evaluated the treatment efficiency of individual plant species in CWs, direct comparative studies on the treatment performance of piggery wastewater after biogas treatment using different plant species under the same VSF CW configuration and operational conditions remained limited. Therefore, this study systematically compared the removal efficiency of key pollutants in piggery wastewater after biogas treatment by umbrella sedge (*C. alternifolius*) and water spinach (*I. aquatica*) in VSF CW systems. The results clarified the role of each plant species in the treatment efficiency of pig farming wastewater and provided a scientific basis for selecting appropriate vegetation in the design and operation of VSF CW systems in Vietnam.

2. Materials and Methods

2.1. Materials.

C. alternifolius and *I. aquatica* were collected from the natural environment in Hung Yen Province, Vietnam. The plants were cultivated in the CW system for two months to allow stable establishment prior to the commencement of the experiment. Pig farming wastewater was collected downstream of a biogas digester from a farm with a capacity of approximately 2,000 pigs in Hung Yen Province, Vietnam (20°47′57.9″N, 105°56′02.0″E). Although the wastewater had undergone anaerobic treatment, the influent still exhibited high levels of organic and nutrient pollution. The concentrations of TSS, COD, TN, and TP exceeded the permitted limits indicated in QCVN 62:2025/BTNMT (Column B) by about 2.30, 3.47, 2.65, and 2.58 times, respectively (Table 1).

Table 1. Characteristics of influent wastewater.

Parameter	Unit	Value	QCVN 62:2025/BTNMT, Column B
COD	mg/l	520.70 ± 22.14	150
TSS	mg/l	230.10 ± 16.19	100
TN	mg/l	158.70 ± 10.12	60
NH_4^+-N	mg/l	52.11 ± 7.54	–
TP	mg/l	36.13 ± 3.38	14

2.2. Experimental setup.

The experiment was conducted under ambient conditions with an average temperature of 27.5 °C, relative humidity of 82%, and an average daily sunshine duration of 12.6 h. A laboratory-scale VSF CW system was established using glass containers with dimensions of 50 × 50 × 50 cm. Each system was filled with filter media arranged in a three-layer structure, consisting of a 10 cm thick yellow sand layer (top layer), a 20 cm thick limestone layer with a particle size of 1 × 2 cm (middle layer), and a 10 cm thick gravel layer with a particle size of 3 × 4 cm (bottom layer). The effluent collection system (outlet/drainage pipe) was installed at the bottom of the tank to collect treated wastewater samples. Two treatments were established according to the plant species: (CW1) the system planted with *Cyperus alternifolius* and (CW2) the system planted with *Ipomoea aquatica*, with a planting density of 18 plants per system. Piggery wastewater after biogas process was introduced into each system at a volume of 30 L per cycle and operated under intermittent conditions. After wastewater loading, the systems were maintained with a hydraulic retention time of 3 days, after which effluent samples were collected, the systems were completely drained, and a new batch of wastewater was supplied for the subsequent cycle. This procedure was continuously repeated for 20 operating cycles to evaluate and compare the treatment performance of the two plant species under the same system configuration and operating regime.

2.3. Data analysis.

Water quality parameters, including TSS, COD, NH_4^+–N, TN, and TP were analyzed in accordance with current Vietnamese standard methods. Specifically, TSS was determined by filtration and drying at 103–105 °C (TCVN 6625:2000). COD was analyzed using the closed reflux dichromate oxidation method (TCVN 6491:1999). NH_4^+–N was determined by the phenate method (TCVN 6179-1:1996). TN was analyzed using the persulfate oxidation method followed by spectrophotometric measurement (TCVN 6638:2000). TP was determined by persulfate oxidation and phosphomolybdate complex formation with spectrophotometric detection (TCVN 6202:2008). The collected data were compiled and statistically analyzed using SPSS software (version 22). An Independent t-test was used to compare the datasets, with $p < 0.05$ considered statistically significant.

3. Results and Discussion

3.1. TSS removal.

The TSS concentration of piggery wastewater after the biogas process had an average value of 230.10 ± 16.19 mg/l, exceeding the allowable limit of QCVN 62:2025/BTNMT, Column B (TSS ≤ 100 mg/l). After treatment using the VSF CW planted with *Cyperus alternifolius* (CW1), the TSS concentration decreased markedly to 32.39 ± 6.98 mg/l, corresponding to an average removal efficiency of 85.82 ± 3.36%, which fully met the discharge standard. In the VSF CW planted with *Ipomoea aquatica* (CW2), the effluent TSS concentration was 44.40 ± 11.07 mg/l, with a removal efficiency of 80.46 ± 5.59%, also complying with the regulation but lower than that of the *C. alternifolius* system ($p < 0.05$). These results indicated that both VSF CW systems were effective in TSS removal; however, the system planted with *C. alternifolius* exhibited higher and more stable treatment performance compared with the system planted with *I. aquatica*. The removal of TSS was largely attributed to filtration mechanisms [15, 16]. This difference could be explained by the dense and deeply distributed root system of *C. alternifolius*, which enhanced the retention and filtration of suspended particles within the filter media, thereby improving TSS removal efficiency in the VSF CW system (Figure 1).

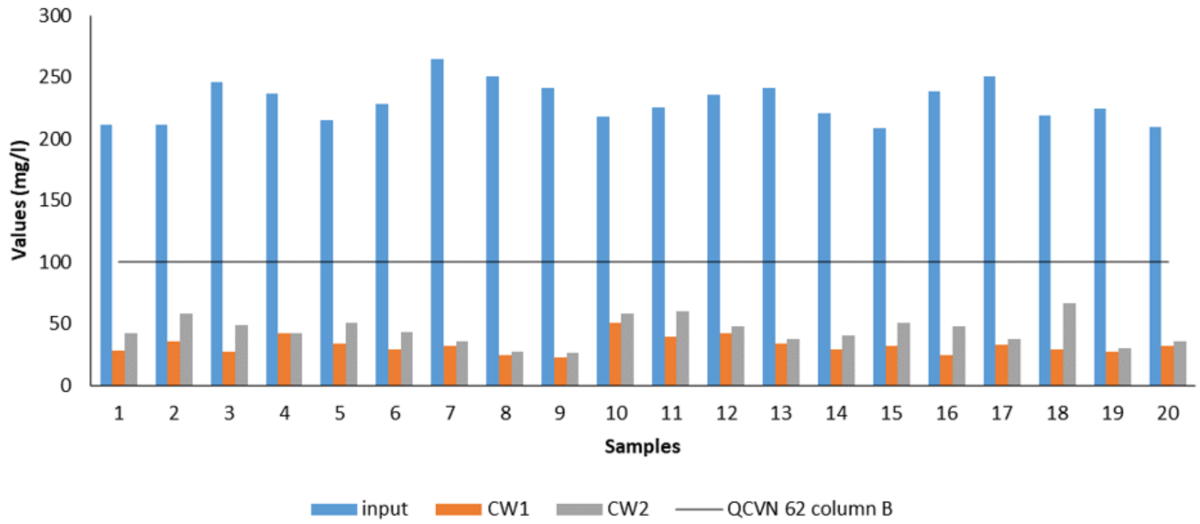

Figure 1. Variation of TSS concentrations in the experimental VSF CW systems.

3.2. COD removal.

The COD concentration of piggery wastewater after biogas process averaged 520.70 ± 22.14 mg/l. After treatment, the COD concentration in CW1 was 134.10 ± 14.13 mg/l, meeting the requirements of QCVN 62:2025/BTNMT, Column B. In contrast, the COD value in CW2 was 239.72 ± 11.42 mg/l, which did not comply with the permitted standard. The COD removal efficiency of *Cyperus alternifolius* (74.18 ± 3.15%) was significantly higher than that of *Ipomoea aquatica* (53.90 ± 2.64%) under the same operating conditions ($p < 0.05$). Organic matter degradation largely depends on rhizosphere microorganisms [9, 17]. This disparity may be ascribed to the robust root system of *C. alternifolius* and its superior ability to improve oxidative conditions in the rhizosphere, thereby promoting the biodegradation of organic compounds (Figure 2).

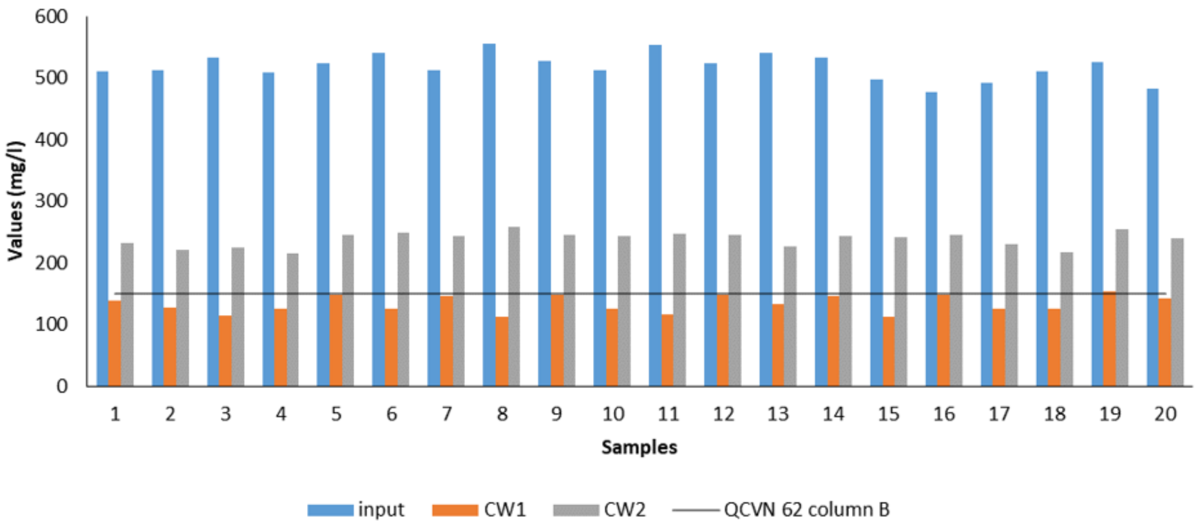

Figure 2. Variation of COD concentrations in the experimental VSF CW systems.

3.3. TN removal.

The TN concentration of piggery wastewater after the biogas process averaged 158.70 ± 10.12 mg/l, which was considerably higher than the allowable limit specified in QCVN 62:2025/BTNMT, Column B (TN ≤ 60 mg/l) (Figure 3). After treatment using the VSF CW planted with *Cyperus alternifolius* (CW1), the TN concentration decreased to 45.92 ± 5.51 mg/l, thereby complying with the discharge standard. In contrast, the TN concentration in CW2 was 71.72 ± 6.68 mg/L, which did not meet the QCVN 62:2025/BTNMT, Column B. These results indicated that the VSF CW planted with *C. alternifolius* achieved significantly higher and more stable TN removal efficiency than the system planted with *I. aquatica* under the same operating conditions ($p < 0.05$). This difference could be explained by the superior oxygen transfer capacity and deeper root development of *C. alternifolius*, which promoted coupled nitrification–denitrification processes as well as nitrogen assimilation into plant biomass, thereby enhancing TN removal in the VSF CW system [18, 19].

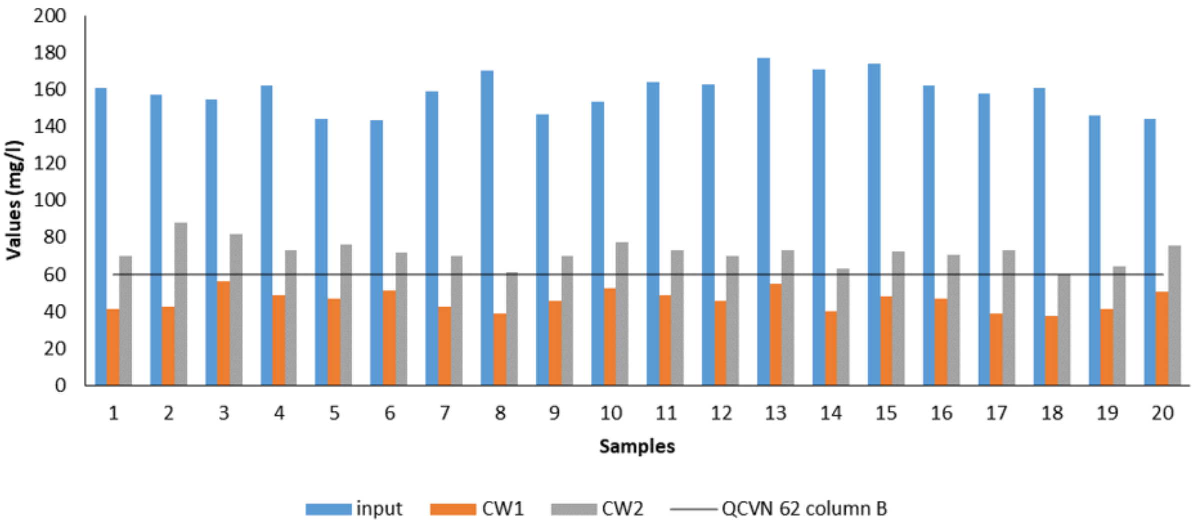

Figure 3. Variation of TN concentrations in the experimental VSF CW systems.

3.4. NH_4^+–N removal.

The results demonstrated a reduction in NH_4^+–N concentrations in both experimental systems. In CW1, the NH_4^+–N concentration decreased to 12.82 ± 2.64 mg/l, whereas in CW2, it remained at 22.10 ± 3.81 mg/l (Figure 4). The removal efficiency achieved by CW1 was 75.10 ± 5.53%, which was significantly higher than that of CW2 (57.01 ± 8.63%) ($p < 0.05$). These findings indicate that the VSF CW planted with *C. alternifolius* provided more effective and stable NH_4^+–N removal compared to the system vegetated with *Ipomoea aquatica*. This difference may be attributed to the enhanced oxygen transfer capacity within the rhizosphere of *C. alternifolius*, which facilitates nitrification processes in the filter media and consequently reduces ammonium concentrations in the wastewater [20]. Additionally, *C. alternifolius* exhibited a greater capacity for NH_4^+–N uptake. In contrast, the lower removal efficiency and higher variability observed in the *I. aquatica* system suggest less stable nitrogen transformation processes under identical operating conditions.

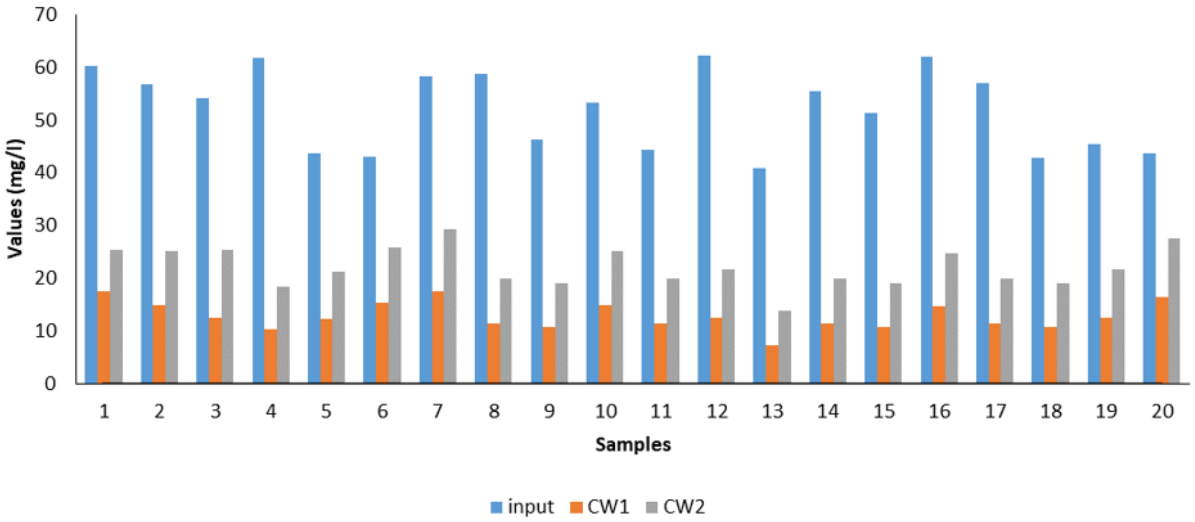

Figure 4. Variation of NH_4^+ concentrations in the experimental VSF CW systems.

3.5. TP removal.

The TP concentration of piggery wastewater after biogas process averaged 36.13 ± 3.38 mg/l, which was considerably higher than the allowable limit specified in QCVN 62:2016/BTNMT, Column B (Figure 5). After treatment using the VSF CW planted with *Cyperus alternifolius* (CW1), the TP concentration decreased to 12.66 ± 2.67 mg/l, corresponding to an average removal efficiency of 64.73 ± 7.86%, meeting the discharge standard. In contrast, the TP concentration in CW2 was 19.93 ± 4.61 mg/l, which failed to meet the regulatory requirement. The removal efficiency in CW2 reached 44.52 ± 13.15%, significantly lower than that observed in CW1 ($p < 0.05$). Phosphorus removal in VSF CWs is primarily governed by plant uptake, adsorption and precipitation within the filter media, as well as retention under favorable redox conditions in the rhizosphere [21]. The superior phosphorus uptake capacity of *C. alternifolius* can be attributed to its extensive root system and stable growth characteristics. Overall, vegetation plays a decisive role in TP removal in constructed wetland systems [22].

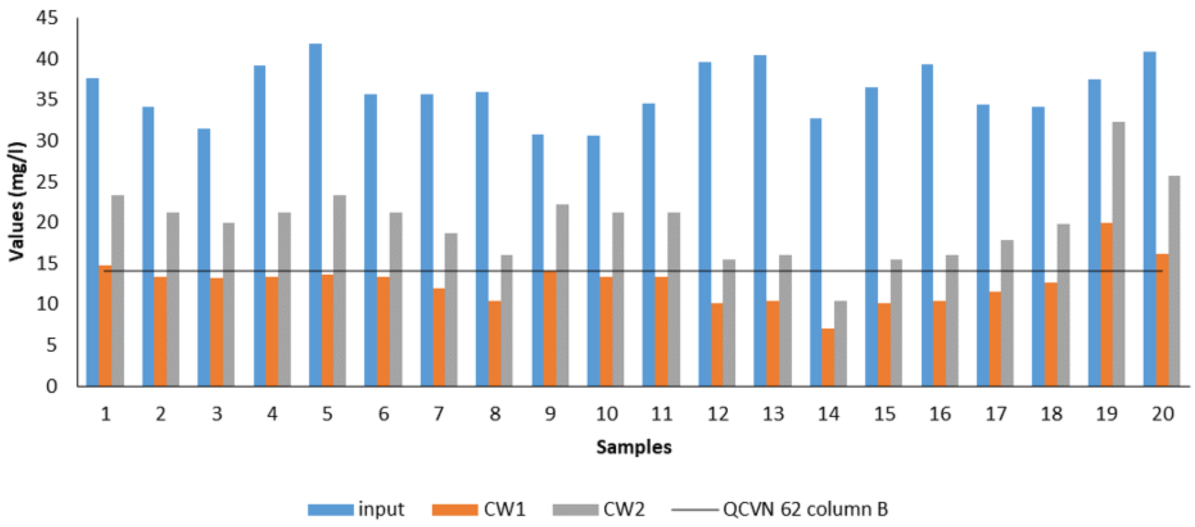

Figure 5. Variation of TP concentrations in the experimental VSF CW systems.

The results indicate that both *C. alternifolius* and *Ipomoea aquatica* are applicable plant species for VSF CW systems treating piggery wastewater after biogas process. However, their treatment performances differed significantly. The VSF CW planted with *C. alternifolius* consistently achieved higher removal efficiencies, and all evaluated parameters complied with QCVN 62:2025/BTNMT, Column B. In addition to its superior treatment performance, *C. alternifolius* shows strong adaptability to the tropical monsoon climate of Vietnam. Its robust growth, dense and deeply developed root system, and high tolerance to organic and nutrient loading make it particularly suitable for long-term operation in constructed wetlands. In contrast, *I. aquatica* is a native and widely cultivated aquatic vegetable in Vietnam. *I. aquatica* exhibited moderate pollutant removal efficiency and greater performance variability, particularly with respect to nitrogen and phosphorus removal, under the same operating conditions. While its good adaptability to local climatic conditions and ease of cultivation are advantageous, the relatively shallow root system and lower oxygen release capacity may limit its effectiveness in treating high-strength livestock wastewater. Nevertheless, *I. aquatica* may still be suitable for low- to medium-strength wastewater, short-term operation, or as a supplementary plant species in multi-stage or hybrid constructed wetland systems commonly applied in rural areas of Vietnam. Overall, *C. alternifolius* is identified as a more promising macrophyte for application in VSF CW systems treating piggery wastewater after biogas process in Vietnam.

4. Conclusions

This study compared the treatment performance of piggery wastewater after biogas process using two aquatic plant species *C. alternifolius* and *I. aquatica*. The results demonstrated that both systems were capable of substantially removing the main pollutants in the wastewater. *C. alternifolius* achieved higher average removal efficiencies for COD, TN, NH_4^+–N, and TP, with effluent concentrations meeting the requirements of QCVN 62:2016/BTNMT, Column B. In contrast, the system planted with *I. aquatica* showed lower treatment performance and did not consistently satisfy discharge standards. Overall, the findings indicate that *C. alternifolius* is a more suitable plant species than *I. aquatica* for application in VSF CW systems treating piggery wastewater after biogas process.

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Author Contribution

Bui Thi Van Nga: Conceptualization, Methodology, Data Analysis, Writing; Chao Rong: Methodology, Data Collection, Data Analysis, Writing.

Competing Interest

The authors declare no competing interests.

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