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Chapter 6
Swine Wastewater Treatment Management in Vietnam: A Sustainable Approach Using Constructed Wetlands

Thi Thuong NGUYEN

Abstract: Pig farming is a vital and longstanding industry in Vietnam, making a significant contribution to the nation's GDP. As the sixth-largest pork producer globally and second in Asia after China, Vietnam is among the top 10 countries in both pork production and consumption. Pig farming constitutes approximately 71% of Vietnam's livestock sector and accounts for 47% of employment within the industry. However, alongside its economic benefits, pig farming poses substantial environmental challenges. One of the primary issues is swine wastewater, which contains high levels of environmental pollutants, including nitrogen (N), phosphorus (P), organic matter, total suspended solids (TSS), and pathogenic microorganisms. If not properly managed, these pollutants can lead to serious environmental degradation. In Vietnam, approximately 80% of swine wastewater is managed through biogas systems. While biogas digestion is the dominant treatment method, it often fails to reduce pollutant levels to meet Vietnamese discharge standards. These challenges underscore the need for more efficient and effective wastewater treatment solutions. Constructed wetlands (CWs) offer a promising solution for enhancing pollutant removal from swine wastewater. CWs are advantageous due to their low cost, simple operation and maintenance, and high biodiversity value. This presentation explores the benefits and applicability of CWs for

sustainable swine wastewater treatment. A case study is highlighted, utilizing CWs filled with white hard clamshells (WHC) and planted with Ubon paspalum grass to remove P from anaerobically digested swine wastewater. The study demonstrated effective P removal in CWs with clamshells as the substrate. The mechanisms of P removal, as well as the study's key findings and limitations, are discussed. To improve swine wastewater treatment efficiency using CWs, strategies such as optimizing design, substrate, and plant selection are recommended. Combining CWs with other treatment processes can also enhance effectiveness. Utilizing recycled materials and economically valuable plants in CWs can further improve pollutant removal and increase the overall value of the systems.

Keywords: *pig farms, swine wastewater, treatment technology, constructed wetlands, sustainable approach*

1. Pig Farming in Vietnam

(1) Pig Production in Vietnam

Pig farming holds a central place in Vietnam's traditional livestock industry, being one of the country's most significant agricultural practices. The rising standard of living and growing middle class in Vietnam have fueled an increase in meat consumption, with pork demand especially surging. Currently, Vietnam's annual pig production has reached approximately 28 million heads, positioning the country as the sixth-largest pork producer globally and the second-largest in Asia, just behind China. Pork production alone contributes about 71% to Vietnam's livestock sector and supports around 47% of employment in the industry.

The pig farming sector in Vietnam is geographically concentrated, with primary production occurring in key agricultural regions. These include the Red River Delta, the Northern Mountains, the North Central and Central region, and the Mekong River Delta (as shown in Figure 1). Each of these regions supports substantial numbers of pig farms, due to favorable conditions for large-scale animal husbandry and proximity to population centers with high demand for pork products.

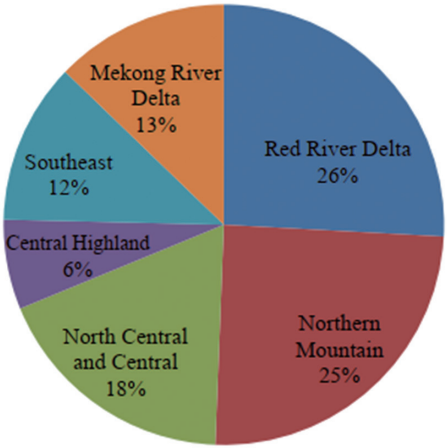


Figure 1. Total pig production by area in 2017. Source: Dao 2021

Despite its scale and economic importance, Vietnam's pig production has been highly susceptible to disease outbreaks, which have periodically disrupted the domestic pork supply. In 2016, Vietnam's pig population was estimated at 29.08 million. However, by 2017, a significant foot-and-mouth disease (FMD) outbreak struck, reducing the population to 27.41 million (Qui and Guntoro 2019; Han 2022). Recovery efforts were quickly implemented, and in 2018 the swine population rose by 1.4 million, bringing it back to 28.81 million. Unfortunately, just as the recovery began, African swine fever (ASF)

emerged and led to severe losses across the sector. By 2019, ASF had decimated pig stocks, bringing the national total down to 20.21 million heads. Since that period, the government and pig farming industry have made concerted efforts to control ASF and rebuild the pig population. As a result, the situation has shown signs of gradual improvement. By June 2021, Vietnam's swine population had increased by 11.6% compared to the previous year, indicating a steady recovery process (Sharifuzzaman et al. 2024).

Pork has long been the most popular and widely consumed meat in Vietnam, accounting for approximately 74% of the country's total annual meat production. Factors such as rising household incomes and a growing population have consistently fueled increased pork demand. This upward trend in pork consumption has been especially notable in recent years. For instance, between 2016 and 2019, per capita pork consumption rose from 25.3 kg to 26.5 kg per year. In 2021, it stood at 26.93 kg per year, with projections suggesting it will increase to 32.72 kg per year by 2029. In 2016 alone, domestic pork consumption reached 2.5 million tons, representing the output of approximately 35.76 million pigs (Sharifuzzaman et al. 2024). While domestic demand remains the primary driver of pork production, a portion of Vietnam's pork is also exported. In 2016, about 13,695 tons of live pork, equating to 195,643 pigs, were shipped to neighboring countries. This export activity, though modest compared to domestic consumption, highlights Vietnam's role as a regional player in the pork market. Between 2017 and 2023, Vietnam consistently ranked among the top 10 pork-producing and consuming countries worldwide, reflecting both the industry's resilience and the Vietnamese population's sustained preference for pork as a staple protein (Sharifuzzaman et al. 2024).

(2) Types of Pig Farms

The Vietnam pig farming sector can be broadly categorized into two primary types: household-scale farming, often referred to as traditional farming, and farm-scale farming, which is characterized as industrial farming. Household-scale farming comprises approximately 4 million households, each managing between 1 and 100 pigs on relatively small plots of land. This type of farming is frequently integrated with other agricultural activities, such as fish farming or crop cultivation, creating a diverse and sustainable farming model. Household farms account for about 65% to 70% of the total pig population in Vietnam, contributing approximately 55% to 60% of the overall pork production in the country. Despite the significant role that smallholder farms play in the pig sector, there is a notable trend of gradual decline in this farming scale (Dao 2021). Nevertheless, even as the number of smallholder farms decreases, it is anticipated that their influence on Vietnam's pork sector will persist for several more decades, shaping the dynamics of pork production and market trends.

On the other hand, industrial farming in Vietnam consists of around 5000 farms that manage more than 100 pigs each, operating on larger tracts of land. These industrial farms are typically categorized into two types: sow farms, which focus on breeding and raising newborn pigs, and market hog farms, which raise pigs for sale. Some farms also adopt a mixed approach, combining both sow and market hog production within the same operation. Collectively, industrial farms represent about 30% to 35% of the total pig population, contributing around 40% to 45% of the country's pork yield. However, the development of this industrial farming scale remains unstable due to various challenges and uncertainties within the sector, which may impact its growth and sustainability in the future.

(3) Water Sources Used in Pig Farming

In Vietnam, pig farms utilize various sources of water for drinking and cleaning purposes, including drilled well water, tap water, and water from natural sources such as ponds, lakes, rivers, and streams. Drilled well water serves as the primary source of drinking water for pigs, accounting for over 80% of their water supply. This high reliance on well water can be attributed to its accessibility and reliability. In addition to its role in providing drinking water, drilled well water is also predominantly used for cleaning pig pens, ensuring a hygienic environment for the animals. In contrast, only about 12% of farmers rely on tap water for their livestock. This limited usage may be due to factors such as cost and availability, with many farmers finding well water to be a more practical option. Furthermore, some farmers turn to natural water sources like ponds, lakes, rivers, and streams for both drinking water and cleaning purposes. While these sources are utilized, their usage may vary among farms, highlighting the adaptability of farmers in sourcing water for their operations.

Table 1. Water sources used in pig farming in Vietnam

1. Source of drinking water	
Drilled/dug well-water	86.75%
Tap water	12.05%
Water from ponds, lakes, rivers and streams	1.20%
2. Water for cleaning	
Drilled/dug well-water	90.36%
Tap water	8.43%
Water from ponds, lakes, rivers and streams	1.20%

Source: Nguyen et al. 2018

2. Environmental Impact of Pig Farms and Pig Manure Treatment Management

(1) Environmental Impact

Pig farming is a major contributor to agricultural profits, but its environmental and public health impacts are cause for concern. The expansion of pig production has amplified these concerns globally, with effects on climate, soil, water, air quality, and health. As demand for pork grows, the environmental footprint of pig farming intensifies. The high density of pig farms leads to concentrated waste that contributes to global warming, land degradation, air and water pollution, and biodiversity loss. These issues are particularly significant in regions with limited regulations on waste disposal and environmental protection, including Vietnam.

Wastewater from pig farms contains an array of pollutants, such as N, P, and TSS, organic matter, and harmful pathogens. The N and P from pig farming are major contributors to nutrient pollution, leading to eutrophication in water bodies and posing a risk to aquatic life and biodiversity. High levels of these pollutants disrupt local ecosystems, leading to the loss of aquatic species diversity and the collapse of fragile food webs. In Vietnam alone, roughly 167,960 tons of N and 195,040 tons of P from pig farms are introduced into public water sources every year, threatening both human health and environmental stability. However, regulation remains minimal: small and medium-sized farms can discharge waste without limits on parameters such as biological oxygen demand (BOD) or chemical oxygen demand (COD), exacerbating water quality issues (Dang et al. 2020).

Air pollution from pig farming is also concerning. The sector is

responsible for significant emissions of greenhouse gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Methane and nitrous oxide are potent greenhouse gases, contributing to climate change and global warming, while ammonia (NH_3) emissions from manure can lead to acid rain and respiratory issues. Furthermore, pig farms generate noise pollution, which affects both animals and farm workers. Noise levels on pig farms can be considerable, with feeding times producing decibel levels as high as 71.95 ± 1.41 dB, which can impact animal stress and welfare (Dang et al. 2020).

Soil degradation is an additional concern, with each pig producing about 4 kg of manure per day. Manure contains high levels of N, P, and other nutrients. When improperly managed, this nutrient overload can lead to soil nutrient imbalances, acidification, and contamination of nearby land and water bodies. Manure is often used as fertilizer, but without adequate control, it can cause excessive nutrient buildup, damaging crops, and altering soil chemistry.

Human and animal health are also at risk from pig farming practices. Manure from pigs often harbors harmful bacteria, viruses, and chemical residues, which may enter the environment and affect surrounding communities. This contamination can result in health issues like antibiotic resistance, zoonotic diseases, and respiratory problems. In areas where biosecurity practices are weak, such as in small-scale, densely populated pig farms, disease spread is particularly difficult to control. Additionally, these farms are often breeding grounds for swine flu and other zoonotic infections, posing risks to farm workers and surrounding communities (Dang et al. 2020).

(2) Pig Manure Treatment Management

A pig produces an average of 2.5 kg of manure and 5 liters of urine

per day. In Vietnam, where there are approximately 28 million pigs, this amounts to around 25.6 million tons of manure and 51.1 billion liters of urine annually. However, the volume of solid and liquid waste generated by pig farming varies depending on the practices used for sows versus market hogs. Sow farming typically uses less water, resulting in manure primarily being collected as solid waste. In contrast, most market hog farms and households use large amounts of water. On average, Vietnamese farmers use approximately 30 to 40 liters of water per pig per day for cooling and cleaning the barns. This high-water usage dilutes much of the manure and urine, transforming it into liquid waste. With Vietnam's farming structure consisting of roughly 10% sows and 90% market hogs, the country produces about 2.6 million tons of solid waste and 367.9 million tons of liquid waste annually (Nguyen 2024). Table 2 compares the characteristics of wastewater from pig farms in Vietnam with effluent standards, showing that pollutant concentrations in pig farm wastewater significantly exceed permissible limits. Consequently, proper treatment of wastewater is essential before its discharge into the environment.

Table 2. The characteristics of swine wastewater and the Vietnam effluent standards

Parameter	**Influent**	**Vietnamese standard (QCVN 40:2011/BTNMT)**	
		A column	**B column**
pH	6.5-8	6-9	5.5-9
BOD (mg/L)	1500-3100	30	50
COD (mg/L)	2200-5200	75	150
SS (mg/L)	1000-3200	50	100
TN (mg/L)	200-400	20	40
TP (mg/L)	30-60	4	6
Coliforms (MPN/100mL)	10^4-10^5	3000	5000

Note: Column A specifies the value of pollution parameters in livestock wastewater when discharged into water sources used for domestic water supply purposes. Column B specifies the value of pollution parameters in livestock wastewater when discharged into water sources not used for domestic water supply purposes.

In pig farming, solid waste includes manure, garbage, bedding, leftover food, animal carcasses, and inorganic waste such as needles, packaging, and bottles. However, the majority of waste generated in the farming process that requires treatment and reuse is pig manure. Pig manure is primarily treated using three methods: as input for biogas systems, composting for agricultural purposes, and fish feed (as shown in Table 3). Among these, biogas is the most common method, accounting for 80% of manure treatment. However, there are significant differences among household groups, with some households applying all three waste treatment methods.

The use of biogas for waste treatment is notably higher among medium- and large-scale farms compared to small-scale farms. Biogas is considered an effective method for treating livestock waste as it helps maintain farm hygiene and allows the gas produced to be used for heating. Additionally, due to the high demand for organic fertilizers in Vietnam, solid pig manure is frequently collected, composted, and applied to farmland (Nguyen et al. 2018).

Regarding the treatment of inorganic waste in pig farming, nearly 94% of households dispose of it together with household waste. A small number of households bury inorganic waste in pits or collect it for recycling.

Table 3. Solid and liquid waste treatment from pig farms

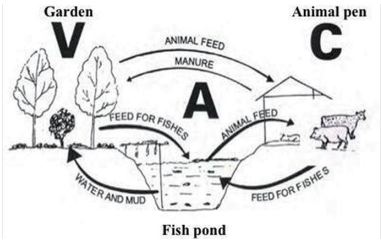
Solid waste treatment	
1. Pig manure treatment	
Biogas	80.72%
Composting	15.66%
Feeding fish	13.25%
2. Treatment of inorganic waste	
Treated together with household waste	93.98%
Buried in a dug hole	3.61%
Collected and sent for recycling	2.41%
Liquid waste treatment	
VAC	10.84%
Biogas	79.52%
Discharge directly into canals	21.69%

Source: Nguyen et al. 2018

For the treatment of liquid waste, pig farms currently employ three main methods: using the VAC model (recycling wastewater for irrigating garden plants and discharging it into fishponds), processing it through biogas systems, and directly discharging it into canals (as outlined in Table 3). Among these methods, direct discharge into canals is not a biosafe practice in livestock farming, as it contributes to environmental pollution and poses a risk of disease transmission among pigs in surrounding areas. Similar to pig manure treatment, biogas systems are the predominant method for treating liquid waste, used by 79.52% of households. Wastewater treatment practices vary across households, with some using all three methods. The average proportion of households discharging wastewater directly into canals is

about 21.69%. However, this figure is significantly higher among small-scale livestock households, where approximately 43.10% discharge wastewater directly into canals.





A) B)

Figure 2. A) Small biogas treatment; B) Internal nutrient flows between components in the integrated VAC (Vuon -Ao -Chuong) system in Vietnam. Source: Author

Swine wastewater in Vietnam is predominantly treated using biogas systems. However, even after undergoing this treatment, the wastewater frequently fails to comply with Vietnamese discharge standards. As shown in Table 4, the characteristics of swine wastewater post-anaerobic biogas treatment indicate that pollutant concentrations remain high, exceeding permissible discharge limits. Therefore, further treatment is essential to achieve compliance with environmental regulations.

Table 4. Characteristics of swine wastewater after biogas treatment

No.	Parameter	Unit	After anaerobic treatment	Vietnamese discharge standard QCVN 40:2011/BTNMT	
				A column	B column
1	Temperature	^{o}C	30.5 ± 0.02	40	40
2	pH		6.8 ± 0.05	6–9	5.5–9.0
3	COD	mg/L	585.35 ± 1.02	75	150
4	BOD	mg/L	380.0 ± 1.0	30	50

5	TN	mg/L	298.36 ± 1.58	20	40
6	TP	mg/L	50.59 ± 0.02	4	6
7	SS	mg/L	302.67 ± 3.06	50	100
8	Coliforms	MPN/100mL	$9.2x10^5$ ± 44.44	$3x10^3$	$5x10^3$

Source: Ho et al. 2021

3. A Sustainable Approach Using Constructed Wetlands for Swine Wastewater Treatment

CWs are emerging as an effective and sustainable solution for treating swine wastewater, leveraging natural processes to achieve wastewater purification. Unlike traditional treatment systems, CWs leverage the ecological functions of wetland vegetation, soils, and microorganisms to remove pollutants through a combination of biological, physical, and chemical processes. CWs offer numerous advantages, including high effectiveness in removing various contaminants such as nutrients and pathogens, and they are also relatively easy to operate and maintain. Their designs can be tailored to suit specific treatment needs, making them versatile for various agricultural contexts. Moreover, CWs are cost-efficient compared to traditional treatment systems, as they often require less energy and chemical inputs, thereby reducing operational costs. Figure 3 illustrates the biogeochemical mechanisms involved in CWs, highlighting how pollutants are removed through a synergy of physical filtration, chemical transformations, and biological interactions. By utilizing these natural processes, constructed wetlands not only improve water quality but also contribute to environmental sustainability, making them a compelling choice for swine wastewater management.

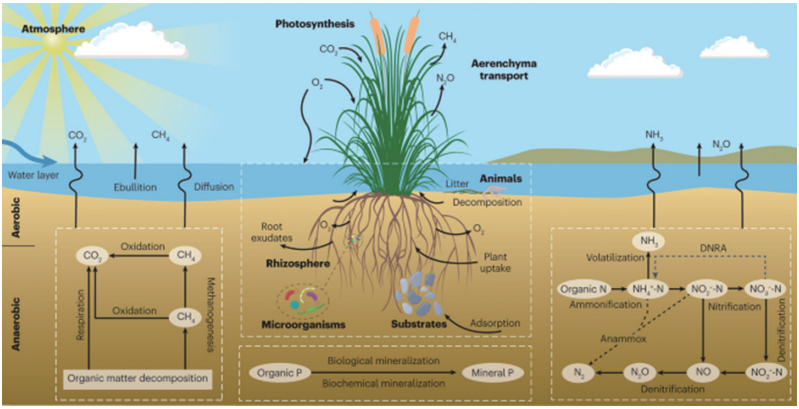


Figure 3. Biogeochemical mechanisms in constructed wetlands.
Source: Wu et al. 2023

CWs have been implemented in many countries to treat various types of wastewaters, including swine wastewater. Table 5 presents the performance of CWs in treating swine wastewater in Vietnam and several other countries.

Table 5. Performance of CWs for swine wastewater treatment in Vietnam and several countries

Country	Type of CWs	Substrate	Plant	HRT	Treatment performance	Reference
Mexico	Horizontal subsurface Flow CWs	Gravel	T domingensis, Eleocharis cellulosa	71 hours	91-92% Zn 100% Cu	Cortes-Esquivel et al., 2012
Spain	CWs Connected in Series	Coarse gravel, sand	P. australis, Suaeda vera	21 days	80% NH_4-N 30% PO_4-P	García-Valero et al., 2024
USA (North Carolina)	Free water surface CWs	Clay, loamy sand topsoil	Bulrushes, cattails		85% NH_4-N 85% TN 25-38% TP	Stone et al., 2002

Mexico	Horizontal subsurface flow CWs in Series	Red volcanic rock and yellow sand	Typha sp. and Scirpus sp	5-10 days	76-80% COD 33–80% TKN 29-91% NH_3-N 30-91% TP	De La Mora-Orozco et al., 2018
USA	Marsh–pond–marsh CWs		T. latifolia, Schoenoplectus americanus	12 days	35–51% TSS 30–50% COD 37–51% TN 13–26% TP	Poach et al., 2004
Ireland	Integrated CWs	Washed rough aggregate	Glyceria maxima	7 days	98–99% NH_4-N	Harrington et al., 2012
Japan	Multistage Subsurface Flow Wetland Systems	Pumice stone (Super sol)	Reed		98% BOD 94% COD 98% SS 71% TN 90% TP	Hayama Kazuyuki, 2017
Vietnam	Multistage Subsurface Flow Wetland Systems	Gravel	Grass		94% TSS 87% BOD 82% COD 66% TN 43% TP 99% Coliforms	Hayama Kazuyuki, 2021
Vietnam	Vertical Flow CWs	Gravel, clay	Cyperus involucratus		55% COD 75% BOD 82 % SS 76% NH_3-N	Ho et al., 2021
Vietnam	Hybrid CWs (Vertical CW+Horizontal CW)	Gravel	Vetiveria zizanioides, Cyperus involucratus, Dracaena sanderiana	30 days	99% COD 98% BOD 89% SS 88% TN 99% Coliforms	Ho et al., 2021

CWs have been employed to remove various pollutants from swine wastewater, including heavy metals, N, P, COD, BOD, TSS, and coliforms. While CWs are effective in removing coliforms, organic matter, and N, their removal efficiency for P remains low without the use of high-capacity sorption filter materials. Therefore, further research aimed at enhancing phosphorus removal from swine wastewater should be conducted intensively.

4. A Case Study: Phosphorus Removal from Anaerobically Digested Swine Wastewater Using CWs Filled with Clamshells

In this chapter, I will introduce a case study on the use of CWs filled with clamshells to remove P from anaerobically digested swine wastewater. The findings from this research were published in Bioresource Technology (Nguyen et al. 2020).

(1) Background

Swine wastewater contains high concentrations of N, P, and organic matter. Even after anaerobic biogas treatment, these concentrations remain elevated, often exceeding discharge standards. While N and organic matter can be effectively removed by CWs, the efficiency of P removal remains low. Since P is a key contributor to eutrophication, its removal from anaerobically digested swine wastewater is crucial for protecting water bodies.

Substrates are widely recognized as playing a key role in P removal in CWs through processes such as sedimentation, filtration, precipitation, and adsorption. Therefore, selecting substrates with strong filtration and adsorption capacity, along with high ecological activity to support the growth of microorganisms and plants, is essential. Additionally, to minimize CW system costs, substrates should ideally be locally abundant materials that incur little or no expense. Recently, with the rapid development of the marine shellfish industry, clamshells have emerged as a by-product, creating significant challenges for solid waste disposal. Recycling this solid waste into a valuable material would not only mitigate its environmental impact but also enhance CW effectiveness. Clamshells, composed mainly of

calcium carbonate ($CaCO_3$), are a non-hazardous material. Their $CaCO_3$ content is comparable to that of limestone, a widely used substrate in CWs for wastewater treatment. Previous studies have investigated the use of various seashells, such as cockle shells (Kim et al. 2018) and scallop shells (Yeom and Jung 2009), as phosphate adsorbents and have demonstrated their effectiveness in retaining P. However, to our knowledge, no studies have explored clamshells as a substrate for P removal from swine wastewater, and their application in CWs remains limited.

To increase the economic value of CWs, this research also incorporates Ubon paspalum grass, commonly used as feed on dairy farms in Vietnam. This study aims (1) to evaluate the effectiveness of clamshell-based CWs in removing P from swine wastewater, (2) to clarify the pathways involved in P removal, and (3) to estimate the lifespan of the clamshell-based substrate in CWs.

(2) Methodology

The lab-scale CWs were established in a greenhouse located in Yen Hoa Ward, Cau Giay District, Hanoi, Vietnam. The system consisted of four horizontal sub-surface flow-constructed wetland units (HSSF-CWs). Each CW unit was constructed from stainless steel in a rectangular shape, with dimensions of 68.5 cm in length, 33.0 cm in width, and 45.0 cm in height. The layout of the CWs is shown in Figure 4. HSSF-CW1 and HSSF-CW2 were filled with WHC, while HSSF-CW3 and HSSF-CW4 were filled with yellow sand, serving as a comparison for P removal efficiency. HSSF-CW1 and HSSF-CW3 were planted with Ubon paspalum grass.

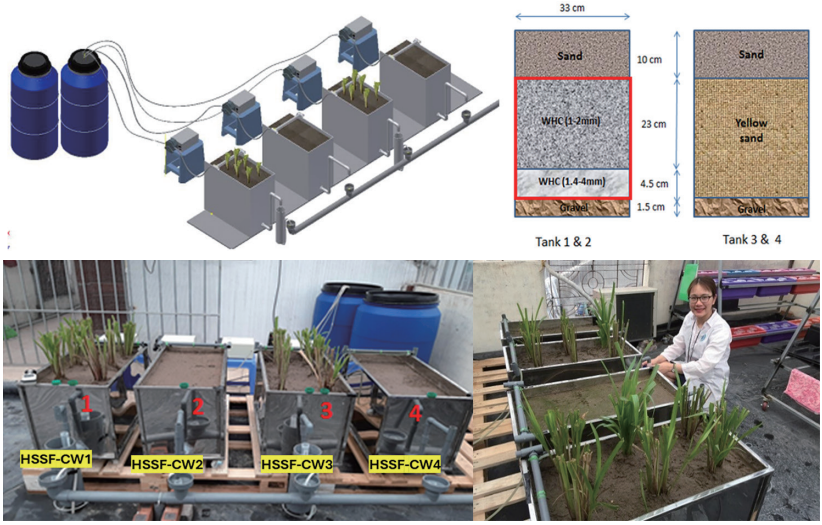


Figure 4. CW systems. Source: Author

Synthetic anaerobically digested swine wastewater containing 12.5 mg P/L and 125 mg NH_4-N/L was introduced into the CWs using four peristaltic pumps. The experiment was conducted in continuous mode with an HRT of 5.4 days. Water samples were collected for analysis of P and other water quality parameters, with a total of 705 water samples collected. Substrate and plant samples were also taken before and after treatment to analyze P accumulation. In each CW, three substrate and three plant samples were collected, resulting in a total of 33 substrate samples and 27 plant samples. P in microbial biomass was determined using an extraction method. All analyses were performed in triplicate, and mean values were recorded.

(3) Results and Discussion

1) Phosphorus Removal

Figure 5 shows the inlet and outlet P concentrations observed throughout the experimental period. In the clamshell-based CWs, P concentrations remained below the Vietnamese effluent discharge standard of 6 mg/L (Column B) over the entire 117-day operation period. However, in the yellow sand-based CWs, P concentrations exceeded this standard after 20 days in the unplanted CW and after 45 days in the planted CW. Additionally, P concentrations in the planted CWs were consistently lower than in the unplanted CWs throughout the experiment.

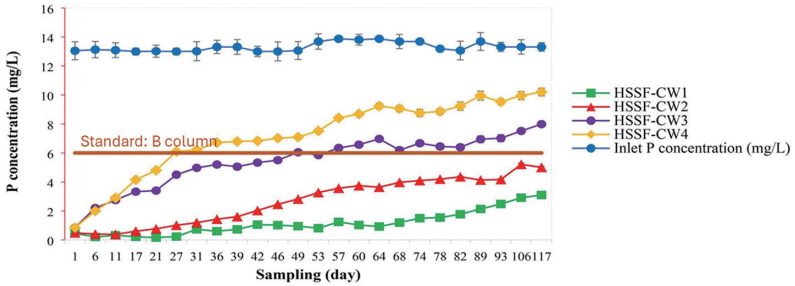


Figure 5. The inlet and outlet P concentration during the experimental period. Source: Nguyen et al. 2020.

The average P removal efficiencies observed in HSSF-CW1, HSSF-CW2, HSSF-CW3, and HSSF-CW4 throughout the experimental period were 89.9%, 78.8%, 57.2%, and 44.4%, respectively (Table 6). The WHC-based CWs (78.8–89.9%) achieved significantly higher P removal efficiencies than the yellow sand-based CWs (44.4–57.2%). Furthermore, the P removal efficiencies in HSSF-CW1 and HSSF-CW2 using WHC media were comparable to or even exceeded those reported in other CWs treating anaerobically digested swine wastewater, including paddy soil-filled CWs (78.2–89.8%; Luo et al. 2017), CWs with gravel, coarse sand, and zeolite (61%; Borin et al. 2013), and CWs

with silty sand and compacted clay (less than 50%; Hunt et al. 2002). Conversely, the yellow sand-based HSSF-CW3 and HSSF-CW4 showed lower P removal efficiencies compared to these studies, underscoring the superior effectiveness of WHC as an adsorptive/reactive medium for P removal over yellow sand and other conventional substrates.

Table 6. The phosphorus treatment performance of the HSSF-CWs.

Parameter	Unit	HSSF-CW1	HSSF-CW2	HSSF-CW3	HSSF-CW4
Inlet P concentration	mg/L	13.3 ± 0.4	13.3 ± 0.4	13.3 ± 0.4	13.3 ± 0.4
Inlet P loading rate	$g/m^2/d$	0.35 ± 0.02	0.39 ± 0.05	0.38 ± 0.03	0.40 ± 0.02
Outlet P concentration	mg/L	1.34 ± 0.95	2.94 ± 1.66	5.66 ± 1.79	7.48 ± 2.55
P removal rate	$g/m^2/d$	0.32 ± 0.03	0.31 ± 0.08	0.22 ± 0.05	0.19 ± 0.09
P removal efficiency	%	89.9 ± 7.1	78.8 ± 12.3	57.2 ± 13.1	44.4 ± 18.7

Source: Nguyen et al. 2020

The Ubon paspalum grass significantly contributed to P removal from swine wastewater, as demonstrated by higher P removal rates in planted systems compared to unplanted systems. Specifically, the data revealed an increase in P removal efficiency of 3.1% in CWs utilizing WHC and a notable increase of 11.0% in CWs based on yellow sand. These findings align with a previous study by Liu et al. (2012), which documented that CWs with vegetation achieved P removal rates that were, on average, 12% higher than their unplanted counterparts.

To assess the applicability of WHC-based CW systems for P removal from swine wastewater under practical conditions, a batch experiment was conducted to compare the P removal efficiency of WHC using both real and simulated wastewater. Results showed that the P

removal efficiency of WHC in real wastewater was 75.6%, only 10.0% lower than in simulated wastewater. This indicates that the negative impacts in real wastewater are within an acceptable range, making the WHC-based CW system feasible for practical implementation. Furthermore, this study was designed to focus on P removal in CWs, however, swine wastewater contains other pollutants, such as organic matter, N and TSS. Thus, a real treatment system typically involves a treatment train comprising multiple stages. The primary treatment stage (e.g., screening, filtration, coagulation) effectively removes TSS, while the secondary treatment stage (e.g., activated sludge, membrane bioreactor) significantly reduces organic content. Consequently, CWs can serve as a tertiary or polishing stage to enhance P removal with minimal interference from TSS or organics.

2) Substrate Sorption

In this study, the effectiveness of P retention by different substrates used in CWs was also examined. The results, as detailed in Table 7, indicated significant retention capacities for both WHC and yellow sand, with retention amounts of 5,885.98 mg and 6,124.6 mg in HSSF-CW1 and HSSF-CW2, respectively, and 3,462.82 mg and 2,180.3 mg in HSSF-CW3 and HSSF-CW4. Additionally, further analysis revealed that the P content remaining in the WHC substrate after being used in CWs ranged from 74 to 77 mg/kg. This level of P content is comparable to that found in spent blast furnace granulated slag in vertical flow CWs, which contains approximately 70 mg/kg (Korkusuz et al. 2007).

Table 7. P removal by substrate sorption in CWs during the experiment

CWs	Substrate	Substrate sorption		
		Mass of substrate (g)	P content in spent substrate (mg/g)	P mass captured by spent substrate (mg)
HSSF–CW1	Black sand	19098	0.031 ± 0.005	584.00 ± 95.85
	WHC	79768	0.074 ± 0.004	5885.98 ± 331.15
HSSF–CW2	Black sand	19098	0.042 ± 0.003	793.48 ± 61.22
	WHC	79768	0.077 ± 0.004	6124.60 ± 279.34
HSSF–CW3	Black sand	19098	0.051 ± 0.003	971.22 ± 61.22
	Yellow sand	77172	0.045 ± 0.003	3462.82 ± 203.59
HSSF–CW4	Black sand	19098	0.128 ± 0.006	2437.56 ± 122.43
	Yellow sand	77172	0.028 ± 0.004	2180.3 ± 311.00

Source: Nguyen et al. 2020

Additionally, a correlation was observed between the calcium (Ca) content in the filter media and P removal efficiency. Ca-based materials, such as limestone and other Ca-rich substrates, often enhance P removal through mechanisms including chemical precipitation, adsorption, co-precipitation, and pH modulation. Furthermore, it was found that plants can utilize Ca-bound P more effectively than P-bound to other metals. This is advantageous for WHC, which has a high percentage of Ca-bound P (44%), contains 53.92% CaO, and lacks significant toxic elements (Nguyen 2019). These findings suggest that spent WHC media could be repurposed as a Ca-rich, P-rich soil amendment, providing an environmentally friendly recycling option.

3) Plant Uptake

Plants are a crucial component in the design of CWs for P-rich wastewater treatment. Key functions of wetland plants in remediation

include the uptake and storage of P within plant cells, providing a habitat for beneficial microorganisms, and reducing waterlogging. Table 8 presents the mass of P absorbed by Ubon paspalum grass during the experimental period. The whole-plant P content of Ubon paspalum grass ranged from 3.16 to 4.02 mg/g, corresponding to a range of 0.32–0.40%. This P content was comparable to that of other emergent CW plant species, such as bryophytes (0.1%), helophytes (0.15%), Phragmites australis (0.2%), Typha domingensis (0.23%), Schoenoplectus validus (0.26%), and Eleocharis acuta (0.34%) (Nguyen et al. 2020). Notably, Ubon paspalum grass exhibited a higher P content than commonly used wetland plants like Phragmites australis and Typha domingensis, suggesting its potential as an effective species for P removal in CWs.

Table 8. P removal by Ubon paspalum uptake in HSSF-CW1 and HSSF-CW3 during the experiment

CWs	Part of plant	Fresh weight (g)	Dry weight (g)	P content in dry weight (mg/g)	P mass captured via plant uptake (mg)
HSSF–CW1	Leaf	398.22 ± 34.25	69.88 ± 4.42	2.72 ± 0.16	189.6 ± 0.88
	Stem	490.74 ± 43.19	61.94 ± 0.18	3.73 ± 0.12	230.82 ± 6.81
	Root	84.30 ± 3.62	11.92 ± 0.03	2.82 ± 0.09	33.62 ± 1.08
	Whole plant	973.26 ± 78.83	143.74 ± 4.24	3.16 ± 0.13	454.03 ± 6.59
HSSF–CW3	Leaf	620.08 ± 53.95	98.06 ± 4.67	3.38 ± 0.09	331.68 ± 23.6
	Stem	666.96 ± 58.66	78.06 ± 0.18	4.99 ± 0.07	389.78 ± 5.16
	Root	103.72 ± 4.56	12.80 ± 0.03	2.93 ± 0.12	37.46 ± 1.44
	Whole plant	1390.76 ± 125.17	188.92 ± 4.83	4.02 ± 0.25	758.91 ± 19.91

Source: Nguyen et al., 2020

The total P content in plants serves as a critical indicator of a plant's capacity to absorb and accumulate P as biomass. Since the overall P reduction process relies on total plant biomass, it is essential to examine both P content and total plant biomass. The fresh and dry weights of Ubon paspalum collected from HSSF-CW1 and HSSF-CW3 during the experimental period are presented in Table 8. The estimated biomass yield of Ubon paspalum was approximately 12.9–18.5 kg fresh weight (FW)/m^2/year, or 1.91–2.51 kg dry weight (DW)/m^2/year. This yield is comparable to that of Myriophyllum aquaticum, which has a biomass yield of 1.95–4.90 kg DW/m^2/year in pilot-scale CWs treating anaerobic swine wastewater (Luo et al. 2017).

The amount of P accumulated in the aboveground parts (leaves and stems) of Ubon paspalum grass in both HSSF-CW1 and HSSF-CW3 was higher than in the belowground part (roots), accounting for 92.6–95.1% of the total P accumulated. This characteristic enhances the capacity of CWs to permanently remove P through plant uptake and regular harvesting.

4) Microbial Assimilation

Table 9 presents the amount of P removed by microbial assimilation in the four CWs during the experimental period. The P removal content by microbial assimilation was lower than that of the substrate but was comparable to that of the plants. Notably, the P removal rate via microbial assimilation was significantly higher in WHC-based CWs than in yellow sand-based CWs. This may be attributed to the higher porosity of WHC (43%) compared to yellow sand (34%), providing more shelter for microorganisms. Additionally, WHC contains a greater diversity of elements, such as Ca and magnesium (Mg), which bacteria can utilize in their metabolism.

Table 9. P removal by microbe assimilation in the CWs during the experiment

CWs	Substrate	Microbial assimilation		
		Mass of substrate (g)	Microbial P content in substrate (mg/g)	P mass captured by microbe (mg)
HSSF–CW1	Black sand	19098	0.007 ± 0.001	129.91 ± 12.57
	WHC	79768	0.014 ± 0.002	1078.57 ± 137.53
HSSF–CW2	Black sand	19098	0.008 ± 0.001	160.8 ± 26.71
	WHC	79768	0.012 ± 0.001	970.72 ± 42.41
HSSF–CW3	Black sand	19098	0.005 ± 0.001	99.02 ± 12.19
	Yellow sand	77172	0.004 ± 0.000	272.07 ± 19.99
HSSF–CW4	Black sand	19098	0.003 ± 0.000	64.16 ± 4.95
	Yellow sand	77172	0.002 ± 0.000	137.64 ± 14.67

Source: Nguyen et al. 2020

The P removal rates in planted CWs consistently surpass those in unplanted CWs, suggesting that the presence of Ubon paspalum grass may stimulate bacterial activity and enhance P accumulation. Plants provide extensive surface areas for microbial colonization, where biofilms containing P-removing microorganisms can develop and thrive. These biofilms are central to P removal through microbial assimilation and related processes. Furthermore, plants release oxygen from their roots into the surrounding area, creating an oxygen-rich environment that supports aerobic bacteria, which can either assimilate P or facilitate its availability for microbial uptake. Additionally, plants release organic compounds, known as root exudates, which serve as carbon sources for microorganisms, stimulating the growth and activity of microbes involved in P uptake and transformation. Plant roots also stabilize and enhance the porosity of the substrate, improving water

flow and expanding the surface area for microbial colonization. This is particularly advantageous in substrates rich in elements like Ca and Mg, which further benefit bacterial metabolism.

5) Mass Balance

In the present study, P removal occurred through the main pathways shown in Figure 6. The primary mechanism was substrate sorption, which contributed 41.3–69.7%, followed by microbial assimilation at 1.8–13.0%. In planted CWs, plant uptake accounted for 4.9–7.5% of influent P. Additionally, other processes, such as chemical precipitation, contributed 0.8–2.3%.

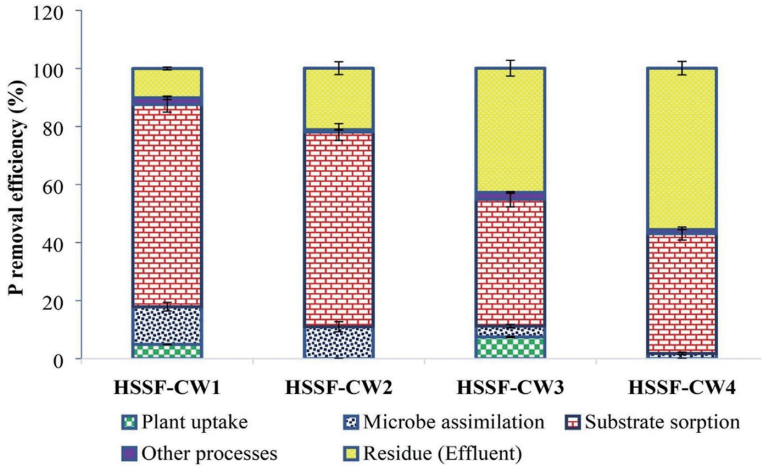


Figure 6. P removal routes in each CW system during the experiment. Source: Nguyen et al. 2020

The lifespan of CWs indicates their long-term sustainability, which was also estimated in this study. The maximum P adsorption capacity (Qmax) of WHC, black sand, and yellow sand (with concentrations

ranging from 0 to 500 mg/L) was found to be 10.34, 0.97, and 1.75 g/kg, respectively (Nguyen 2019). Based on Qmax, the estimated lifespans of the WHC-based and yellow sand-based CWs were 29.24 and 4.84 years, respectively. However, using Qmax to estimate lifespan may lead to overestimation due to other factors affecting P removal efficiency and the lower inlet P concentrations in real wastewater. Therefore, it is suggested that the lifespan of CWs be calculated based on 50% of the Qmax value. As a result, in this research, the estimated lifespan is approximately 14.62 years for WHC-based CWs and 2.42 years for yellow sand-based CWs.

Generally, the WHC-based CWs planted with Ubon paspalum grass demonstrated high P removal from swine wastewater and exhibited greater longevity compared to yellow sand-based CWs. This finding reinforces the potential of using CWs for swine wastewater treatment and highlights the feasibility of recycling seashells as substrates in CWs. Additionally, incorporating economically valuable plants can enhance the overall value of CWs. However, this study was conducted on a small scale and focused solely on P removal. Further research using CWs filled with WHC should investigate additional pollutants such as N, TSS, and organic matter, and should be carried out under practical conditions.

5. Conclusion

Pig farming is vital to Vietnam's agriculture, significantly contributing to the livestock sector and GDP growth while providing livelihoods for millions and supporting meat supply and exports. However, it poses environmental challenges, particularly in wastewater management.

Swine wastewater contains high levels of organic matter, suspended

solids, N, P, and pathogenic microorganisms, which can cause severe environmental degradation if not managed properly. While biogas digestion is commonly used to treat this waste and generate renewable energy, it often fails to address all contaminants. As a result, treated wastewater frequently retains high concentrations of P and N, often exceeding Vietnamese discharge standards. The inadequacy of current treatment systems underscores the need for innovative and sustainable wastewater management solutions, essential for reducing environmental contamination and ensuring the long-term viability of pig farming in Vietnam.

CWs are a promising technology for treating swine wastewater, offering advantages such as simple operation, low cost, and high biodiversity value. They are particularly suitable as tertiary or polishing stages in wastewater treatment. To enhance the efficiency of CWs for swine wastewater treatment, strategies such as optimizing design, substrate, and vegetation are essential. Additionally, combining CWs with other treatment processes can further improve effectiveness. Utilizing recycled materials and economically valuable plants can enhance pollutant removal and increase the overall value of CWs.

References

Borin, M., M. Politeo and G. De Stefani. 2013. Performance of a Hybrid Constructed Wetland Treating Piggery Wastewater. *Ecological Engineering*, 51, 229–236.

Cortes-Esquivel, J. A., G. Giácoman-Vallejos, I. D. Barceló-Quintal, R. Méndez-Novelo, and M. C. Ponce-Caballero. 2012. Heavy Metals Removal from Swine Wastewater Using Constructed Wetlands with Horizontal Sub-Surface Flow. *Journal of Environmental Protection*, 3(8A).

Dao, M. K. 2021. Unlocking the Electricity Recovery Potential from Sustainable Management of Pig Manure Based on Geographic Information System Analysis: Case Study in Hanoi, Vietnam (Doctoral Dissertation, Graduate School of Life and Environmental Sciences, University of Tsukuba).

Dang, H. H., T. T. N. Ly, C. Uruen, and T. N. C. Luong. 2020. Influence of Pig Farms on the Environment in Northern Vietnam: Effect of Some Solutions: A Review. *IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)*, 14(9), 52–59.

De La Mora-Orozco, C., I. J. González-Acuña, R. A. Saucedo-Terán, H. E. Flores-López, H. O. Rubio-Arias, and J. M. Ochoa-Rivero. 2018. Removing Organic Matter and Nutrients from Pig Farm Wastewater with a Constructed Wetland System. *International Journal of Environmental Research and Public Health*, 15(5), 1031.

García-Valero, A., J. A. Acosta, Á. Faz, M. D. Gómez-López, D. M. Carmona, M. A. Terrero, O. El Bied, and S. Martínez-Martínez. 2024. Swine Wastewater Treatment System Using Constructed Wetlands Connected in Series. *Agronomy*, 14(1), 143.

Han, Q. H. 2022. *Sustainable Development of Livestock Production in Vietnam: Driving Forces, Challenges, and Strategies*. GRAESE: Groupe de Recherches Asie de l'Est et du Sud Est. <https://www.gembloux.ulg.ac.be/economie-et-developpement-rural/wp-content/uploads/sites/34/2022/05/24_GRAESE_HAN-QUANG-HAnh.pdf> (accessed on 15 September 2024).

Harrington, C., M. Scholz, N. Culleton, and P. G. Lawlor. 2012. The Use of Integrated Constructed Wetlands (ICW) for the Treatment of Separated Swine Wastewaters. *Hydrobiologia*, 692(1), 111–119.

Hayama Kazuyuki. 2017. Multistage Hybrid Wetland Systems for Pig

Wastewater Treatment. *WEPA Group Workshop on Pig Wastewater Management in Asia Chiang Mai, Thailand*. 21 February 2017.

———. 2021. Introduction of Multistage Subsurface Flow Wetland Systems for Livestock Wastewater Treatment in Japan and Vietnam. *Report "Trends of Policies and Measures for Improving Water Environment in Vietnam and Japan's Technical Cooperation,"* 15 December 2021.

Ho, B. L., T. H. Le, D. A. Doan, D. N. D. Nguyen, M. H. Vuong and T. D. H. Le. 2021. Hiệu quả xử lý nước thải sau Biogas của hệ thống đất ngập nước kiến tạo ở thị xã Tân Uyên - Bình Dương (Efficiency of Wastewater Treatment after Biogas of Constructed Wetland System in Tan Uyen Town, Binh Duong). *Science Magazine - Thu Dau Mot University*, 30. (in Vietnamese)

Hunt, P. G., A. A. Szögi, F. J. Humenik, J. M. Rice, T. A. Matheny and K. C. Stone. 2002. Constructed Wetlands for Treatment of Swine Wastewater from an Anaerobic Lagoon. *Transactions of the ASAE*, 45(3), 639–647.

Kim, Y., D. Kim, S. W. Kang, Y. H. Ham, J. H. Choi, Y. P. Hong and K. S. Ryoo. 2018. Use of Powdered Cockle Shell as A Bio-Sorbent Material for Phosphate Removal from Water. *Bulletin of the Korean Chemical Society*, 39(12), 1362–1367.

Korkusuz, E. A., M. Beklioğlu and G. N. Demirer. 2007. Use of Blast Furnace Granulated Slag as a Substrate in Vertical Flow Reed Beds: Field Application. *Bioresource Technology*, 98(11), 2089–2101.

Liu, X., S. Huang, T. Tang, X. Liu and M. Scholz. 2012. Growth Characteristics and Nutrient Removal Capability of Plants in Subsurface Vertical Flow Constructed Wetlands. *Ecological Engineering*, 44, 189–198.

Luo, P., F. Liu, X. Liu, X. Wu, R. Yao, L. Chen, X. Li, R. Xiao and J.

Wu. 2017. Phosphorus Removal from Lagoon-Pretreated Swine Wastewater by Pilot-Scale Surface Flow Constructed Wetlands Planted with *Myriophyllum aquaticum*. *Science of the Total Environment*, 576, 490–497.

Nguyen, T. A. H., H. H. Ngo, W. S. Guo, T. H. H. Nguyen, S. Soda, N. D. Vu, T. K. A. Bui, T. D. H. Vo, X. T. Bui, T. T. Nguyen and T. T. Pham. 2020. White Hard Clam (Meretrix lyrata) Shells Media to Improve Phosphorus Removal in Lab-Scale Horizontal Sub-Surface Flow Constructed Wetlands: Performance, Removal Pathways, and Lifespan. *Bioresource Technology*, 312, 123602.

Nguyen, T. H. 2024. Ô nhiễm môi trường trong chăn nuôi lợn thịt ở Việt Nam và đề xuất một số giải pháp (Environmental Pollution in Pig Farming in Vietnam and Proposed Solutions. Environment and Construction Magazine). <https://moitruongxaydungvn.vn/o-nhiem-moi-truong-trong-chan-nuoi-lon-thit-o-viet-nam-va-de-xuat-mot-so-giai-phap> (accessed on 12 August 2024). (in Vietnamese)

Nguyen, T. T. 2019. Study on Potential Filter Materials for Use as Substrates in Constructed Wetlands to Strengthen Phosphorus Treatment Performance from Swine Wastewater (Master's thesis). VNU Vietnam Japan University, Hanoi, Vietnam.

Nguyen, V. P., V. H. Pham and T. T. H. Nguyen. 2018. Thực trạng chăn nuôi lợn theo hướng an toàn thực phẩm ở huyện Lương Tài, tỉnh Bắc Ninh (Current Status of Pig Farming in Relation to Food Safety in Luong Tai District, Bac Ninh Province). *Vietnam Journal of Agricultural Science*, 16(10), 924–932. (in Vietnamese)

Poach, M. E., P. G. Hunt, G. B. Reddy, K. C. Stone, M. H. Johnson, and A. Grubbs. 2004. Swine Wastewater Treatment by Marsh–Pond–Marsh Constructed Wetlands under Varying Nitrogen Loads. *Ecological Engineering*, 23(3), 165–175.

Qui, N. H. and B. Guntoro. 2019. Challenges, Opportunities and Prospects of Swine Industry in Vietnam. In *Proceedings of the 4th International Conference on Green Agro-Industry*, Yogyakarta, Indonesia, 22–23 October 2019, 189–196.

Sharifuzzaman, M., H. S. Mun, K. M. B. Ampode, E. B. Lagua, H. R. Park, Y. H. Kim, M. K. Hasan and C. J. Yang. 2024. Smart Pig Farming: A Journey Ahead of Vietnam. *Agriculture*, 14(4), 555.

Stone, K. C., P. G. Hunt, A. A. Szögi, F. J. Humenik, and J. M. Rice. 2002. Constructed Wetland Design and Performance for Swine Lagoon Wastewater Treatment. *Transactions of the ASAE*, 45(3), 723–730.

Truong, A. H., M. T. Kim, T. T. Nguyen, N. T. Nguyen and Q. T. Nguyen. 2018. Methane, Nitrous Oxide and Ammonia Emissions from Livestock Farming in the Red River Delta, Vietnam: An Inventory and Projection for 2000–2030. *Sustainability*, 10(10), 3826.

Wu, H., R. Wang, P. Yan, S. Wu, Z. Chen, Y. Zhao, C. Cheng, Z. Hu, L. Zhuang, Z. Guo, H. Xie, and J. Zhang. 2023. Constructed Wetlands for Pollution Control. *Nature Reviews Earth & Environment*, 4(4), 218–234.

Yeom, S. H. and K. Y. Jung. 2009. Recycling Wasted Scallop Shell as an Adsorbent for the Removal of Phosphate. *Journal of Industrial and Engineering Chemistry*, 15(1), 40–44.

6. Dr. Thi Thuong NGUYEN



Chapter 6. Swine Wastewater Treatment Management in Vietnam: A Sustainable Approach Using Constructed Wetlands

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