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Perspectives on Wastewater Treatment Technology for Sustainable Pig Farming: Comparative Studies on Problem Structures in China, Japan, and Vietnam

Editors
Thi Thuong NGUYEN and Rongxuan WANG

Asia-Japan Research Institute
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ISBN 978-4-910550-16-9 (Online)
ISBN 978-4-910550-17-6 (Print)

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Note:
Authors' names in this publication are ordered according to their preference and their surnames are capitalized.

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Editors' Preface

The rapid urbanization and industrialization of Asia, particularly in China, Japan, and Vietnam, have brought about significant transformations in agricultural practices, with pig farming intensification playing a central role. While this evolution has been crucial for food security, it has also created considerable environmental challenges. The wastewater generated by pig farming—rich in nutrients, organic matter, and potentially harmful contaminants—poses serious threats to water quality, and ecosystem health, and contributes to greenhouse gas emissions. To address these concerns, innovative technological solutions are necessary, but they must also be contextualized within the socio-economic and environmental frameworks of each country.

This book "Perspectives on Wastewater Treatment Technology for Sustainable Pig Farming: Comparative Studies on Problem Structures in China, Japan, and Vietnam," seeks to examine the shared and unique challenges faced by these three nations in managing pig farming wastewater. By analyzing the "problem structures"—the interaction of technical, economic, and policy factors that influence wastewater management—this work aims to provide a comprehensive understanding of how each country is addressing the complexities of wastewater treatment in the context of sustainable pig farming.

The chapters in this book are based on the discussions held at the Asia-Japan Research Institute International Workshop on 3 August 2024, where researchers from China, Japan, and Vietnam convened to explore wastewater treatment technologies for sustainable pig farming. The workshop presented a rich platform for sharing insights and collaborating across borders, resulting in a valuable exchange of ideas and practices.

Chapter 1, authored by Dr. Rongxuan Wang, focuses on China,

the world's largest pork producer. Dr. Wang examines the wastewater management challenges facing China's pig farming industry, reviewing both current and emerging treatment technologies, with an emphasis on nature-based solutions. He also discusses the need for policy support, farmer education, and innovation to ensure sustainable management practices. In Chapter 2, Dr. Dan A introduces constructed wetlands as an effective green technology for livestock wastewater treatment. She explores how optimizing plant-substrate combinations and bacterial reactions can improve treatment efficiency and reduce greenhouse gas emissions.

Dr. Obey Gotore addresses the challenge of antibiotic contamination in swine wastewater in Chapter 3. He reviews various treatment methods implemented in Japan and China, highlighting a promising approach that uses biochar combined with manganese oxide for antibiotic removal. In Chapter 4, Dr. Chikako Ishimoto explores the structural changes in Japan's pig farming industry and examines current waste management practices. She also presents an energy-efficient, cost-effective solution using Anammox bacteria for treating pig wastewater.

In Chapter 5, Dr. Thi Huong Giang Nguyen discusses the challenges of reusing swine wastewater in Vietnam, examining the regulatory and policy frameworks around livestock waste management. Finally, in Chapter 6, Dr. Thi Thuong Nguyen highlights the ongoing challenges in Vietnam's pig farming industry, where outdated practices and insufficient infrastructure contribute to significant wastewater management issues. She proposes a sustainable solution using constructed wetlands for effective wastewater treatment.

This book owes its creation to the contributions of the outstanding researchers who shared their valuable insights during the workshop. We extend our heartfelt gratitude to them for enriching the discussions and content of this publication. Our sincere appreciation also goes to

the Asia-Japan Research Institute for their support in organizing the workshop and facilitating this publication. A special thanks to Professor Yasushi Kosugi, Satoshi Soda, and Anthony Brewer for their invaluable guidance, advice, and editorial efforts throughout the entire process—from selecting the workshop topic to the final stages of this publication. We also wish to express our deep gratitude to our colleagues and the domestic and international participants whose encouragement and support were instrumental in bringing this work to fruition.

We hope that this book will serve as a valuable resource for researchers, policymakers, and practitioners dedicated to advancing sustainable wastewater management practices in pig farming. By addressing the critical issues surrounding pig farming wastewater treatment, we aim to contribute to global efforts toward environmental sustainability and the well-being of future generations.

Thi Thuong NGUYEN
Rongxuan WANG

Contributors

1. Dr. Rongxuan WANG



Chapter 1. Insight into the Removal of Pollutants by Various Treatment Technologies from Swine Wastewater in China

Dr. Rongxuan Wang is a Senior Researcher in Water Environment Engineering at Ritsumeikan University, Japan. He earned his Ph.D. from the Graduate School of Science and Technology, Environmental Design, Kanazawa University. His research focuses on wastewater treatment technologies, particularly the use of constructed wetlands for water purification. His work also involves developing innovative technologies for antibiotic removal, virus control, and swine wastewater treatment, with the goal of enhancing the sustainability and efficiency of wastewater management systems, contributing to environmental protection and public health.

2. Dr. Dan A



Chapter 2. Optimization of Substrate-Plant Combinations in Horizontal Subsurface Flow Constructed Wetlands and Their Microbial Responses: Enhancement of Livestock Wastewater Treatment and Greenhouse Gas Emission Reduction

Dr. Dan A is an Associate Professor at Zhongkai University of Agriculture and Engineering, China, with a Ph.D. in Environmental Engineering from the University of Osaka, Japan. Her research focuses on the rhizosphere micro-interface processes of emerging pollutants and their molecular response mechanisms. She also explores ecological remediation technologies for agricultural non-point source pollution, including livestock wastewater. Dr. Dan has successfully led 9 national, provincial, and municipal projects and has published 36 research papers in these areas.

3. Dr. Obey GOTORE



Chapter 3. Challenges of Veterinary Antibiotic Pollution from Swine Farms and Possible Wastewater Treatment Options

Dr. Obey Gotore is a Research Associate at International Institute for Carbon Neutral Energy Research (WPI-I2CNER), Kyushu University, Japan. He holds a Ph.D. from the Graduate School of Engineering at Nagasaki University, Japan. He has extensive experience in environmental science, with expertise in the ecological aspects of water and wastewater treatment. His research includes work on acid mine drainage, microbiology, ecology, environmental bioremediation, and the use of porous materials derived from agricultural waste for livestock wastewater treatment. Additionally, he applies data science techniques, utilizing the R programming language to enhance the interpretation and understanding of environmental science research findings.

4. Dr. Chikako ISHIMOTO



Chapter 4. Current Status and Issues in the Treatment of Swine Wastewater in Japan: Towards the Development of an Innovative Nitrogen Removal Process Using Anammox

Dr. Chikako Ishimoto is a Senior Researcher at the Shizuoka Prefectural Research Institute of Animal Industry, Swine & Poultry Research Center, Japan. She holds a Ph.D. from the Graduate School of Science and Engineering at Ritsumeikan University, Japan. Her research focuses on advancing the proper treatment and sustainable utilization of livestock waste. Currently, she is conducting extensive research on developing a simple and efficient system for nitrogen removal from swine wastewater using anaerobic ammonium oxidation (anammox) bacteria.

5. Dr. Thi Huong Giang NGUYEN



Chapter 5. Challenges of Recycling Swine Wastewater in Vietnam to Approach a Circular Economy

Dr. Thi Huong Giang Nguyen is a Senior Lecturer in the Department of Environmental Management at Vietnam National University of Agriculture, Vietnam. She earned her Ph.D. from the Faculty of Environmental Sciences at the same university. She has led and contributed to numerous projects focused on livestock and domestic waste management, as well as investigating the gendered impacts of climate change in rural areas in Vietnam. Her current research focuses on managing swine wastewater in rural communities and evaluating the effectiveness of environmental policies in driving behavioral change using modeling tools.

6. Dr. Thi Thuong NGUYEN



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

Dr. Thi Thuong Nguyen is a Senior Researcher at the Asia-Japan Research Institute, Ritsumeikan University, Japan. She completed her Ph.D. in Advanced Architectural, Environmental, and Civil Engineering at the Graduate School of Science and Engineering, Ritsumeikan University, Japan. Her current research focuses on sustainable wastewater treatment by recycling by-product waste as a substrate in constructed wetlands for livestock and mine wastewater treatment.

Chapter 1
Insight into the Removal of Pollutants by Various Treatment Technologies from Swine Wastewater in China

Rongxuan WANG

Abstract: Swine wastewater is a type of livestock and poultry breeding wastewater that contains high concentrations of organic matter, nitrogen, and phosphorus. Improper disposal of wastewater poses significant risks to both the environment and human health. China, as a leading livestock and poultry breeding nation in Asia, has been actively exploring and developing swine wastewater treatment technologies to prevent pollution of surface and groundwater. However, the applicability of various technologies for treating swine wastewater remains a challenge. In this study, the applicability of wastewater treatment technologies in pig farming was investigated in China. Several full-scale case studies were reviewed, focusing on different treatment processes, including anaerobic, aerobic, and combined systems. Additionally, the current status of livestock farming, management practices, and the technologies used for wastewater treatment are discussed in detail. Finally, the challenges and key strategies for improving swine wastewater treatment, as well as future perspectives for the field, are highlighted, with emphasis on the importance of selecting appropriate treatment technologies based on factors such as the scale of the pig farming, local environmental conditions, and economic feasibility. Anaerobic treatment processes, such as biogas production, have proven effective in reducing organic matter and producing renewable energy. Aerobic processes,

on the other hand, are efficient in removing nitrogen and phosphorus but require more energy input. Combined systems, integrating both anaerobic and aerobic treatments as well as natural treatment such as constructed wetlands (CWs), offer promising results in addressing the diverse challenges associated with swine wastewater. Furthermore, the research emphasizes the need for policy support, livestock farmer awareness, and technological innovation to enhance the sustainability of wastewater management in China's pig farming industry.

Keywords: *swine wastewater, treatment technologies, anaerobic and aerobic systems, constructed wetlands, sustainability*

1. Pork and Feed Production in China

Swine wastewater is a byproduct of pig farming, one of the most significant sectors in global livestock production. As intensive pig farming continues to grow, particularly in countries and regions with large agricultural industries such as China, the United States, Europe, and Southeast Asia, the management of swine wastewater has become a critical environmental challenge. Swine wastewater is rich in organic matter, nitrogen, phosphorus, and pathogens due to the high volume of feces and urine produced by pigs. It also contains a variety of other pollutants, including suspended solids, heavy metals, and pharmaceutical residues like antibiotics used in pig farming. These contaminants can severely impact water bodies and even human health if not properly treated before disposal or reuse.

Consequently, this study provides an overview of the pig farming status, management practices, and swine wastewater treatment technologies in China. It supplies valuable data for scientists or technical staff to understand the utilization status of these technologies, assists

in selecting suitable swine wastewater treatment methods, and aids engineers in the design and operation of swine wastewater treatment facilities. The status of technologies and their applications for swine wastewater treatment in China has not yet been extensively examined.

Therefore, this study aims to (i) investigate pork and feed production in China; (ii) describe the current challenges related to swine wastewater in China, including issues associated with antibiotics, total nitrogen (TN), total phosphorus (TP), and chemical oxygen demand (COD); and (iii) evaluate the application of swine wastewater treatment technologies at full scale.

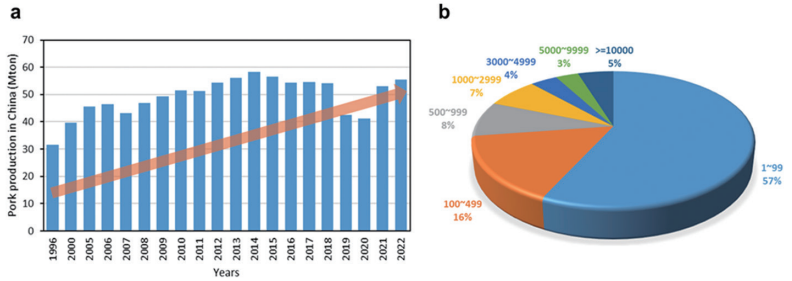
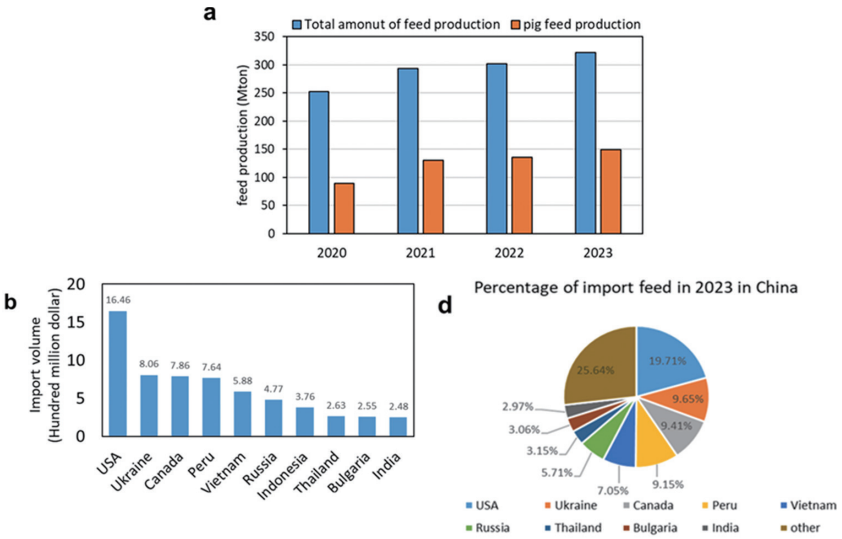


Figure 1. (a) Pork production from 1996 to 2022 and (b) percentage of pig breeding scale in China. Source: (National Bureau of Statistics of China 2023; Discharge Standard of Water Pollutants for Livestock and Poultry Breeding GB18596 2011).

The amount of feed and pig feed production in China is significant due to the country's large-scale pig farming industry. China is the largest pig producer in the world, which accounts for 50% of global pork production, reflecting its vast pig population. From 1996 to 2022, pork production in China has shown a fluctuating trend, with periods of growth and decline influenced by various factors such as policy changes, market demand, outbreaks of diseases (such as COVID-19), and

advancements in farming technology (Figure 1a). Moreover, China's pig farming industry is primarily composed of small-scale farms. An annual number of 1 to 99 pigs accounted for the largest proportion, which is 57% of the total number of pigs slaughtered in 2008, while those with more than 500 pigs accounted for only around 27% (Figure 1b). Therefore, Livestock and poultry breeding is still dominated by small and medium-scale operation in China. However, with the progress of agricultural modernization, it is expected that small-scale family farming will gradually decrease, while large-scale industrial farming will become more dominant. This shift toward large-scale farming is likely to enhance production efficiency and support the continued growth of pork output.



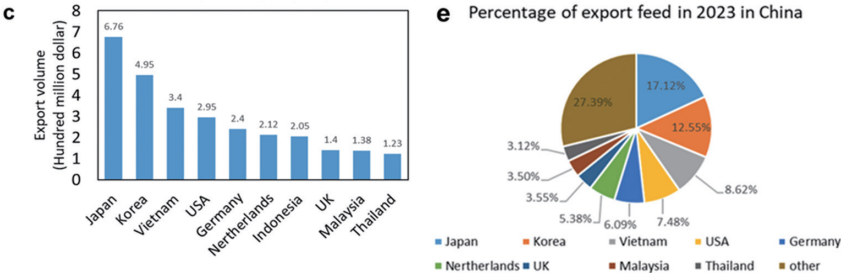


Figure 2. Total amount of feed and pig feed production in China from 2020 to 2023; The percentage of feed import and export feed in 2023 in China. Source: (CFNA 2023).

China's industrial feed production in 2022 reached 302.2 million metric tons (MMT), marking a 3% increase compared to 2021 (Figure 2a). The feed production remained relatively stable in 2023, with only minor fluctuations expected. During this period, corn usage in feed increased significantly, while the utilization of other grains like wheat and barley decreased. The feed production in China comprises various ingredients, including corn, soybean meal, and other grains, tailored to meet the nutritional requirements of pigs at different growth stages. This robust feed production sector plays a crucial role in ensuring a consistent supply to pig farms across the country, thereby contributing to the stability and growth of China's pork industry.

In 2024, China's feed production has been influenced by several factors, leading to an expected decline in total production due to reduced demand from the poultry and livestock sectors. This trend is largely attributed to fluctuations in the corn and wheat markets, although corn production is anticipated to increase slightly due to improved yields. Despite these challenges, China remains one of the largest global producers of pig feed, although demand has been volatile, particularly due to disease outbreaks and changing consumer preferences.

The development of the feed industry and the percentage of feed imports/exports in China are illustrated in Figure 2b, 2c, 2d and 2e. In 2023, the total feed production amounted to 321.627 MMT, with pig feed production totaling 149.752 MMT (CFNA 2020–2023). Overall, China's feed market is more import-dependent, with the United States being the most significant source of feed imports, valued at US$1.646 billion. Conversely, Japan is China's most important market for feed exports, with an export value of US$676 million (CFNA 2023).

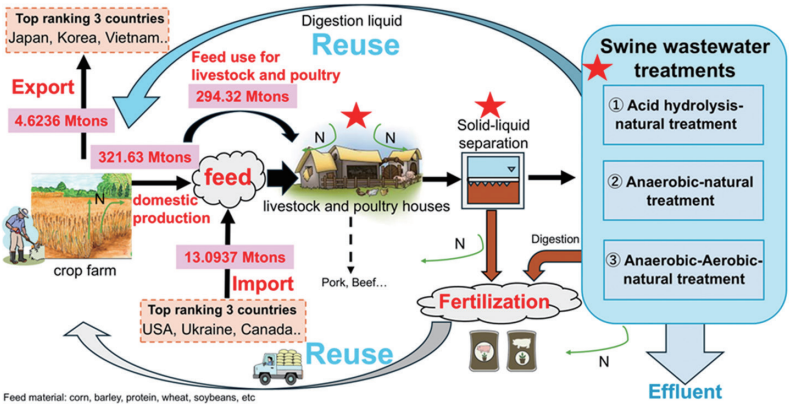


Figure 3. Flow diagram for feed use and swine wastewater in China 2023. Source: Author

2. Pretreatment of Swine Wastewater

Livestock manure is predominantly produced by cattle, pigs, and poultry. According to statistics, approximately 551 million tons of livestock manure (dry weight) were produced in China in 2014 (Jia et al. 2018). In this study, three main types of pig farming models are identified in China: (i) Open Pig Houses: these have a simple construction, which saves materials, ensures good ventilation and

lighting, and facilitates the easy discharge of harmful gases. (ii) Closed Pig Houses: these offer excellent thermal insulation and high space utilization, but their complex structure leads to higher construction costs. (iii) Greenhouse-style Pig Houses: these have constant temperature, good lighting, and are particularly convenient for daily disinfection and epidemic prevention. Regarding the management of feces and urine produced in pig houses, liquid components account for a large portion, reaching 56%. Pig slurry (a combination of urine and feces) accounts for 36%, which contains a lot of water. Therefore, the method of treating the liquid is important. Furthermore, solid waste makes up 8% of the amount of waste which is treated and used as fertilizer. It is evident that urine management plays a significant role in the overall waste treatment process in pig farming, with about 12% of the liquid waste flowing into sewage treatment facilities. Additionally, mechanical separation, which is used for treating mixed manure, accounts for 24% of the waste management methods employed.

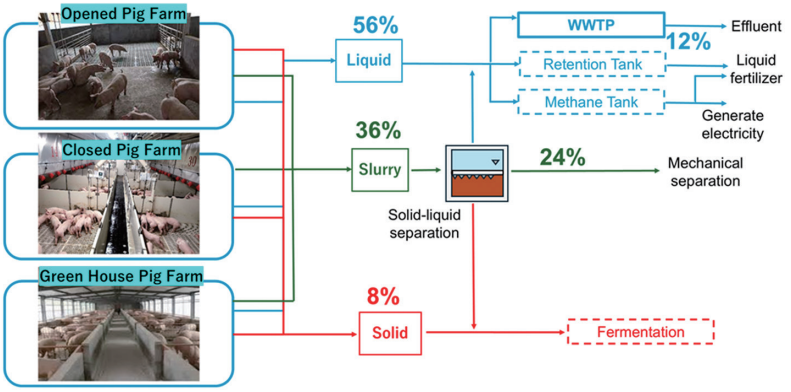


Figure 4. The three types of opened, closed and greenhouse pig house. Source: Author

3. Swine Wastewater Pollution Problems on Organic Matters and Antibiotics

(1) Bibliometric Analysis in Swine Wastewater

A comprehensive search of the Web of Science database of the time between 2010 and 2025 was conducted using the keywords "swine wastewater," while the search terms were screened in the "subject" of the publication. A "title, summary" analysis was performed using Vosviewer software to determine the keyword evolution of swine wastewater treatment (Figure 5). The size of nodes in the figure represents the frequency of keywords used. From the analysis of keywords, we note that the treatment of swine wastewater by water quality parameters is closely related, which mainly involves some treatment technologies to remove pollutions. The main keywords in terms of swine wastewater are COD, production, antibiotic, bacterium, wetland, etc.

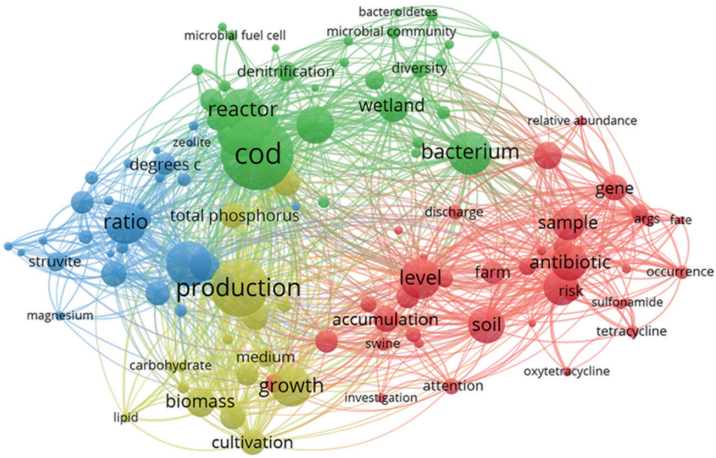


Figure 5. Network analysis of relevance keywords related to swine wastewater. Source: Author

(2) Organic Matters in Swine Wastewater

The pig industry is the largest polluter among all livestock and poultry breeding industries. The manure and urine produced are as follows: 0.55 kg/head/day and 1.14 kg/head/day for nursery pigs, 1.17 kg/head/day and 2.87 kg/head/day for fattening pigs, and 1.73 kg/head/day and 6.42 kg/head/day for sows (Table 1). Livestock and poultry breeding wastewater primarily includes urine, manure, and flush water. Each pig generates 10 to 15 liters of wastewater. Consequently, the wastewater concentrations of TN and TP are 1.43 g/L and 0.27 g/L for nursery pigs, 3.84 g/L and 0.73 g/L for fattening pigs, and 4.99 g/L and 1.25 g/L for sows. Furthermore, swine wastewater contains high pollutant concentrations, with biochemical oxygen demand (BOD_5), COD, and ammonia nitrogen (NH_3-N) generally being 10 to 100 times higher in intensive pig farms compared to municipal wastewater (Table 3). The high concentration of organic matter poses a significant pollutant risk to the water environment. In China, the amount of manure and wastewater discharged by swine accounts for 76.8% of the total manure and wastewater from all livestock and poultry (Wu et al. 2018). Therefore, it is essential to treat and utilize swine wastewater.

Table 1. Average daily feces and urine production per pig in China

Pig type	Feces (dry weight base) (kg/head/d)	Urine (kg/head/d)	TN (g/head/d)	TP (g/head/d)	Wastewater (L/d/head)
Nursery pig	0.55	1.14	14.26	2.74	
Fattening pig	1.17	2.87	38.42	7.29	10–15L
Sow	1.73	6.42	49.89	12.46	

Table 2. Cleaning methods and concentration of pollutants in pig wastewater in average mg/L

Feces cleaning	CODcr	NH_3-N	TN	TP	pH
Water flushing	21600	590	805	127	6.3–7.5
Dry collection	2640	261	370	43.5	

(3) Concentration of Antibiotics in Swine Wastewater

In the livestock and poultry breeding process, some antibiotics are used in animal therapy, while others enter the animal body through feed additives. In 2020, the total amount of veterinary antibiotics used in China was 32,776.298 tons, representing a 6.06% increase compared to 2019. Of this total, 9,000 tons were used as feed additives to promote animal growth, and 23,000 tons were used for animal therapy (Ministry of Agriculture and Rural Affairs of the People's Republic of China 2021). The top three veterinary drugs in terms of usage are tetracyclines, sulfonamides, and β-lactams and inhibitors, accounting for 30.52%, 13.08%, and 12.55%, respectively (Figure 6a). Unmetabolized veterinary antibiotics directly contribute to antibiotic residues in wastewater (Robles-Jimenez et al. 2022). The average concentration of major veterinary antibiotics in swine wastewater is approximately 1,145 μg/L. Among these, sulfonamides are the most dominant antibiotics in swine wastewater in China (Wan et al. 2021). Furthermore, Chen et al. (2012) reported high concentrations of tetracycline and sulfadiazine, detected at 41.6×10^3 and 98.8×10^3 ng/L, respectively, in swine wastewater in East China (Figure 6b). Consequently, the large discharge of antibiotics facilitates the spread of antibiotic resistance genes (ARGs) in swine wastewater, which can lead to microbial risks and contamination of reused water.

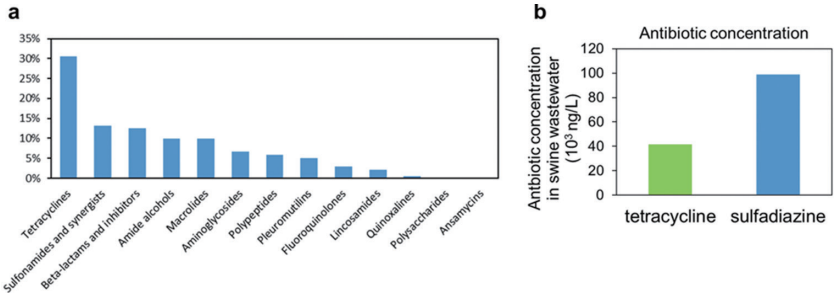


Figure 6. (a) Proportion of use of various types of veterinary antibiotics in China and (b) antibiotic concentration in swine wastewater. Source: (a) Ministry of Agriculture and Rural Affairs of the People's Republic of China 2021; (b) Chen et al. 2012.

4. Treatment of Swine Wastewater in Various Processes

In China, there are two main types of agricultural and livestock wastewater treatment methods. One is the anaerobic and natural treatment approach, while the other is the anaerobic and aerobic treatment approach. Both methods are widely used and promoted for their effectiveness in removing pollutants from agricultural and livestock wastewater.

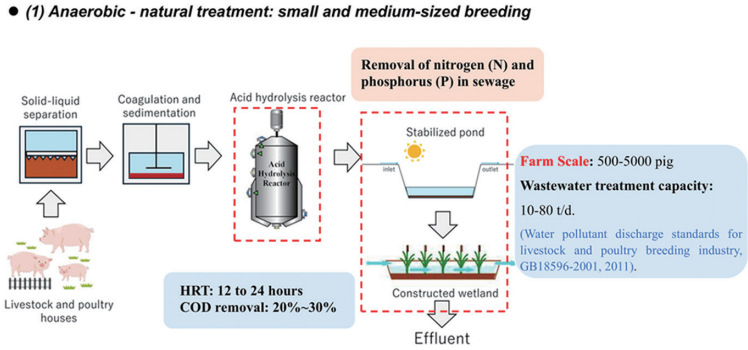


Figure 7. Anaerobic (acid hydrolysis reactor)-natural treatment in the small and medium-sized breeding farms. Source: (Discharge Standard of Water Pollutants for Livestock and Poultry Breeding GB18596 2011)

In 500–5,000 pig farms with a daily wastewater volume of 10 to 80 tons, the treatment process begins with a hydrolysis reactor. This reactor, equipped with a biological filler, provides an environment where wastewater is held for 12 to 24 hours. During this time, the reactor reduces the COD by 20% to 30%, which helps to break down organic pollutants. After the initial treatment, the wastewater proceeds to the subsequent treatment stage, which combines stabilization techniques with CWs. The stabilization processes help to further reduce contaminants and stabilize the wastewater quality. The final step involves passing the wastewater through CWs. These wetlands are effective in removing nitrogen and phosphorus, which are critical for meeting discharge standards and minimizing environmental impact (Discharge Standard of Water Pollutants for Livestock and Poultry Breeding GB18596 2011). By employing this multi-stage treatment approach, pig farms ensure that their wastewater is managed effectively, reducing pollution and adhering to regulatory standards.

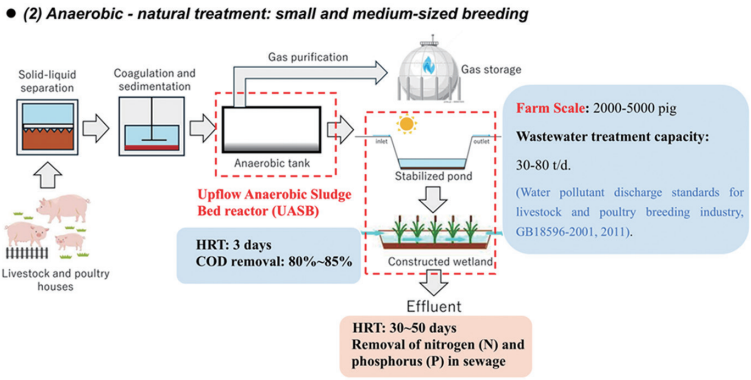


Figure 8. Anaerobic (upflow anaerobic sludge bed reactor)-natural treatment in the small and medium-sized breeding farms. Source: (Discharge Standard of Water Pollutants for Livestock and Poultry Breeding GB18596 2011)

In pig farms with capacities ranging from 2,000 to 5,000 pigs, where daily wastewater treatment capacities range from 30 to 80 tons, an efficient treatment process is crucial for managing environmental impact and adhering to regulatory standards. The treatment process begins with an anaerobic stage using an Up flow Anaerobic Sludge Bed (UASB) reactor. This reactor operates with a hydraulic retention time (HRT) of approximately 3 days. The UASB reactor is designed to facilitate the anaerobic digestion of organic matter in the wastewater, where microorganisms break down the organic pollutants in the absence of oxygen. This stage achieves a substantial reduction in the COD, with removal rates ranging from 80% to 85%. This significant reduction helps in mitigating the load of organic contaminants before the wastewater moves on to the next treatment stages. After the anaerobic treatment, the wastewater proceeds to the secondary treatment stage. This stage typically involves a combination of stabilized ponds and CWs. The wastewater first enters stabilized ponds, where it undergoes natural biological processes that further stabilize and reduce contaminants. This stage has an HRT of 30 to 50 days, allowing for thorough treatment through sedimentation and microbial activity. Following stabilization, the wastewater is directed to CWs. These wetlands are specifically designed to remove nitrogen and phosphorus from the wastewater, which are critical for meeting discharge standards and reducing the environmental impact. CWs utilize natural processes involving plant roots, soil, and microorganisms to effectively treat the water. The combination of the anaerobic UASB reactor and the stabilization + CWs approach ensures comprehensive treatment of the wastewater. This multi-stage process not only meets the stringent water pollutant discharge standards for the livestock and poultry breeding industry (Discharge Standard of Water Pollutants for Livestock and Poultry Breeding GB18596 2011) but also minimizes the potential

environmental impact. By efficiently removing organic matter, nitrogen, and phosphorus, the treatment system helps to prevent pollution and supports sustainable waste management practices.

In summary, this well-structured treatment process — starting with anaerobic digestion, followed by stabilization ponds, and concluding with CWs — ensures that wastewater from pig farms is managed effectively, reducing pollution and complying with environmental regulations.

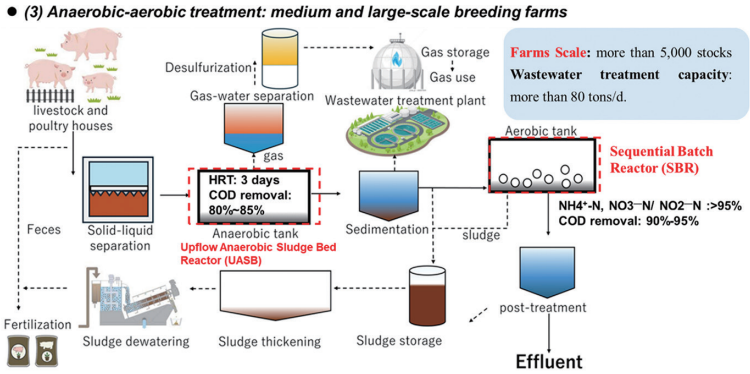


Figure 9. Anaerobic-aerobic treatment in the medium and large-scale breeding farms. Source: (Discharge Standard of Water Pollutants for Livestock and Poultry Breeding GB18596 2011)

For farms with over 5,000 animals and a daily wastewater treatment capacity exceeding 80 tons, a comprehensive and multi-stage treatment process is essential to effectively manage and reduce wastewater pollutants. The treatment process begins with an anaerobic stage using a UASB reactor. This reactor operates with an HRT of 3 days. During this period, the UASB reactor facilitates the anaerobic digestion of organic matter, where microorganisms break down the organic pollutants in the absence of oxygen. This stage achieves a

significant reduction in the COD, with removal rates ranging from 80% to 85%. This initial treatment effectively reduces the organic load of the wastewater before it progresses to the next treatment phase. Following the anaerobic treatment, the wastewater undergoes further treatment using a Sequential Batch Reactor (SBR). The SBR is an advanced aerobic treatment process that operates in batch mode, allowing for efficient removal of COD, nitrogen, and phosphorus. The SBR provides aeration and mixing in a controlled environment, which enhances the degradation of organic matter and the removal of nutrients. The SBR achieves a high COD removal rate of 90% to 95%, ensuring that the organic pollutants are effectively reduced. The SBR is also highly effective in removing ammonia and nitrogen, with removal rates exceeding 95%. This is crucial for meeting discharge standards and minimizing environmental impact. This multi-stage treatment process, combining anaerobic digestion with advanced aerobic treatment, ensures comprehensive management of wastewater. It not only meets the stringent water pollutant discharge standards for the livestock and poultry breeding industry (Discharge Standard of Water Pollutants for Livestock and Poultry Breeding GB18596 2011) but also minimizes the potential environmental impact by efficiently removing organic matter, nitrogen, and phosphorus. Overall, the wastewater treatment process for large-scale farms involves an initial anaerobic treatment using a UASB reactor followed by advanced aerobic treatment with an SBR. This approach provides effective pollution control and ensures compliance with regulatory standards, supporting sustainable waste management practices.

Table 3. Livestock wastewater parameters from intensive pig farm

Wastewater type	pH	SS (mg/L)	BOD_5 (mg/L)	CODcr (mg/L)	NH_3-N (mg/L)
Pig farm	7.5–8.1	5000–12000	2000–6000	5000–10000	100–600
Municipal wastewater	8.1	211.8	67.7	320.1	–

Source: (Guidelines for Best Available Techniques for Pollution Prevention and Control in Livestock and Poultry Farming 2011)

Table 4. The highest daily concentration of water pollutants discharged from the intensive livestock and poultry breeding industry.

Item	BOD_5 (mg/L)	COD (mg/L)	SS (mg/L)	NH_3-N (mg/L)	TP (mg/L)	Ecoli (CFU/mL)	Ascaris eggs (No./L)
Discharge Standard	150	400	200	80	8.0	1000	2.0

Source: (Discharge Standard of Water Pollutants for Livestock and Poultry Breeding GB18596 2011)

TN and TP are the two primary concerns in manure management due to their significant impact on environmental pollution (Cahoon et al. 1999). Table 3 and Table 4 show the pollution indicators for centralized pig houses and the highest daily discharge limits, respectively. Effective management of these nutrients is crucial to mitigate their adverse effects on water quality and ecosystem health. The 13th Five-Year Plan in China highlights the importance of controlling the discharge of pollutants, including COD, NH_3-N, TP, and TN. This plan aims to address and co-control these pollutants to reduce their environmental impact (State Council of the People's Republic of China 2016). Over 60% of farms in China lack proper dry and wet separation systems for manure management. This deficiency hinders the efficient handling and treatment of manure, exacerbating pollution issues. More than 80%

of large-scale livestock and poultry farms are deficient in essential pollution control facilities and investments. This lack of infrastructure impedes effective waste treatment and management. The extensive and often inadequate management practices in livestock and poultry farms contribute to significant environmental challenges. Despite regulatory efforts to control key pollutants, the current state of infrastructure and investment in pollution control remains a critical barrier to achieving effective manure management and environmental protection.

5. Perspectives

From a broader perspective, improving feed availability to increase self-sufficiency in pig farming presents significant opportunities for the agricultural sector in China. As one of the largest producers and consumers of pork globally, China faces immense pressure to ensure a stable and sustainable supply of pork to meet domestic demand. Enhancing feed availability contributes to reducing reliance on feed imports, promoting agricultural self-sufficiency, and stabilizing production costs for farmers. However, while the benefits of this approach are evident, it also introduces a new set of challenges that need to be addressed to ensure the sustainability of the pig farming industry in China. One of the key challenges is the environmental impact associated with the expansion of pig farming operations. As production scales up to meet increasing demand, the generation of waste, particularly wastewater, also increases significantly. This wastewater, if not properly managed, can lead to serious environmental issues, including water pollution, soil contamination, and the degradation of local ecosystems. The environmental footprint of pig farming is further exacerbated by nutrient runoff and greenhouse gas emissions, making it a critical area of concern for policymakers, researchers, and industry stakeholders.

Effective wastewater treatment is fundamental to addressing these environmental challenges. In China, the need for robust wastewater management systems is particularly urgent given the scale of pig farming activities and the potential for environmental harm if waste is improperly handled. Constructing and maintaining efficient treatment facilities that are specifically designed to address the unique characteristics of wastewater from pig farming is key to mitigating these impacts. Such systems must not only treat pollutants effectively but also be economically viable and adaptable to the varying scales of farming operations across different regions in China.

Ensuring the proper operation and maintenance of wastewater treatment facilities is another crucial aspect of sustainable pig farming practices in China. Regular upkeep and technical support are necessary to optimize system performance, prevent failures, and ensure compliance with environmental regulations. In many cases, small- and medium-scale farmers may require additional support in terms of training, resources, and financial assistance to implement and sustain these measures.

Evaluating and adopting the most effective wastewater treatment technologies is essential to achieving sustainable pig farming practices. In the context of China, it is important to consider solutions that are tailored to the specific needs and conditions of the region. Technologies that integrate low-cost materials, utilize locally available resources, and align with the environmental and economic goals of the country are particularly promising. For example, green technologies such as CWs, which use natural processes involving plants, microorganisms, and substrate materials to treat wastewater, could offer a cost-effective and environmentally friendly alternative for small-scale farmers.

6. Conclusion

These findings highlight that pork production and pig feed demand show an overall upward trend. Therefore, the issues related to feed supply and subsequent farm management present new challenges. Mechanical separation is a crucial method for pre-treating pig feces and urine and helps reduce the environmental burden of subsequent wastewater treatment. Swine wastewater treatment typically involves two main approaches: anaerobic-natural treatment for small to medium-scale operations and anaerobic-aerobic treatment for medium to large-scale operations. Selecting appropriate wastewater treatment technologies based on the scale of pig houses helps ensure compliance with safety discharge standards. This study gives a perspective and thus supports the safe reuse of water and its safe discharge into water environments.

References

Cahoon, L. B., J. A. Mikucki and M. A. Mallin. 1999. Nitrogen and Phosphorus Imports to The Cape Fear and Neuse River Basins to Support Intensive Livestock Production. *Environmental Science & Technology*, 33(3), 410–415.

Chen, Y., H. Zhang, Y. Luo and J. Song. 2012. Occurrence and Dissipation of Veterinary Antibiotics in Two Typical Swine Wastewater Treatment Systems in East China. *Environmental Monitoring and Assessment*, 184, 2205–2217.

China Chamber of Commerce of I/E of Foodstuffs, Native Produce and Animal By-products (CFNA). Available online: <https://www.cccfna.org.cn/maoyitongji/hangyetongji/> (accessed on 15 September 2024).

China Feed Industry Association (CFIA) (中国饲料工业协会). Available online: <http://www.chinafeed.org.cn/hyfx/> (accessed on 15 September 2024). (in Chinese)

Discharge Standard of Water Pollutants for Livestock and Poultry Farming (Draft for Comments), Compilation Notes (《畜禽养殖业水污染物排放标准》(征求意见稿)编制说明) (GB 18596-2001). 2001. <https://www.mee.gov.cn/gkml/hbb/bgth/201103/W020110328492079276914.pdf> (in Chinese)

Guidelines for Best Available Techniques for Pollution Prevention and Control in Livestock and Poultry Farming (畜禽养殖污染防治最佳可行技术指南). 2011. <https://www.mee.gov.cn/gkml/hbb/bgth/201105/W020110520345011089657.pdf> (in Chinese)

Jia, W., W. Qin, Q. Zhang, X. Wang, Y. Ma and Q. Chen. 2018. Evaluation of Crop Residues and Manure Production and Their Geographical Distribution in China. *Journal of Cleaner Production*, 188, 954–965.

Ministry of Agriculture and Rural Affairs of the People's Republic of China. 2021. 2020 Annual Report on the Use of Veterinary Antibiotics in China. *Official Veterinary Bulletin*, 23(9), 33–36. Available online: <http://www.moa.gov.cn/gk/sygb/202111/P020211104353940540082.pdf> (accessed on 15 September 2024).

National Bureau of Statistics of China. 2023. 12-14 Livestock Product Output (12-14 畜产品产量). In *China Statistical Yearbook 2023* (中国统计年鉴—2023). Available online: <https://www.stats.gov.cn/sj/ndsj/2023/indexch.htm> (accessed on 15 September 2024). (in Chinese)

Robles-Jimenez, L. E., E. Aranda-Aguirre, O. A. Castelan-Ortega, B. S. Shettino-Bermudez, R. Ortiz-Salinas, M. Miranda, X. Li, J. C. Angeles-Hernandez, E. Vargas-Bello-Pérez and M. Gonzalez-Ronquillo. 2022. Worldwide Traceability of Antibiotic Residues

from Livestock in Wastewater and Soil: A Systematic Review. *Animals*, 12(1), 60. <https://doi.org/10.3390/ani12010060>

State Council of the People's Republic of China. 2016. Notice of the State Council on Issuing the 13th Five-Year Plan for Ecological and Environmental Protection, (2016) No. 65 (「国务院关于印发。"十三五"生态环境保护规划的通知。国发〔2016〕65号」). Available online: <http://www.gov.cn/zhengce/content/2016-12/05/content_5143290.htm> (accessed on 15 September 2024). (in Chinese)

Wan, Y. P., Z. H. Liu and Y. Liu. 2021. Veterinary Antibiotics in Swine and Cattle Wastewaters of China and the United States: Features and Differences. *Water Environment Research*, 93(9), 1516–1529.

Wu, S., H. Liu, H. Huang, Q. Lei, H. Wang, L. Zhai, S. Liu, Y. Zhang and Y. Hu. 2018. Analysis on the Amount and Utilization of Manure in Livestock and Poultry Breeding in China. *Strategic Study of Chinese Academy of Engineering*, 20(5), 103–111.

Chapter 2
Optimization of Substrate-Plant Combinations in Horizontal Subsurface Flow Constructed Wetlands and Their Microbial Responses: Enhancement of Livestock Wastewater Treatment and Greenhouse Gas Emission Reduction

Dan A

Abstract: In this study, six different substrate-plant combinations of horizontal subsurface flow constructed wetlands (CWs) were implemented using two functional substrates (ceramsite and blast furnace slag) and three plant conditions (*Canna indica*, *Typha orientalis*, and unplanted). The primary aim was to evaluate these CWs for their ability to purify livestock wastewater and to measure their greenhouse gas emission fluxes. Subsequently, through 16S rRNA gene sequencing and molecular biological analysis, the mechanisms influencing livestock wastewater purification and greenhouse gas emission reduction in these CW combinations were elucidated. The results showed that the removal efficiencies of chemical oxygen demand (COD), total nitrogen (TN), ammonia nitrogen (NH_4-N), and nitrate nitrogen (NO_3-N) in livestock wastewater by the CWs ranged from 33–44%, 70–87%, 82–98%, and 25%–80%, respectively. The emission fluxes of Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) varied between 2.05–88.8 mg/m^2/h, 0.12–7.55 μg/m^2/h, and 2.19–8.89 mg/m^2/h, respectively. Although the unplanted CWs produced lower greenhouse gas emission,

the planted CWs demonstrated superior wastewater purification performance. Notably, the CWs featuring ceramsite and *Canna indica* (CS+CI-CWs) exhibited the best overall performance in both wastewater treatment and greenhouse gas reduction. This was partly due to the higher abundance of aerobic and anaerobic bacteria in the CS+CI-CWs, which facilitated simultaneous nitrification and denitrification processes, thereby providing favorable conditions for the complete conversion of nitrogen to N_2. Furthermore, the increased abundance of nosZ gene in the CS+CI-CWs promoted N_2 production, effectively reducing N_2O emission flux and thus lowering the global warming potential.

Keywords: *horizontal subsurface flow constructed wetlands, substrate-plant combinations, livestock wastewater purification, greenhouse gas reduction, microbial response*

1. Introduction

CWs remove pollutants from water primarily through plant uptake, substrate adsorption, and microbial transformation (de Oliveira Souza et al. 2023). Due to their stable treatment performance, low cost, and low energy consumption, they have been widely used in recent years for treating various types of wastewaters, including livestock wastewater (Hu et al. 2020; Parde et al. 2021). However, CWs involve biotransformation processes of carbon and nitrogen, which inevitably release greenhouse gases such as CO_2, CH_4, and N_2O, thus having a negative environmental impact (Cocozza et al. 2023). Particularly, livestock wastewater, characterized by high organic loads and high nutrient content, is more prone to greenhouse gas production, exacerbating global warming (Hu et al. 2020). Therefore, it is necessary to understand how substrate-plant combinations in CWs can be

optimized to balance the purification efficiency of livestock wastewater with the control of greenhouse gas emissions.

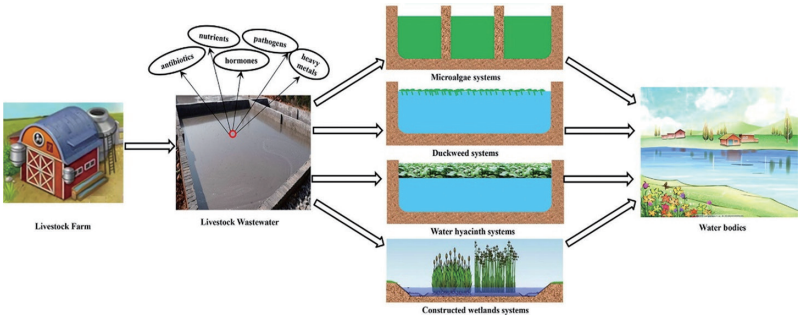


Figure 1. Sustainable livestock wastewater treatment via phytoremediation: Current status and future perspectives. Source: (Hu et al. 2020)

The presence of plants in CWs not only helps remove pollutants from water but also plays a crucial role in regulating the production, consumption, and transmission of greenhouse gases (Sun et al. 2013). Research on the impact of plants on greenhouse gas emissions shows significant differences, sometimes even yielding contradictory conclusions (Gu et al. 2015; Xu et al. 2023). Furthermore, different types of plants vary in their effects on greenhouse gas emissions from CWs (Maltais-Landry et al. 2009). The substrate is also a core component of CWs and plays an indispensable role in the wastewater purification process (Mlih et al. 2020). The type of substrate and the order in which it is filled can affect the pH level of the wetland system, plant growth, and the structure of the microbial community (Ding et al. 2018), thereby indirectly influencing the emission of greenhouse gases. There is significant interaction among these factors, and the combined effects of these interactions determine the purification function and

greenhouse gas emission capabilities of the CWs (Chen et al. 2020). Hence, it is necessary to reveal how the substrate-plant combinations in CWs affect the treatment of livestock wastewater and the flux of greenhouse gas emissions.

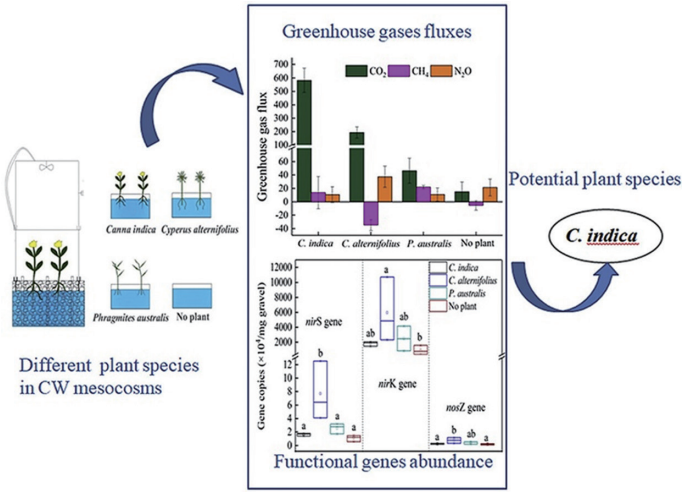


Figure 2. Greenhouse gas emissions and wastewater treatment performance by three plant species in subsurface flow CW mesocosms. Source: (Chen et al. 2020)

The aims of this study are to (a) compare the pollutant removal efficiencies and greenhouse gas emission fluxes in different CWs, and to select substrate-plant combinations that excel in both water purification and greenhouse gas reduction; (b) combine 16S rRNA gene sequencing with molecular biology analysis to explain how these combinations of CWs affect the purification of livestock wastewater and the reduction of greenhouse gas emissions.

2. Materials and Methods

The synthetic livestock wastewater used in this experiment was artificially prepared, and the formulation of its components is as follows. The prepared synthetic wastewater was stored in a storage tank and was fed into the CWs in batches with a hydraulic retention time of 24 hours. The average concentrations of COD, TN, NH_4-N, and NO_3-N in the synthetic wastewater are 348±40.6 mg/L, 25.5±4.36 mg/L, 19.7±3.72 mg/L, and 11.5±2.50 mg/L, respectively. These values are close to the known compositions of real livestock wastewater (Knight et al. 2000), indicating that the synthetic wastewater effectively simulates the real wastewater.

The CW was set up on January 22, 2022, within the Zhongkai University of Agriculture and Engineering in Guangzhou, China. The wetland units utilized polyethylene tanks; common substrates such as sand, pebbles, and gravel were used as the base, while novel substrates such as blast furnace slag (BFS) and ceramsite (CS) were used as functional substrates. Common wetland plants *Canna indica* and *Typha orientalis* were selected as test plants. Based on the different functional substrates and plant species, six CW treatments were set up (Figure 3): CS-CW and BFS-CW with ceramsite and blast furnace slag as functional substrates, respectively. CS+CI-CW and BFS+CI-CW were planted with *Canna indica*, CS+TO-CW and BFS+TO-CW were planted with *Typha orientalis*, and CS+UP-CW and BFS+UP-CW had no plants. The planting density was 12 plants per unit. Each treatment had two replicates.

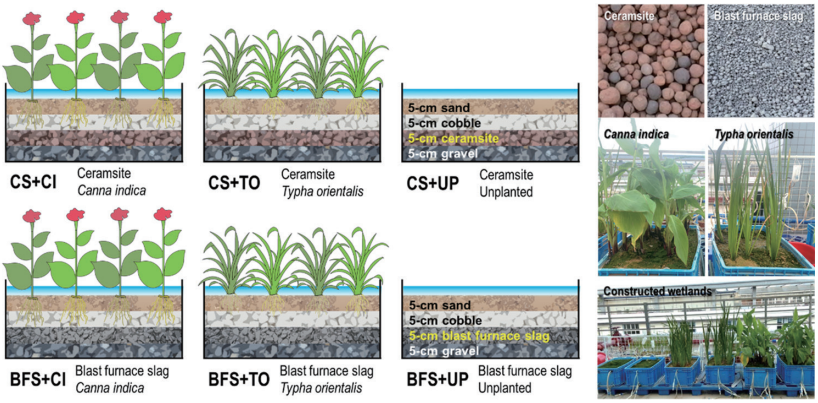


Figure 3. Schematic diagram and pictures of the horizontal subsurface flow CWs. Source: Author

Water samples were collected from April 1 to June 22, 2022, totalling 20 sampling events. The physicochemical parameters measured in the water samples were water temperature and pH. The pollutants measured were concentrations of COD, TN, NH_4-N, and NO_3-N. Greenhouse gas samples were collected from February 28 to June 24, 2022, totalling 15 sampling events. The gases measured were CH_4, CO_2, and N_2O concentrations, which were then converted to corresponding gas emission fluxes. After the collection of gas and water samples, microbial samples were collected on June 28, 2022, for 16S rRNA sequencing. The microbial samples were taken from the biofilm of the substrate near the rhizosphere of the planted systems and from the corresponding locations of the substrate in the unplanted systems.

3. Results and Discussion

(1) Purification of Livestock Wastewater

Figure 4 shows the removal efficiencies of water quality parameters in different CWs: COD, TN, NH_4-N, and NO_3-N. The average removal efficiencies for COD, TN, NH_4-N, and NO_3-N are 38±5%, 80±7%, 92±6%, and 62±20%, respectively. All CWs demonstrate high nitrogen and low carbon removal efficiencies for livestock wastewater. Among these, the type of substrate does not significantly affect the pollutant removal performance of the CWs. However, planted systems, particularly those with *Canna indica*, significantly enhance the removal efficiencies of TN and NO_3-N.

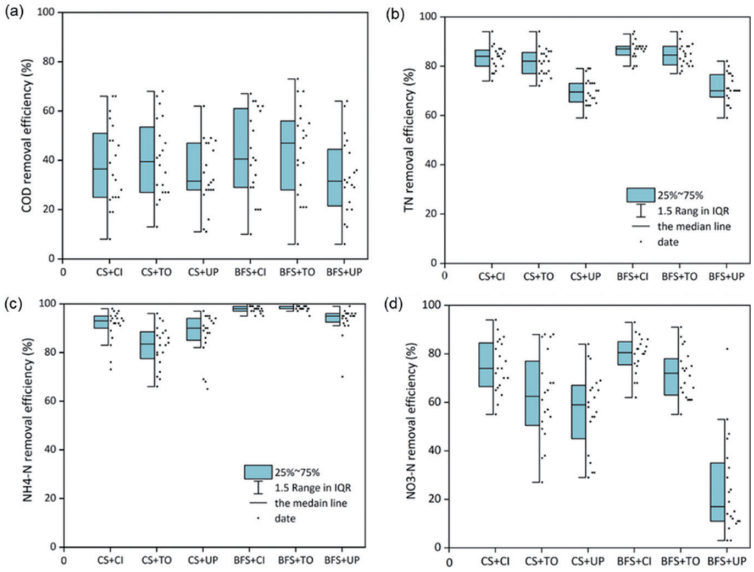


Figure 4. Removal efficiencies of water quality parameters in different CWs: (a) COD, (b) TN, (c) NH_4-N, and (d) NO_3-N. Source: Author

By comparing the correlation between the top 10 most abundant bacterial phyla and environmental factors, it was found that the relative abundance of *Bacteroidota* is significantly negatively correlated with

the removal efficiency of NH_4-N ($p < 0.05$), while *Chloroflexi* and *Planctomycetota* are significantly negatively correlated with the removal efficiency of TN ($p < 0.05$). Generally, these bacteria are mainly associated with the decomposition of organic matter and are not greatly related to nitrogen transformation processes. However, the high carbon and nitrogen pollution load in livestock wastewater, along with the low carbon and high nitrogen removal effectiveness in CWs, leads to an extremely high C/N ratio (30–60) in the wetlands. Although a high C/N ratio is favorable for denitrification reactions, it may lead to a drop in O_2 levels, thereby affecting the nitrification process and other oxygen-dependent biochemical reactions.

By comparing the correlation between the top 10 most abundant bacterial genera and environmental factors, we found that the relative abundances of *Ralstonia* and *Sediminibacterium* are significantly negatively correlated with the removal of TN ($p < 0.05$), while the relative abundance of *Sphingomonas* is significantly negatively correlated with the removals of COD and TN ($p < 0.05$), as well as the emission fluxes of CO_2 and N_2O ($p < 0.05$). These bacteria have the highest relative abundances in unplanted systems. On one hand, these bacteria may compete with nitrogen-transforming microbes for ecological niches and O_2 consumption, thus impacting the removal effectiveness of COD and TN. This phenomenon is particularly pronounced in unplanted systems lacking plant roots and root oxygenation. On the other hand, the decreased removal performance of organic matter and nitrogen in unplanted systems leads to reduced production of CO_2 and N_2O during decomposition, hence the removal efficiencies of COD and TN show a significant positive correlation with the emission fluxes of CO_2 and N_2O ($p < 0.05$).

(2) Reduction of Greenhouse Gas Emission

Figure 5 shows the emission fluxes of greenhouse gases: CO_2, CH_4, and N_2O. The average emission fluxes for CO_2, CH_4, and N_2O are 46.3±37.1 mg/m^2/h, 2.99±2.76 μg/m^2/h, and 5.52±2.84 mg/m^2/h, respectively. All CWs demonstrate high CO_2 and N_2O emission and low CH_4 emission. The type of substrate does not significantly affect the greenhouse gas emission flux in CWs, but the global warming potential (GWP) of CS-CWs is less than that of BFS-CWs. The presence of plants increases the greenhouse gas emission flux and enhances the GWP. The greenhouse gas emission flux and GWP of CI-CWs are lower than those of TO-CWs.

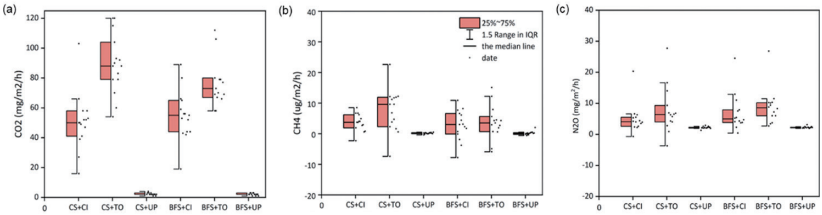


Figure 5. Emission fluxes of greenhouse gases in different CWs: (a) CO_2, (b) CH_4, and (c) N_2O. Source: Author

The pmoA and mcrA genes encode enzymes that respectively participate in the conversion of CH_4 to methanol and the reduction of compounds to produce CH_4. Both the abundance of the pmoA gene and the pmoA/mcrA ratio are higher in CS-CWs than in BFS-CWs; within CS-CWs, the unplanted systems show significantly higher pmoA gene abundance and pmoA/mcrA ratios compared to planted systems; correspondingly, these CWs with higher pmoA gene abundance and pmoA/mcrA ratios also have lower CH_4 emission fluxes. Methanotrophs prefer neutral to slightly acidic environments, and the typically higher

alkalinity of blast furnace slag is not conducive to the growth and activity of these bacteria, resulting in a reduced abundance of the pmoA gene.

The nosZ gene encodes a nitrous oxide reductase that participates in the production of N_2, while the nirS and nirK genes encode nitrite reductases involved in the production of N_2O. The abundance of the nosZ gene and the nosZ/(nirS+nirK) ratio are higher in CS-CWs than in BFS-CWs; these ratios and abundances are higher in unplanted systems than in planted systems; correspondingly, these CWs with higher nosZ gene abundance and nosZ/(nirS+nirK) ratios also have lower N_2O emission fluxes. Blast furnace slag is alkaline and contains heavy metals that hinder the growth of microbes like denitrifying bacteria. In contrast, ceramsite balances pH well and doesn't contain heavy metals, making it better for microbial growth. This is why the nosZ gene is more abundant in CS-CWs. Also, plants can increase oxygen in the rhizosphere, possibly limiting anaerobic denitrifying microbes. In unplanted systems, the lower oxygen conditions can better support these microbes, enhancing nosZ gene activity and reducing N_2O emissions.

4. Conclusion

(a) In summary, the bacterial community structure in CWs is influenced by the combination of different substrates and plants. The presence of ceramsite and plants promotes bacterial enrichment, while the diversity of rhizosphere bacteria is primarily affected by the species of plant. Unplanted systems enrich more specific bacteria, which may inhibit the removal of organic matter and nitrogen by competing for limited ecological niches and dissolved oxygen, thereby directly reducing the emissions of CO_2 and N_2O. Among these, CS+CI-CWs exhibit the best performance in terms of diversity and abundance of

bacterial communities, providing favorable conditions for the effective biodegradation of pollutants in livestock wastewater.

(b) Systems with ceramsite and those without plants have higher nosZ gene abundance and nosZ/(nirS+nirK) ratios, which help reduce N_2O emissions. Although unplanted systems have lower greenhouse gas emissions, their effectiveness in purifying livestock wastewater is also lower. Overall, CS+CI-CWs perform the best in both livestock wastewater treatment and greenhouse gas reduction. This is partly due to the higher abundance of aerobic and anaerobic bacteria in CS+CI-CWs, which facilitates the simultaneous processes of nitrification and denitrification, providing favorable conditions for the complete transformation of nitrogen to N_2. Moreover, the higher nosZ gene abundance in CS+CI-CWs promotes the production of N_2, effectively reducing N_2O emission flux and thereby lowering the GWP.

References

Chen, X., H. Zhu, B. Yan, B. Shutes, D. Xing, G. Banuelos, R. Cheng and X. Wang. 2020. Greenhouse Gas Emissions and Wastewater Treatment Performance by Three Plant Species in Subsurface Flow Constructed Wetland Mesocosms. *Chemosphere*, 239, 124795.

Cocozza, C., C. Di Iaconi, S. Murgolo, A. Traversa, F. De Mastro, M. De Sanctis, V. G. Altieri, C. Cacace, G. Brunetti and G. Mascolo. 2023. Use of Constructed Wetlands to Prevent Overloading of Wastewater Treatment Plants. *Chemosphere*, 311(2), 137126.

de Oliveira Souza, A., J. K. Brasil Bernardelli, L. de Carvalho Silva, F. Perretto, A. Nagalli, V. Mymrin, F. Hermes Passig and K. Q. de Carvalho. 2023. Plasterboard Sheet Applied in Vertical-Flow Constructed Wetlands: Nutrients Removal, Microbial Diversity, and Mechanisms. *Journal of Water Process Engineering*, 53, 103811.

Ding, X., Y. Xue, Y. Zhao, W. Xiao, Y. Liu and J. Liu. 2018. Effects of Different Covering Systems and Carbon Nitrogen Ratios on Nitrogen Removal in Surface Flow Constructed Wetlands. *Journal of Cleaner Production*, 172, 541–551.

Gu, X., K. Chen and C. Fan. 2015. Preliminary Evidence of Effects of *Phragmites australis* Growth on N_2O Emissions by Laboratory Microcosms. *Ecological Engineering*, 83, 33–38.

Hu, H., X. Li, S. Wu and C. Yang. 2020. Sustainable Livestock Wastewater Treatment Via Phytoremediation: Current Status and Future Perspectives. *Bioresource Technology*, 315, 123809.

Knight, R. L., V. W. E. Payne Jr., R. E. Borer, R. A. Clarke Jr. and J. H. Pries. 2000. Constructed Wetlands for Livestock Wastewater Management. *Ecological Engineering*, 15(1-2), 41–55.

Maltais-Landry, G., R. Maranger, J. Brisson and F. Chazarenc. 2009. Greenhouse Gas Production and Efficiency of Planted and Artificially Aerated Constructed Wetlands. *Environmental Pollution*, 157(3), 748–754.

Mlih, R., F. Bydalek, E. Klumpp, N. Yaghi, R. Bol and J. Wenk. 2020. Light-Expanded Clay Aggregate (LECA) as a Substrate in Constructed Wetlands: A Review. *Ecological Engineering*, 148, 105783.

Parde, D., A. Patwa, A. Shukla, R. Vijay, D. J. Killedar and R. Kumar. 2021. A Review of Constructed Wetland on Type, Treatment and Technology of Wastewater. *Environmental Technology & Innovation*, 21, 101261.

Sun, H., C. Zhang, C. Song, S. X. Chang, B. Gu, Z. Chen, C. Peng, J. Chang and Y. Ge. 2013. The Effects of Plant Diversity on Nitrous Oxide Emissions in Hydroponic Microcosms. *Atmospheric Environment*, 77, 544–547.

Xu, P., M. Jiang, I. Khan, M. Shaaban, J. Zhao, T. Yang and R. Hu. 2023. The Effect of Upland Crop Planting on Field N_2O Emission from Rice-Growing Seasons: A Case Study Comparing Rice-Wheat and Rice-Rapeseed Rotations. *Agriculture, Ecosystems & Environment*, 347, 108365.

Chapter 3
Challenges of Veterinary Antibiotic Pollution from Swine Farms and Possible Wastewater Treatment Options

Obey GOTORE

Abstract: The rapid growth of pig farming in Asia has led to increased antibiotic use in swine production, resulting in significant environmental pollution from antibiotic residues in wastewater. These residues pose risks to ecosystems, human health, and agricultural productivity, but research on the extent of contamination and effective mitigation strategies remains limited. Conventional wastewater treatment methods often fall short in eliminating veterinary antibiotics, allowing these contaminants to persist in the environment. This issue is exacerbated by the structure, persistence, resistance, toxicity, and high risks associated with antibiotics, making their treatment particularly challenging. As a result, there is a pressing need for more efficient treatment technologies. Recent studies have explored various methods and optimal conditions for removing antibiotic residues from swine farm effluents. Advanced technologies, such as upflow anaerobic sludge blankets (UASB) and membrane bioreactors, show promise but are costly and difficult to implement on a larger scale. In contrast, more affordable and accessible approaches like adsorption and nature-based solutions, including constructed wetlands (CWs) and phytoremediation, offer significant advantages due to their low cost, simplicity, and minimal energy requirements. One particularly promising approach involves combining biochar with manganese oxides for antibiotic removal. Manganese oxides are abundant, easy

to process, and environmentally friendly, while biochar modified with manganese oxides possesses a high positive surface charge and strong antibiotic immobilization capacity. This combination enhances the removal efficiency of antibiotics and helps reduce the spread of antibiotic-resistant genes, addressing both environmental pollution and public health concerns. This innovative method holds great potential for mitigating the environmental impacts of antibiotic residues in swine wastewater. However, further research is needed to optimize the use of biochar-manganese oxide composites for effective antibiotic removal, ultimately contributing to more sustainable and safer agricultural practices by reducing environmental harm and combating antibiotic resistance.

Keywords: *antibiotic residues, swine wastewater, biochar-manganese oxide composites, antibiotic resistance, constructed wetlands*

1. Introduction

(1) Antibiotic Pollution from Swine Farm

Wastewater pollution from agricultural activities, particularly pig farming, has become a critical environmental challenge. Pig farming produces substantial waste, including both organic and inorganic pollutants, that negatively impact ecosystems. Among these pollutants, antibiotics and antimicrobials, such as fluoroquinolones, are especially concerning due to their extensive use in animal husbandry and their persistence in the environment. The issue of antibiotic pollution from swine farms has garnered significant attention because of its harmful effects on ecosystems and public health.

Antibiotics are essential for maintaining livestock health and improving feed efficiency, facilitating the production of high-quality

meat. In Japan, tetracycline is the most widely used antibiotic in food-producing animals, followed by polyethers, penicillins, sulfonamides (SAs), and macrolides (MLs). Table 1 highlights nine antibiotics commonly employed in Japanese livestock farming.

Table 1. Classification and application of 16 pharmaceuticals and metabolites in Japan

Compound	Classification	Use in
Lincomycin (LCM)	Lincosamides	Livestock
Tylosin (TYL)	Macrolides	Livestock
Tilmicosin (TMC)	Macrolides	Livestock
Tiamulin (TML)	Pleuromutilins	Livestock
Sulfamonomethoxine (SMM)	Sulfonamides	Livestock
Sulfamethazine (SMZ)	Sulfonamides	Livestock
Oxytetracycline (OTC)	Tetracyclines	Livestock
Sulfamethoxazole (SMX)	Sulfonamides	Livestock & human
N-Acetyl sulfamethoxazole (N-SMX)	Metabolite of SMX	Livestock & human
Trimethoprim (TMP)	Synthetic antibiotic	Livestock & human
Carbamazepine (CBZ)	Antiepileptics	Human
Crotamiton (CRT)	Antipruritics	Human
Sulfapyridine (SPD)	Metabolite of sulfasalazine	Human
Diclofenac (DCF)	Non-steroidal anti-inflammatory drugs	Human
Clarithromycin (CAM)	Macrolides	Human
Acetaminophen (ACT)	Antipyretic analgesics	Human

Source: (Hanamoto et al. 2023)

However, the overuse and improper application of antibiotics have led to the emergence of antibiotic-resistant bacteria (ARB) and antibiotic-resistant genes (ARGs), posing significant risks to both human and environmental health. Globally, annual antibiotic usage is estimated to range between 100,000 and 200,000 tons, with

consumption increasing by 65% between 2000 and 2015. In Japan, large quantities of antibiotics are sold each year, predominantly for veterinary purposes. Alarmingly, 30–90% of administered antibiotics are excreted by animals through urine and feces, eventually entering the environment via livestock manure. In 2017, Japan produced approximately 22 million tons of swine waste, representing nearly 30% of the nation's total livestock waste. Swine waste is typically managed by separating it into solid and liquid fractions. The liquid fraction is treated aerobically using activated sludge systems, while the solid fraction is composted. However, conventional treatment methods are largely ineffective at removing antibiotics, allowing these pollutants to persist in the environment and exacerbate pollution.

The environmental consequences of antibiotic pollution are profound. Residual antibiotics in soil and water disrupt microbial communities that are essential for maintaining ecosystem balance. Of greater concern is the role of antibiotic residues in the proliferation of ARB. These bacteria can transfer resistance genes to other microorganisms, including human pathogens, through horizontal gene transfer. The spread of antibiotic resistance poses a significant global public health threat by diminishing the effectiveness of antibiotics in treating infectious diseases. Addressing this issue requires innovative approaches and sustainable solutions to mitigate antibiotic pollution and its associated risks to ecosystems and human health.

(2) Challenges in Antibiotic Removal from Swine Wastewater

Antibiotic contamination in swine wastewater is a significant and growing environmental issue, with far-reaching impacts on ecosystems and public health. The complex chemical properties of antibiotics, their toxicological effects on aquatic organisms, and their role in fostering

antimicrobial resistance (AMR) present numerous challenges for effective wastewater treatment. This section outlines the major obstacles in addressing the removal of antibiotics from swine wastewater:

1) Persistence and Resistance of Antibiotics

Antibiotics such as sulfonamides and tetracyclines are highly persistent in the environment, making their removal from wastewater difficult. Their microparticle size allows them to bypass conventional treatment systems, such as sedimentation or biological treatments, and persist in treated effluent. For example, high concentrations of sulfonamide antibiotics (560–4660 ng/L) and tetracycline antibiotics (810−2420 ng/L) have been detected in surface waters near livestock farms, such as those in Jiangsu Province, China (Wei et al. 2011). These concentrations illustrate the inefficiency of traditional wastewater treatment systems in fully eliminating these contaminants.

Tetracycline, in particular, poses a significant challenge due to its resistance to degradation. Its continued presence in wastewater creates a cycle of environmental reintroduction, with resistant bacteria and genes re-entering agricultural systems. This feedback loop exacerbates AMR, making disease treatment in livestock and humans increasingly difficult and less effective over time.

2) High Costs of Advanced Treatment Technologies

While advanced technologies, such as membrane filtration, show promise for removing antibiotics from wastewater, their prohibitive costs make them inaccessible for large-scale application, particularly in agriculture. For many livestock operations, especially in developing countries, investing in such technologies is economically unfeasible. This leaves a critical gap in treatment capabilities, allowing antibiotics to persist in wastewater discharged into the environment. Efficient and

cost-effective alternatives are urgently needed. The development of affordable technologies that can effectively remove antibiotics at the source, such as in agricultural wastewater streams, is fundamental to addressing this issue. Without such innovations, the economic burden of advanced treatment technologies will continue to hinder progress in tackling antibiotic contamination.

3) Mixture Toxicity

Antibiotics in wastewater pose significant toxicological risks to aquatic ecosystems. Their presence disrupts microbial communities, affecting processes such as growth, respiration, and enzyme activity in aquatic organisms, including proteobacteria, cyanobacteria, algae, daphnia, and fish. Antibiotics such as sulfonamides and tetracyclines inhibit the replication and metabolic pathways of algae, which are essential for maintaining ecological balance. Moreover, mixtures of antibiotics present in wastewater can have synergistic toxic effects, leading to stronger adverse impacts on aquatic organisms than individual compounds. These disruptions can cascade through the ecosystem, reducing biodiversity and impairing critical ecological functions.

4) Seasonal Variability in Antibiotic Concentrations

Antibiotic concentrations in wastewater vary with seasonal changes, often peaking during the summer months. This seasonal variability complicates the operation and design of treatment systems, which must handle fluctuating levels of contaminants. The higher concentrations observed in warmer months increase the risk of environmental contamination, requiring dynamic and adaptable treatment methods capable of addressing seasonal variations effectively.

5) Need for Source-Level Treatment and Management

The most effective approach to addressing antibiotic contamination in swine wastewater is to prevent its release at the source. Agricultural operations must implement measures to reduce the discharge of antibiotics into water bodies, including better waste management practices and more targeted use of antibiotics in livestock farming. Efforts should also focus on developing innovative, low-cost, and scalable technologies capable of removing antibiotics before they enter surface water or groundwater. By targeting the source of contamination, it is possible to minimize the spread of antibiotics and reduce their environmental and public health impacts.

2. Treatment of Swine Wastewater

(1) Swine Wastewater Treatment Methods in Japan

Various methods have been developed to remove antibiotics from wastewater, with several approaches specifically applied to swine wastewater in Japan, as shown in Table 2. Among these methods, aeration — particularly continuous and intermittent aeration — plays a significant role by providing oxygen, which can facilitate the removal of antibiotics. However, some treatment methods, such as membrane bioreactors, are prohibitively expensive and may not be feasible for widespread application.

More cost-effective alternatives, such as batch reactors, offer practical solutions. These systems utilize specific microbes capable of breaking down certain antibiotics. Nevertheless, not all antibiotics are easily degradable by bacteria, particularly those that are highly concentrated or chemically resistant. For such cases, additional or alternative methods must be employed to ensure the effective removal of these persistent compounds.

Table 2. Swine wastewater treatment methods in various pig farms in Japan

Numbers of Sows	Production and growth stage	Separation process of solid and liquid	Treatment method	Aeration condition
81	Sows - weaning Fattening	Yes, Fermentation bed	Membrane bioreactor	Continuous
610	Sows - weaning, fattening	Yes, partly fermentation bed	Activated sludge process	Continuous
	Fattening	Fermentation bed	–	–
1867	All	No, partly fermentation bed	Activated sludge process	Continuous
523	All	Yes	Activated sludge process	Intermittent
863	All	Yes	Activated sludge process	Intermittent
4934	Sows - lactating	Yes	Aerated lagoon	Intermittent
	Weaning - fattening	Yes	Aerated lagoon	Intermittent
502	Sows-lactating, fattening	Yes	Membrane bioreactor	Continuous
	Weaning - fattening	Yes	Activated sludge process	Continuous
321	Sows - weaning	No	Aerated lagoon	Intermittent
	Fattening	Fermentation bed	–	–
90	All	Yes, partly fermentation bed	Sequencing batch reactor	Intermittent
236	All	Yes	Two-stage activated sludge process	Continuous
n.i.	–	Yes	Two-stage activated sludge process	Continuous

Source: (Watanabe et al. 2023)

(2) A Case Study on Antibiotic Removal in Two Swine Wastewater Treatment Systems in China

China, being the world's largest producer and consumer of pork, uses significantly more antibiotics in its swine industry compared to other countries, such as the United States, to achieve comparable levels of meat production. This heavy reliance on antibiotics has raised significant environmental and public health concerns. In 2013, it was

estimated that the total antibiotic usage in China was approximately 162,000 tons, with around 52% of this amount consumed by animals (Zhang et al. 2018). A large portion of these antibiotics eventually enters the environment through manure and wastewater, posing risks of antibiotic contamination and the development of ARB.

One of the key challenges facing the Chinese swine industry is the inadequate treatment of wastewater from pig farms. Many farms rely on simple and outdated treatment methods, such as lagoons or anaerobic digesters. While these systems are cost-effective, they are largely ineffective at removing antibiotics and their residues from the wastewater. Recently, more advanced treatment systems, such as UASB and anaerobic-aerobic oxidation systems, have been introduced to some farms. However, these systems require further evaluation to determine their efficiency and feasibility for widespread use in mitigating antibiotic contamination.

This study aimed to investigate the effectiveness of two different treatment technologies employed at two separate swine farms, referred to as Farm A and Farm B, in reducing antibiotic contamination in wastewater. Figure 1 illustrates the technical flowcharts of the swine wastewater treatment systems implemented in Farm A and Farm B. The study provided insights into the performance of these treatment systems and the challenges they faced in removing various antibiotics.

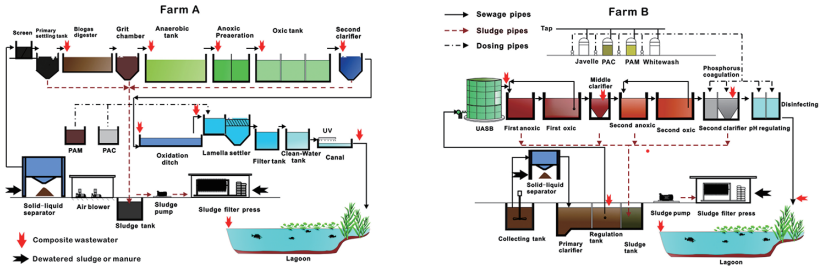


Figure 1. Diagram of wastewater treatment systems in Farm A and Farm B. Source: (Zhang et al. 2018)

Farm A employed a combination of an anaerobic digester, an A^2/O system (anaerobic-anoxic-oxic), and a lagoon system, with the anaerobic digester serving as the primary treatment component. The wastewater underwent successive treatment stages, including anaerobic, anoxic, and aerobic processes, before being discharged into the lagoon. Despite these efforts, the system demonstrated limited effectiveness in removing certain antibiotics. Among the 21 targeted antibiotics detected in wastewater samples from Farm A (Figure 2), the predominant compounds in the influent included sulfachloropyridazine, sulfamonomethoxine, oxytetracycline, and lincomycin. In the effluent, the dominant antibiotics were sulfamonomethoxine, chlortetracycline, tetracycline, oxytetracycline, and lincomycin. Tetracycline and its related compounds proved particularly difficult to remove, persisting throughout the treatment process. The highest concentrations detected in Farm A's effluent were 166 ± 3.64 μg/L for lincomycin and 1.40 ± 1.00 μg/L for oxytetracycline.

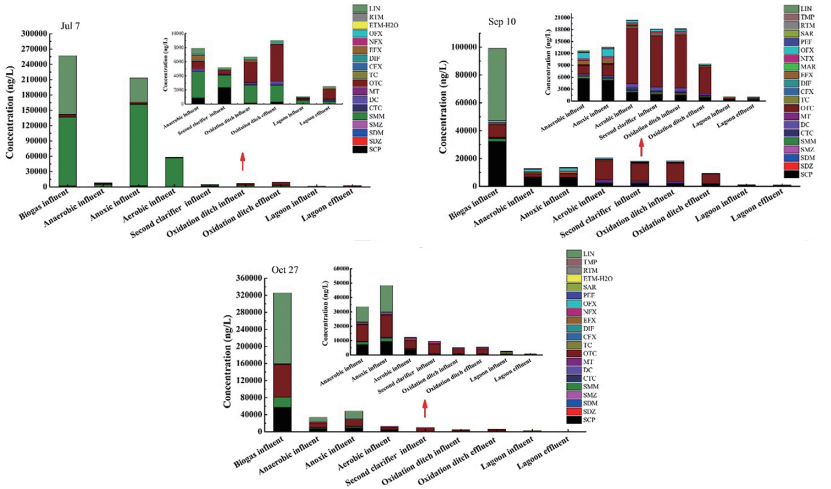


Figure 2. Antibiotic concentrations in the liquid phase of each treatment unit at Farm A during three sampling times (July 7, September 10, and October 27, 2016). Abbreviations: SCP (sulfachlorpyridazine), SDZ (sulfadiazine), SDM (sulfadimethoxine), SMZ (sulfamethazine), SMM (sulfamonomethoxine), CTC (chlortetracycline), DC (doxycycline), MT (methacycline), OTC (oxytetracycline), TC (tetracycline), CFX (ciprofloxacin), DIF (difloxacin), EFX (enrofloxacin), MAR (marbofloxacin), NFX (norfloxacin), OFX (ofloxacin), PEF (pefloxacin), SAR (sarafloxacin), ETM-H2O (erythromycin-H2O), RTM (roxithromycin), TMP (trimethoprim), and LIN (lincomycin). Source: (Zhang et al. 2018)

Farm B, on the other hand, used a combination of a UASB system, an $(A/O)^2$ system (anoxic/oxic-anoxic/oxic), and a lagoon system for wastewater treatment. The UASB system is considered an advanced anaerobic treatment method that enhances the degradation of organic matter. The study targeted 22 antibiotics in the wastewater samples from Farm B, including 5 sulfonamides, 5 tetracyclines, 7 fluoroquinolones,

3 macrolides, lincomycin, and trimethoprim. In the influent of Farm B's treatment system, sulfachloropyridazine and oxytetracycline were the most predominant antibiotics. After treatment, the effluent still contained significant concentrations of sulfachloropyridazine, sulfamonomethoxine, oxytetracycline, trimethoprim, and lincomycin (Figure 3). Similar to Farm A, tetracycline and its related compounds remained persistent and were detected in all samples, indicating the difficulty of removing these antibiotics even with advanced treatment technologies.

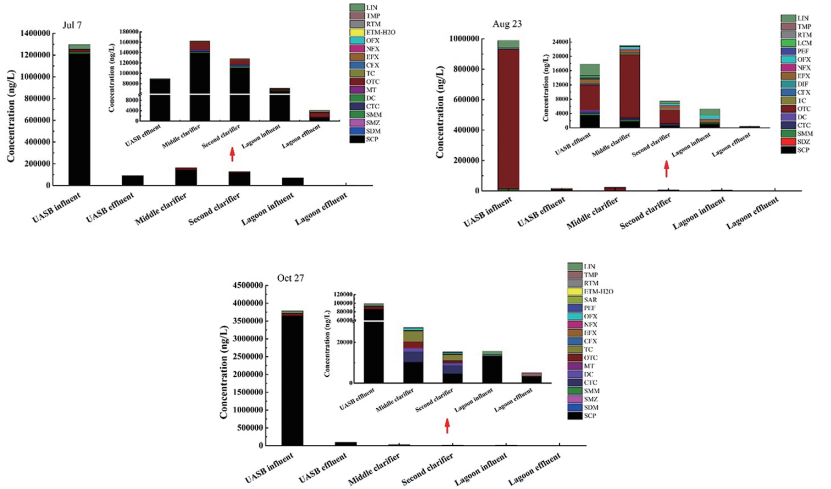


Figure 3. Antibiotic concentrations in the liquid phase of each treatment unit at Farm B during three sampling times (July 7, August 23, and October 27, 2016). Source: (Zhang et al. 2018).

The study revealed that both wastewater treatment systems demonstrated some degree of effectiveness in reducing the total concentration of antibiotics in swine wastewater. The anaerobic digester from Farm A and the UASB system from Farm B, each made significant

contributions to antibiotic reduction. However, neither technology was fully capable of eliminating antibiotics from the wastewater. Overall, the findings highlight the challenges of treating antibiotic-laden wastewater from swine farms, even with the use of advanced technologies. Both Farm A and Farm B faced notable limitations in removing certain antibiotics, particularly tetracycline and its derivatives, which remained prevalent in the treated effluents. These results emphasize the need for additional or alternative treatment methods to achieve higher removal efficiencies and prevent the release of antibiotic residues into the environment.

Future research should focus on exploring and optimizing advanced treatment technologies. Possible solutions include integrating CWs, membrane bioreactors, or other nature-based approaches to enhance antibiotic removal from swine farm wastewater. Furthermore, the implementation of stricter regulations on antibiotic usage in livestock farming, coupled with improved waste management practices, could play a crucial role in mitigating the environmental impact of antibiotic contamination.

3. Removal of Veterinary Antibiotics from Swine Wastewater

(1) Phytoremediation

The treatment of swine wastewater, particularly with a focus on the removal of veterinary antibiotics, remains a significant challenge in environmental engineering. Among the various potential approaches, the utilization of algae has emerged as a promising solution. Algae, with their inherent ability to remove antibiotics, represent a sustainable and nature-based method for wastewater treatment. Through the

process of phytoremediation, both microalgae (unicellular organisms) and macroalgae (multicellular organisms) can play a critical role in addressing this issue.

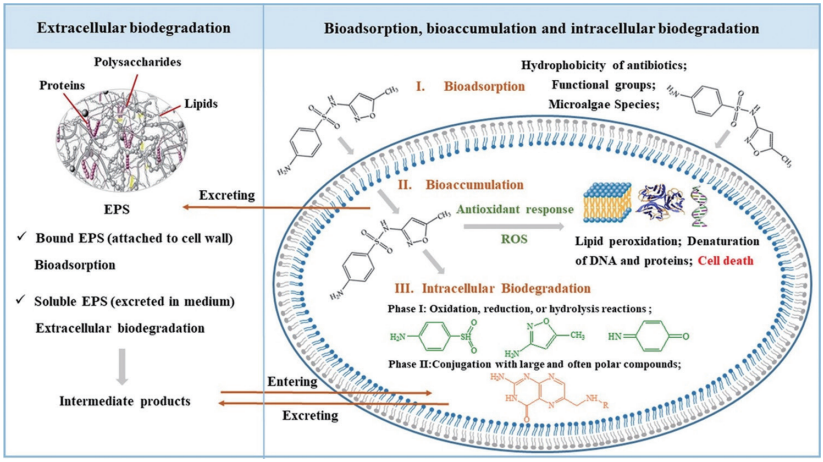


Figure 4. Mechanisms underlying antibiotic removal by microalgae. Source: (Xiong et al. 2021)

One of the notable pathways through which algae contribute to the degradation of antibiotics is biodegradation, which includes indirect photodegradation. Since algae require light and carbon dioxide to grow, their exposure to sunlight plays a vital role in facilitating this process. Studies have demonstrated that when algae, particularly microalgae, are present in an aqueous solution containing tetracycline (a commonly used veterinary antibiotic), the rates of bio-adsorption and bioaccumulation of tetracycline are significantly reduced. In fact, it has been observed that these rates can decrease by as much as 50% when the solution is exposed to sunlight in the presence of algae. Furthermore, microalgae exhibit an additional advantage by influencing the pH levels of their environment. As these organisms grow, they naturally regulate

the pH, particularly within reactor systems designed for wastewater treatment (Ding et al. 2015; Wu et al. 2019). The photosynthetic activity of algae not only promotes their growth but also leads to an increase in pH levels. This rise in pH is a crucial factor in the effective removal of certain ionic antibiotics, including tetracycline. The hydrolysis of tetracycline and similar compounds is strongly pH-dependent, and the pH adjustments facilitated by algae create an environment conducive to breaking down these antibiotics.

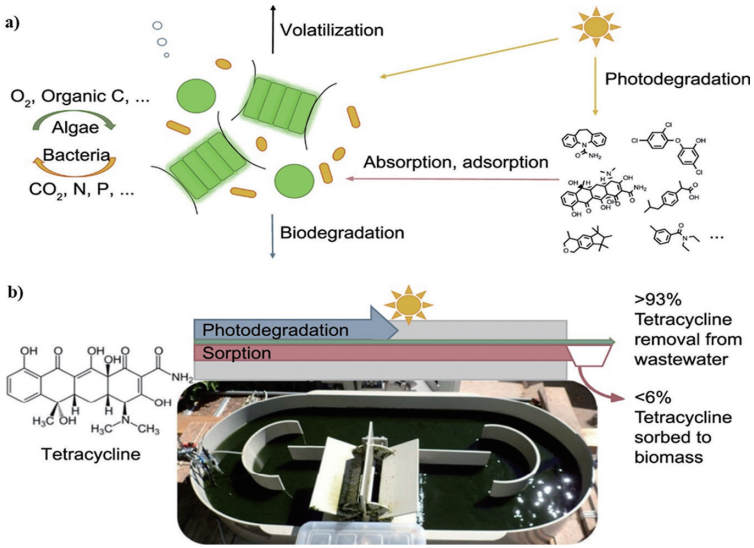


Figure 5. a) Removal of antibiotics using algae-bacteria method, b) Tetracycline removal through algal pond system. Source: (Li et al. 2022)

(2) Constructed Wetlands

CWs have proven to be highly effective in removing antibiotics from wastewater, which is one of the key advantages they offer.

However, it is essential to consider not only the presence of suitable substrates and plants but also the characteristics of the materials used in the system. In particular, the addition of biochar has been found to significantly enhance or modify the treatment mechanisms in CWs.

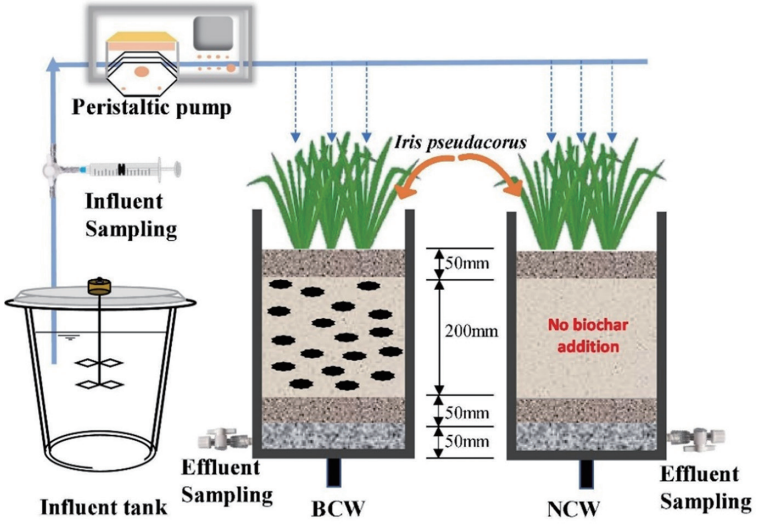


Figure 6. Experimental diagram of biochar-based CWs for antibiotic removal. Source: (Ajibade et al. 2023)

Biochar, known for its nearly neutral pH and predominantly negative surface charge, plays a critical role in the efficiency of antibiotic removal. When incorporated into CWs, biochar's surface properties enable it to attract and retain positively charged antibiotics through adsorption or absorption. This process helps to sequester the antibiotics within the system, where they can be accessed by plants for uptake. Additionally, biochar acts as a physical medium that can hold the antibiotics within the CWs, reducing the likelihood of their release back into the environment. Over time, biochar's capacity to

adsorb or absorb contaminants can be enhanced by the presence of microorganisms within the system. Though the degradation of biochar can be a complex process, the likelihood of biodegradation increases significantly in the long term. Microbial activity can gradually break down biochar and further contribute to the removal of antibiotics, though this depends on the specific microorganisms available in the system.

From a broader perspective, the use of biochar in CWs has the potential to reduce the proliferation of ARGs that can accumulate in wastewater. These ARGs pose a serious risk, particularly in agricultural systems where pigs or livestock may ingest antibiotic-laden waste. By sequestering antibiotics in the biochar, the spread and uptake of ARGs can be mitigated, preventing further contamination of the food chain. Biochar's properties, including its ability to adsorb and retain contaminants, play a key role in this process.

Additionally, biochar's surface chemistry, which includes hydroxyl (-OH) and carboxyl (-COOH) functional groups, allows it to engage in various interactions, such as hydrogen bonding and hydrophobic exchange. These interactions contribute to its ability to trap contaminants and facilitate their removal from wastewater. The biochar surface can also provide a habitat for microorganisms, which can further enhance the removal of nutrients and contaminants, as noted by other researchers.

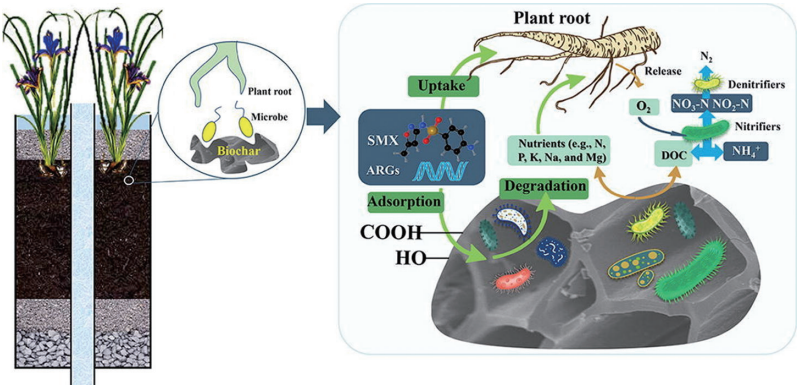


Figure 7. Processes involved in the removal of antibiotics using biochar-based CWs. Source: (Ajibade et al. 2023)

Figure 7 illustrates some of the functional groups present on the surface of biochar, including hydroxyl and carboxyl groups, which contribute to its adsorption capacity. These functional groups also help support the colonization of microorganisms, enabling them to thrive on the biochar surface. In turn, this microbial activity accelerates the removal of antibiotics and other nutrients, improving the overall treatment efficiency of the CWs.

(3) Enhancing Anaerobic Processes with Biochar Derived from Swine Manure

Another important consideration involves the treatment of solid waste, such as manure, through a process known as pyrolysis. By pyrolyzing swine manure, it is possible to repurpose the resulting biochar as an additive to enhance the anaerobic digestion (AD) of swine wastewater. This approach not only facilitates the recovery of energy but also contributes to the attenuation of ARGs.

This process creates a beneficial cycle, where waste is effectively managed by first undergoing pyrolysis to produce carbon-rich biochar. The biochar can then be utilized to adsorb and remove antibiotics and other contaminants from the wastewater, leveraging its adsorption properties. This dual function of waste conversion — generating energy while reducing contamination — presents a sustainable solution for managing swine wastewater.

Wang et al. (2022) demonstrated that the use of dewatered swine manure-derived biochar (DSMB) in AD systems enhances microbial activity and promotes energy recovery. DSMB also plays a key role in limiting the spread of ARGs by preventing their re-ingestion by pigs. Additionally, the study found that DSMB positively influences CH_4 production during the digestion of swine wastewater (Figure 8a), making it a promising additive for in situ biogas production during AD.

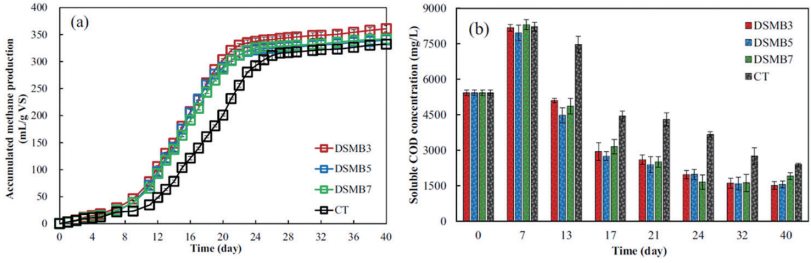


Figure 8. a) Methane production, b) COD removal. Source: (Wang et al. 2022)

Microbial community analysis revealed that dominant microorganisms at the genus level, such as Clostridium sensu stricto, Defluviitoga, Terrisporobacter, and Syntrophomonas, are crucial in the AD process. These microorganisms not only aid in digesting the wastewater but also contribute to the degradation of antibiotics, further

improving process efficiency.

The results show a clear distinction from the control group, with a significant decrease in chemical oxygen demand (COD) concentration (Figure 8b). This demonstrates the effectiveness of biochar-enhanced AD in reducing both organic matter and antibiotic contamination.

(4) Combined Effects of Active Manganese Species and Biochar

Developing efficient catalysts for antibiotic degradation is an effective strategy to combat environmental pollution through advanced oxidation processes. One such approach involves leveraging the effects of active manganese. Research on manganese oxidation has revealed that manganese oxides, the products of heavy metal oxidation, can play a crucial role in this process. These manganese oxides, particularly manganese (IV), are produced from manganese (II), a soluble and toxic form of manganese that can pose significant risks to human health. However, through the action of certain microorganisms, manganese (II) can be oxidized to manganese (III) and predominantly to manganese (IV), which is less harmful.

When combined with biochar, these manganese oxides can create a modified biochar that is effective in treating or removing antibiotics, such as tetracycline, through adsorption. The potential for using manganese oxides on different biochar materials to remove antibiotics is still being explored. Initially, biochar without modification was used to consider cost factors. It has been observed that manganese oxides are naturally produced through bacterial oxidation, allowing for their collection and attachment to biochar for use in antibiotic removal.

In a similar study (Zhang et al. 2024), tetracycline removal from livestock wastewater was examined using four systems: activated persulfate (PS), biochar (BC) loaded with PS, δ-MnO_2/PS, and BC

loaded with δ-MnO_2/PS. The tetracycline removal rates were tested under different temperatures, revealing that higher temperatures facilitated the reaction. At lower temperatures (15°C), the removal effect for all systems decreased; however, the δ-MnO_2/BC/PS system showed only a slight decrease, from 83% to 79%. When temperatures dropped further to 5°C–10°C, the effectiveness of all systems declined, but the δ-MnO_2/BC/PS system maintained a tetracycline removal rate of 40% at 5°C, outperforming the other systems (Figure 9).

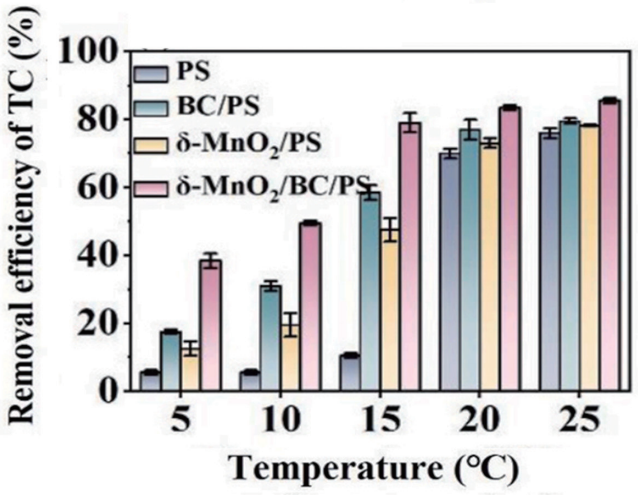


Figure 9. Tetracycline removal efficiency at different temperatures. Source: (Zhang et al. 2024)

This indicates that tetracycline removal remains a challenge, even when combining manganese oxides and biochar. Temperature conditions play a critical role in the efficiency of the process. The use of manganese oxides for wastewater treatment is an area that continues to develop. Ongoing research aims to identify which types of manganese oxides and what modifications can be implemented to enhance the effectiveness of

manganese oxides and biochar, especially in the treatment of antibiotics from farm wastewater.

(5) Combined Manganese Oxides and Modified Biochar

Modifying biochar is crucial for creating multifunctional materials with enhanced capabilities for remediating contaminated water. A promising approach involves using sunlight-sensitive micro-catalysts (SSMs), created by loading MnO_2 onto the porous structure of honeycomb-like KOH-modified biochar (MBC) to enhance photocatalytic performance. Ma et al. (2023) demonstrated the effectiveness of this composite material in degrading CTC under various conditions. The SSM exhibited significantly higher photocurrent intensity compared to pure MnO_2, underscoring its superior ability to transfer and separate photoinduced carriers, a key factor for efficient photocatalysis. This improvement is attributed to the confinement effect of the KOH-modified biochar, which enhanced MnO_2 dispersion and increased sunlight absorption for photocatalysis. Furthermore, electrostatic interactions between MnO_2 and CTC contributed to higher CTC removal efficiency. Overall, the integration of MnO_2 with KOH-modified biochar not only boosts photocatalytic performance but also ensures optimal CTC removal across a range of pH conditions. Figure 10 illustrates the synthesis process of SSM and the chlortetracycline degradation process by SSM.

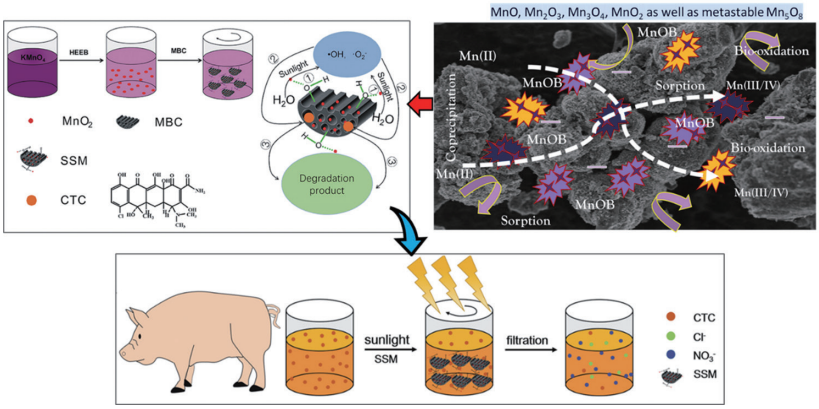


Figure 10. The synthesis process of SSM and the chlortetracycline degradation process by SSM in swine urine. Sources: (Gotore et al. 2025; Ma et al. 2023).

4. Conclusion

Intensive pig farming significantly contributes to environmental pollution, including antibiotic contamination. Many countries are implementing policies to address this issue by focusing on the treatment of swine wastewater and the safe recycling of livestock manure and wastewater in ways that minimize environmental harm. The combination of biochar and nanomaterials, such as manganese oxides, presents a cost-effective solution with enhanced antibiotic removal capacity while promoting environmental safety.

Manganese oxides are abundant, easy to process, and environmentally friendly. Biochars modified with manganese oxides often exhibit a high point of zero charge, strong positive surface charges, high oxidation potential, and a remarkable ability to immobilize antibiotics. These properties make them highly effective in mitigating

the spread of ARGs in agricultural environments. Furthermore, manganese oxide-modified biochar demonstrates a strong capacity for the adsorption and immobilization of antibiotics, further enhancing its utility in addressing pollution challenges.

Given these advantages, further research is essential to optimize the use of nanomaterials, including biochar and its modified forms, for effectively removing antibiotics from swine wastewater. This approach not only minimizes the environmental impact of intensive livestock farming but also reduces the risk of spreading ARGs, contributing to a safer and more sustainable agricultural system.

References

Abdelfattah, A., S. S. Ali, H. Ramadan, E. I. El-Aswar, R. Eltawab, S. H. Ho, T. Elsamahy, S. Li, M. M. El-Sheekh, M. Schagerl, M. Kornaros and J. Sun. 2023. Microalgae-Based Wastewater Treatment: Mechanisms, Challenges, Recent Advances, and Future Prospects. *Environmental Science and Ecotechnology*, 13, 100205.

Ajibade, F. O., W. X. Yin, A. Guadie, T. F. Ajibade, Y. Liu, M. N. Kumwimba, W. Z. Liu, J. L. Han, H. C. Wang and A. J. Wang. 2023. Impact of Biochar Amendment on Antibiotic Removal and ARGs Accumulation in Constructed Wetlands for Low C/N Wastewater Treatment. *Chemical Engineering Journal*, 459, 141541.

Ding, S. L., X. K. Wang, W. Q. Jiang, R. S. Zhao, T. T. Shen, C. Wang and X. Wang. 2015. Influence of pH, Inorganic Anions, and Dissolved Organic Matter on the Photolysis of Antimicrobial Triclocarban in Aqueous Systems under Simulated Sunlight Irradiation. *Environmental Science and Pollution Research*, 22, 5204–5211.

Gotore, O., M. Watanabe, K. Okano, N. Miyata, T. Katayama, T. Yasutaka, Y. Semoto and T. Hamai. 2025. Effects Of Batch and Continuous-Flow Operation on Biotreatment of Mn (II)-Containing Mine Drainage. *Journal of Environmental Sciences*, 152, 401–415.

Hanamoto, S., Y. Minami, S. S. T. Hnin and D. Yao. 2023. Localized Pollution of Veterinary Antibiotics in Watersheds Receiving Treated Effluents from Swine Farms. *Science of the Total Environment*, 902, 166211.

Li, S., P. L. Show, H. H. Ngo and S. H. Ho. 2022. Algae-Mediated Antibiotic Wastewater Treatment: A Critical Review. *Environmental Science and Ecotechnology*, 9, 100145.

Ma, H., Z. Wang, L. Qian, G. Jin, P. Yang, D. Wang, S. Xu, D. Cai, Z. Wu and X. Zhang. 2023. Honeycomb-Like MnO_2/Biochar Catalyst Fabricated by High-Energy Electron Beam Irradiation for Degradation of Antibiotics in Swine Urine. *Biomimetics*, 8(1), 32.

Wang, G., J. Zhu, Y. Xing, Y. Yin, Y. Li, Q. Li and R. Chen. 2022. When Dewatered Swine Manure-Derived Biochar Meets Swine Wastewater in Anaerobic Digestion: A Win-Win Scenario Towards Highly Efficient Energy Recovery and Antibiotic Resistance Genes Attenuation for Swine Manure Management. *Science of the Total Environment*, 803, 150126.

Watanabe, M., K. S. Guruge, R. Uegaki, K. Kure, I. Yamane, S. Kobayashi and M. Akiba. 2023. Occurrence and the Potential Ecological Risk of Veterinary Antimicrobials in Swine Farm Wastewaters in Japan: Seasonal Changes, Relation to Purchased Quantity and after Termination of Oxytetracycline Usage. *Environment International*, 173, 107812.

Wei, R., F. Ge, S. Huang, M. Chen and R. Wang. 2011. Occurrence of Veterinary Antibiotics in Animal Wastewater and Surface Water around Farms in Jiangsu Province, China. *Chemosphere*, 82(10),

1408–1414.

Wu, Y., L. Deng, L. Bu, S. Zhu, Z. Shi and S. Zhou. 2019. Degradation of Diethyl Phthalate (DEP) by Vacuum Ultraviolet Process: Influencing Factors, Oxidation Products, and Toxicity Assessment. *Environmental Science and Pollution Research*, 26, 5435–5444.

Xiong, Q., L. X. Hu, Y. S. Liu, J. L. Zhao, L. Y. He and G. G. Ying. 2021. Microalgae-Based Technology for Antibiotics Removal: From Mechanisms to Application of Innovational Hybrid Systems. *Environment International*, 155, 106594.

Zhang, M., Y. S. Liu, J. L. Zhao, W. R. Liu, L. Y. He, J. N. Zhang, J. Chen, L. K. He, Q. Q. Zhang and G. G. Ying. 2018. Occurrence, Fate and Mass Loadings of Antibiotics in Two Swine Wastewater Treatment Systems. *Science of the Total Environment*, 639, 1421–1431.

Zhang, R., Z. Lin, J. Chen, Y. Zhang, Y. Zhang, Y. Ma, Z. Zhang and Y. Sun. 2024. Mechanistic Insights into δ-MnO_2/Biochar–Activated Persulfate-Treated Wastewater Containing Antibiotics and Heavy Metals: Nonradical Pathway and Pivotal Role of Cu (II) at Low Temperature. *Chemosphere*, 362, 142715.

Chapter 4
Current Status and Issues in the Treatment of Swine Wastewater in Japan: Towards the Development of an Innovative Nitrogen Removal Process Using Anammox

Chikako ISHIMOTO

Abstract: In Japan, approximately 82.5 million tons of livestock waste are produced annually, with pig farms contributing significantly. As these farms grow larger and more specialized, they lack cultivated land for recycling livestock waste, necessitating proper treatment and removal. On average, 76% of pig farm waste is separated into solid and liquid components. The solids are composted and supplied to arable farmers, while liquids are predominantly treated using the activated sludge process and discharged into public water bodies. The Water Pollution Prevention Act mandates water quality standards for effluent discharged into public waters. Most pig farms, with a piggery area of 50 m^2 or more, must regulate inorganic nitrogen concentrations, including ammonia, nitrite, and nitrate compounds. Due to the high nitrogen content in swine wastewater, meeting the general effluent standard (100 mg/L) is challenging. A provisional standard of 400 mg/L has been established, but stricter compliance with general standards is imperative, making nitrogen reduction a critical goal. Conventional nitrification-denitrification methods demand significant aeration for ammonia oxidation and require external carbon sources to compensate for the low carbon-nitrogen ratio in swine wastewater, resulting in high operational costs. Alternatively, anaerobic ammonium oxidation (anammox) offers a

cost-effective, energy-efficient solution by coupling ammonia and nitrite removal without external carbon sources or extensive aeration. Reports of spontaneous anammox bacteria accumulation in swine wastewater treatment plants in Japan and China highlight its potential. Our research confirms that maintaining low dissolved oxygen (DO) levels (≤0.3 mg/L) in aeration tanks fosters simultaneous partial nitrification, anammox, and heterotrophic denitrification. Using DO as an operational indicator, we developed an aeration control system to enhance nitrogen removal efficiency under low DO conditions. This system also reduces electricity consumption through optimized aeration, offering a sustainable and practical solution for nitrogen removal in swine wastewater treatment.

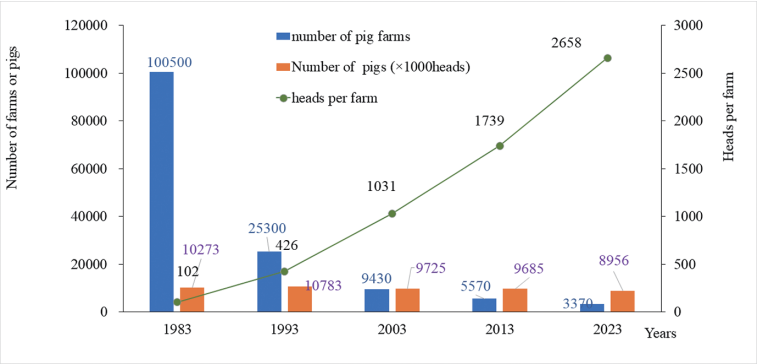
Keywords: *swine wastewater, nitrogen removal, innovative process, anammox, activated sludge process*

1. Introduction

(1) Pig Farming in Japan

Pig farming in Japan plays a crucial and prominent role in the country's agricultural sector, particularly in the production of high-quality pork, which is an essential part of Japanese cuisine. Pork is a staple food in many traditional and modern Japanese dishes, such as tonkotsu ramen, tonkatsu, and yakiniku, making the pig farming industry an integral part of Japan's food culture and economy.

a)



b)

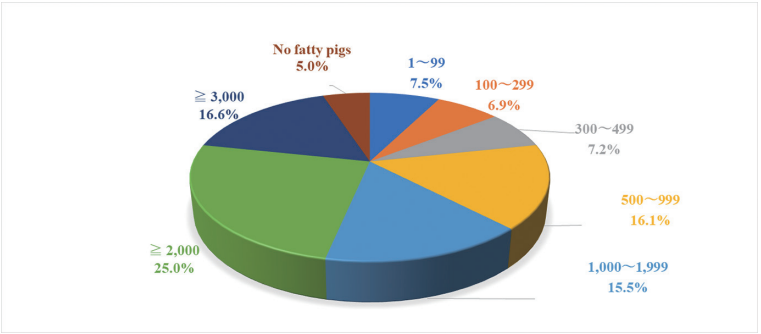


Figure 1. (a) Number of pig farms, total pig population, and average number of pigs per farm in Japan over the years; (b) percentage distribution of pig farm scales in 2023. Source: Author

Over the years, the structure of pig farming in Japan has undergone notable changes, particularly in the number and size of farms. Figure 1a presents a striking visual representation of the changes in Japan's pig farming operations over the past 40 years. It highlights the dramatic decline in the number of pig farms, which has decreased to approximately one-thirtieth of its original size. This sharp reduction underscores the ongoing trend of farm consolidation and the decreasing role of small-scale operations in Japan's agricultural sector. Despite

the reduction in the number of farms, the total population of pigs has not experienced the same drastic decline. Instead, the decrease in farm numbers has been accompanied by an increase in the average number of pigs per farm, which has grown nearly twenty-six times larger. This increase reflects the shift toward larger, more intensive farming operations, which are capable of housing and managing a significantly larger number of pigs, benefiting from economies of scale and improved efficiency.

Figure 1b further illustrates this transformation by showing the distribution of pig farms based on the number of pigs per household. The chart reveals that the largest proportion of farms now fall within the range of 2,000 to 3,000 fattening pigs, indicating that medium to large-scale farms have become the dominant type in the industry. This shift to larger operations reflects the increasing specialization and mechanization of pig farming in Japan, driven by technological advancements and the need for more sustainable, efficient production methods.

(2) Pig Waste Management and Excrement Disposal Methods in Japan

Pig farming plays a crucial role in Japan's livestock industry, with pork being a staple and highly valued source of protein in Japanese cuisine. However, the industry faces several challenges, particularly in the area of waste management, which is becoming an increasingly significant concern in the country. As the demand for pork continues to rise, so does the amount of waste generated by pig farming operations, creating considerable environmental and operational challenges (Waki et al. 2020; Wang and Li 2024).

Figure 2 presents data on the total industrial waste generated in Japan in 2023. According to this data, livestock waste alone amounted

to 82,457,000 tons, representing approximately 22% of the total industrial waste produced in the country. Among the various types of livestock waste, pig-derived waste ranks third in terms of volume (Table 1), accounting for about 25% of the total livestock waste produced. This indicates that pig farming is a significant contributor to the overall waste generated by the agricultural sector. A key characteristic of pig waste, compared to other types of livestock waste, is the higher volume of urine produced relative to feces. This is in stark contrast to cattle and poultry farming, where feces typically surpass urine in volume. The unique composition of pig-derived waste presents additional challenges in terms of waste treatment and disposal, further emphasizing the need for effective management solutions in the industry.

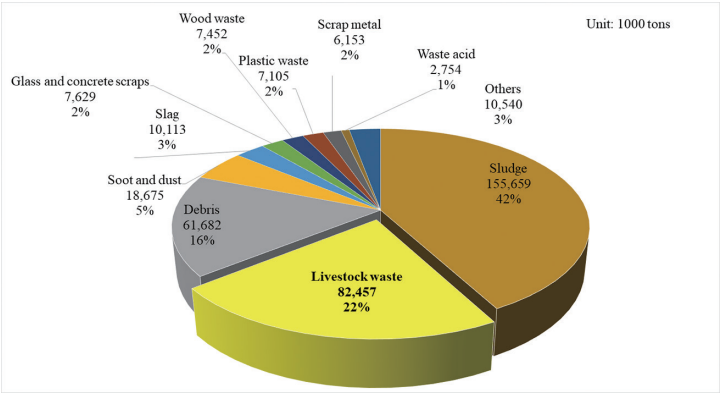


Figure 2 . Waste generated in Japan in 2023. Source: Author

Table 1. Livestock waste in Japan in 2023

Breed	**Amount of waste (×1000 t)**	
Dairy cattle	Feces	16,839
	Urine	5,023
Beef cattle	Feces	19,121
	Urine	6,959
Pig	**Feces**	**7,223**
	Urine	**13,377**
Layer	Feces	7,271
Broiler	Feces	6,643
Total	82,457	

As pig farming in Japan becomes more specialized, a significant portion of the feed materials — about 75% — are imported. Specialized pig farms often do not have their own farmland to recycle waste back into the soil, which creates the challenge of finding appropriate waste disposal methods to prevent environmental pollution. Effective waste management is therefore essential to ensure that waste is removed in an environmentally responsible manner.

Figure 3 shows the various methods used for treating pig excrement. Of the total waste, 76% undergoes solid-liquid separation. The solid portion is mainly composted and then distributed to arable farmers for use as organic fertilizer. The liquid waste, which makes up 71% of the total, is primarily treated and discharged into public water bodies after undergoing aerobic purification through an activated sludge process. Only 13% of the liquid waste is reused for agricultural purposes. Regarding solid-liquid mixtures, 75% are composted with the addition of moisture-controlling materials, while a surprising 12% of the mixture is discharged after septic treatment. Anaerobic treatment, specifically methane fermentation, is not widely adopted in Japan, with only 4% of the solid-liquid mixture processed through this method. This is largely

due to challenges in securing storage space for the digested liquid and the difficulty of finding farmland where the by-products can be returned.

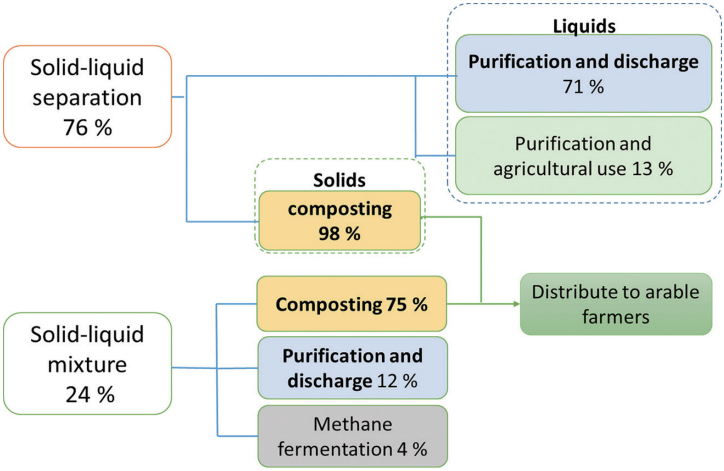


Figure 3. Pig waste disposal methods used in Japan. Source: Author

(3) Effluent Standards for Swine Wastewater under the Water Pollution Control Act

In Japan, pig farming operations are required to comply with the effluent standards set by the Water Pollution Control Act, which is enforced by the government. The application of these standards varies based on the size of the piggery. Specifically, farmers with a piggery area of 50 m^2 or larger must adhere to regulations for 27 hazardous substances, including inorganic nitrogen. Furthermore, farms that discharge 50 m^3 or more of effluent daily must comply with 15 environmental standards. These standards cover a range of parameters, such as pH, BOD (Biochemical Oxygen Demand), COD (Chemical Oxygen Demand), SS (Suspended Solids), coliform bacteria counts, nitrogen, and phosphorus. Some of these standards may vary depending

on the final destination of the discharge. Even in cases where the daily effluent volume is below 50 m^3, certain prefectures still enforce standards for BOD and SS. These regulations are designed to mitigate environmental pollution and ensure that wastewater from pig farming operations does not negatively impact water quality in the surrounding areas. The main parameters in swine wastewater and their limits are outlined in detail, as shown in Table 2.

Table 2. Effluent discharge standards for swine wastewater in Japan

Item	**pH***	**BOD****	**SS**	**Coliform**	**Nitrogen*****	**Phosphorus*****
		COD				
Unit		mg/L	mg/L	CFU/mL	mg/L	mg/L
Standard value	5.8-8.6 [a]	160	200	3000	120	16
	5.0-9.0 [b]	(120)	(160)		[130]	[22]

* “a” for discharge into freshwater, “b” for discharge into the ocean; ** BOD for discharge into rivers, COD for discharge into oceans and lakes; BOD/COD and SS values represent the maximum allowable limits; the values in parentheses are the average daily amounts; *** In [ ], provisional standards are applied for effluent flowing into inner bays via rivers, etc.

(4) Regulation of “Inorganic Nitrogen” in Swine Wastewater

The standard value for inorganic nitrogen in wastewater is determined using the following formula:

$$\textit{Ammonium nitrogen} \times 4 + \textit{Nitrite nitrogen} + \textit{Nitrate nitrogen} \leq 100\ \textit{mg/L}$$

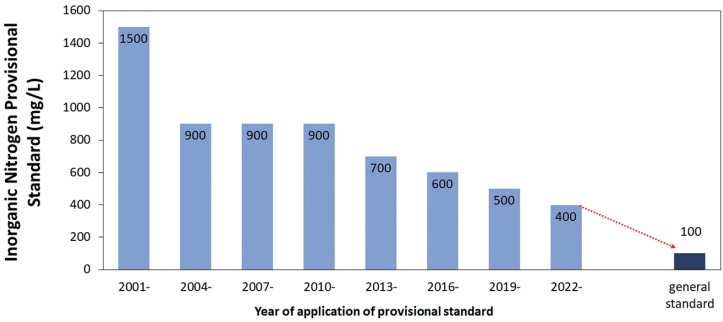


Figure 4. Inorganic nitrogen provisional standard over the years.
Source: Author

Generally, the standard value for inorganic nitrogen is set at 100 mg/L, which applies broadly to various wastewater sources. However, livestock wastewater, particularly swine wastewater, typically contains significantly higher concentrations of nitrogen. Due to these elevated levels, achieving compliance with the general standard of 100 mg/L has proven to be extremely challenging for pig farming operations. Recognizing these difficulties, a provisional standard value of 400 mg/L has been established specifically for swine wastewater to accommodate the unique characteristics of this type of effluent. Nevertheless, the provisional standard is not intended to be permanent. It is reviewed and adjusted every three years, as illustrated in Figure 4. During these periodic reviews, the standard is often revised to be more stringent, gradually moving closer to the general standard of 100 mg/L. This ongoing tightening of the standard reflects a long-term goal of eventually applying the general standard uniformly across all wastewater types, including swine wastewater. Given this trajectory, it is reasonable to assume that the provisional standard for swine wastewater will be replaced by the general standard sooner rather than later. This shift

highlights the urgent need for the development of advanced nitrogen removal technologies that can enable pig farming operations to meet the stricter general standard. Research and innovation in wastewater treatment methods, particularly those that focus on effective nitrogen reduction, are therefore essential to ensure compliance with these evolving regulatory requirements and to minimize the environmental impact of swine farming.

2. Nitrogen Removal Processes Applied to Swine Wastewater

(1) Conventional Nitrogen Removal Process

Swine wastewater in Japan is predominantly treated using the activated sludge treatment process, which is a widely employed method for wastewater management. This process is particularly effective in reducing organic pollutants and nitrogen compounds present in swine wastewater (Suto et al. 2017). A detailed diagram of the activated sludge treatment process, including the nitrogen removal process, is presented in Figure 5.

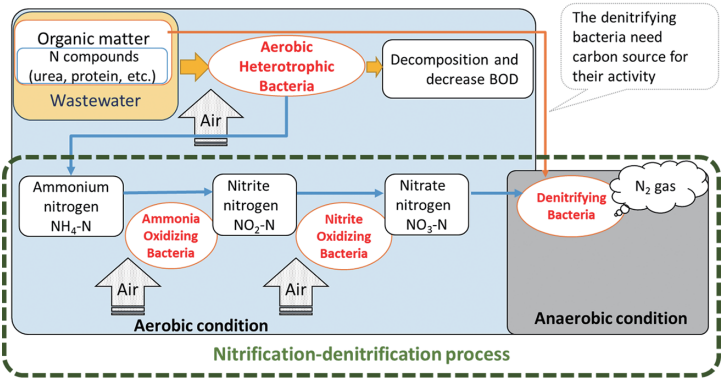


Figure 5. Schematic diagram of the activated sludge treatment process. Source: Author

The treatment begins with the decomposition of organic matter by aerobic heterotrophic bacteria. These bacteria thrive in an oxygen-rich environment, breaking down organic pollutants and resulting in a reduction in BOD, a critical parameter for assessing water quality. Following this stage, the process transitions into the conventional nitrification-denitrification pathway, which is designed to remove nitrogen compounds from the wastewater.

In the nitrification phase, ammonium (NH_4^+), produced from the breakdown of nitrogen-containing compounds, is first converted into nitrite (NO_2^-) by ammonia-oxidizing bacteria (AOB). Subsequently, nitrite is further oxidized into nitrate (NO_3^-) by nitrite-oxidizing bacteria (NOB). These steps require a significant supply of oxygen and extensive aeration, making them energy-intensive processes. The denitrification phase follows nitrification and is crucial for converting the nitrate into nitrogen gas (N_2), which is released harmlessly into the atmosphere. This conversion occurs under anaerobic conditions, where oxygen is absent, and is facilitated by heterotrophic denitrifying bacteria. These bacteria use nitrate as an electron acceptor while metabolizing organic carbon as an energy source. However, a challenge arises in the case of swine wastewater. After solid-liquid separation, the liquid fraction of swine wastewater often contains insufficient organic carbon to support the denitrifying bacteria. As a result, an external source of organic matter must be added to ensure effective denitrification. Moreover, livestock wastewater, including swine wastewater, is characterized by its high nitrogen content. The elevated levels of nitrogen require prolonged aeration during the nitrification phase to achieve complete oxidation, significantly increasing energy consumption and operational costs. These challenges — high nitrogen levels, the need for extensive aeration, and the addition of external carbon sources — make efficient nitrogen removal by the activated sludge treatment process more costly

in pig farming operations across Japan.

Given these constraints, the activated sludge process, although widely implemented in pig farming, faces challenges in nitrogen removal due to its high resource demands and associated costs. This underscores the need for alternative treatment methods or modifications to the existing process to address the unique challenges posed by swine wastewater.

(2) A Novel Nitrogen Removal Process Using Anammox Bacteria

Nitrogen removal from swine wastewater using conventional methods, such as activated sludge, faces several challenges and limitations (as mentioned in Section 2(1)). Consequently, the search for alternative, more efficient, and sustainable wastewater treatment technologies has become a significant area of focus.

One promising approach that has gained attention in recent years is the novel nitrogen removal process involving anaerobic ammonium oxidation, commonly known as the anammox process. First discovered in the 1990s, the anammox process is an innovative biological pathway where specific microorganisms, known as anammox bacteria, convert ammonium (NH_4^+) and nitrite (NO_2^-) into nitrogen gas (N_2) with a small by-product of nitrate (NO_3^-). This process can be described by the following chemical reaction:

$1.0\ NH_4^+ + 1.32\ NO_2^- + 0.066\ HCO_3^- + 0.13\ H^+ \rightarrow 1.02\ N_2 + 0.26\ NO_3^- + 0.066\ CH_2O_{0.5}N_{0.15} + 2.03\ H_2O$

The anammox process (Figure 6) offers a highly efficient nitrogen removal mechanism with several key advantages. First, since only approximately half of the ammonium needs to be converted to nitrite during the process, the requirement for aeration is significantly reduced compared to conventional nitrification-denitrification systems. This

reduction in aeration demand translates into lower energy consumption, making the process more cost-effective.

Second, anammox bacteria are autotrophic microorganisms, meaning they can grow and function without the need for an external carbon source. This eliminates the necessity for additional carbon inputs, further reducing operational costs and making the process suitable for treating swine wastewater, which often has a low carbon-to-nitrogen ratio.

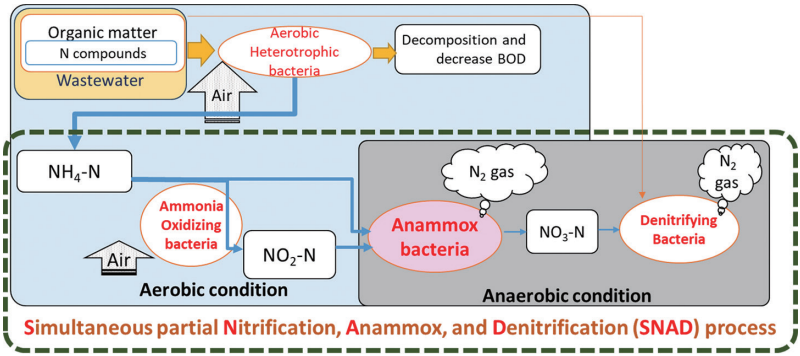


Figure 6. A novel nitrogen removal process using anammox bacteria. Source: Author

An advanced application of the anammox process is the Simultaneous partial Nitrification, Anammox, and Denitrification (SNAD) process. This process integrates partial nitrification (conversion of ammonium to nitrite), anammox, and denitrification in a single reactor. By streamlining these processes into one system, the SNAD approach not only enhances nitrogen removal efficiency but also minimizes the footprint and complexity of the treatment system. This innovation is particularly beneficial for swine wastewater treatment, where simplicity, cost-effectiveness, and sustainability are paramount considerations (Chen et al. 2009).

Given its advantages, including reduced energy requirements, elimination of external carbon sources, and enhanced nitrogen removal efficiency, the anammox process and its derivatives, such as SNAD, are regarded as promising solutions for addressing the limitations of traditional nitrogen removal methods. As research and technological advancements continue, the application of anammox-based processes is expected to play a pivotal role in the development of sustainable and energy-efficient wastewater treatment systems, particularly for challenging waste streams like swine wastewater.

3. A Case Study: Nitrogen Removal from Swine Wastewater Using Anammox Bacteria

(1) Challenges and Solutions for Implementing the Anammox Process in Swine Wastewater Treatment Facilities

Anammox bacteria, known for their distinctive ability to perform anaerobic ammonium oxidation, are remarkable microorganisms that play a crucial role in the nitrogen cycle. When these bacteria accumulate, they often form a characteristic red biofilm, which serves as a visible indicator of their presence. Despite their significance, anammox bacteria are classified as strict anaerobes, meaning they can only thrive in environments devoid of oxygen. This characteristic poses a considerable challenge, as their growth rate is notably slow, making their cultivation a complex and time-intensive process. To obtain sufficient quantities of anammox bacteria for wastewater treatment applications, researchers typically rely on artificial media and strictly controlled anaerobic conditions. These conditions are essential to provide an environment conducive to their growth and reproduction. However, despite these meticulous efforts, cultivating anammox bacteria

in the laboratory remains a demanding task that requires patience and precision.

Interestingly, a surprising phenomenon has been observed at several swine wastewater treatment plants in Japan and China (Qiao et al. 2010; Suto et al. 2017). At these sites, anammox bacteria have been found to accumulate spontaneously without the need for artificial cultivation. This natural enrichment of anammox bacteria in swine wastewater treatment systems is particularly intriguing because it has rarely been reported in other types of wastewater treatment plants. The spontaneous accumulation of anammox bacteria in these specific settings is believed to be influenced by the unique characteristics of swine wastewater, which may create favorable conditions for their growth and activity. Understanding this phenomenon holds great potential for advancing nitrogen removal technologies. By studying the underlying mechanisms that enable anammox bacteria to thrive naturally in swine wastewater treatment plants, researchers can gain valuable insights that may lead to the development of a novel and efficient nitrogen removal process tailored specifically for swine wastewater treatment.

This emerging approach could offer a sustainable and cost-effective solution to managing nitrogen pollution in swine farming, contributing to the broader goal of improving wastewater treatment practices worldwide.

(2) Overview of a Swine Wastewater Treatment Plant

This experiment was carried out at the Swine and Poultry Research Center, Shizuoka Prefectural Research Institute of Animal Industry, Japan. The experimental setup is depicted in Figure 7, illustrating a wastewater treatment plant that supports the accumulation of anammox bacteria.

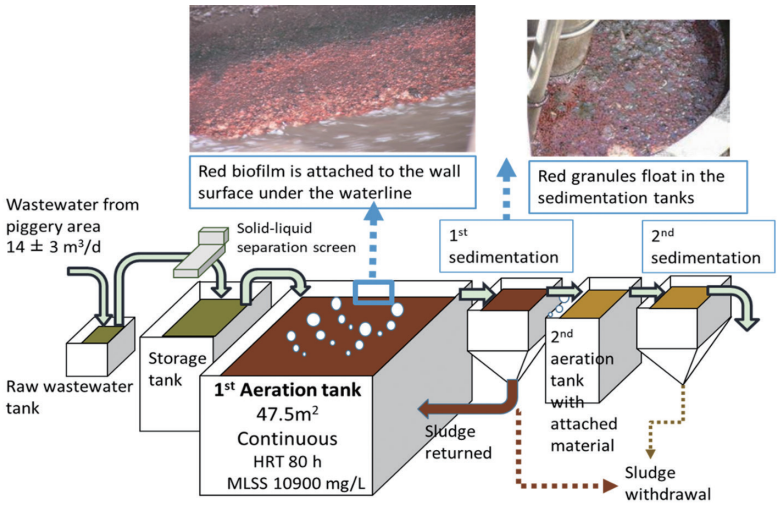


Figure 7. Diagram of a swine wastewater treatment plant accumulating anammox bacteria. Source: Author

In this system, the influent wastewater is initially separated into solid and liquid fractions in the piggery area. The liquid portion is then fed into the treatment system at an average flow rate of 14 m^3 per day. The wastewater is continuously introduced into the first aeration tank, where aeration is maintained to ensure optimal conditions for microbial activity. The system operates with an average hydraulic retention time (HRT) of 80 hours and mixed liquor suspended solids (MLSS) concentration of 10,900 mg/L, which are critical for efficient treatment. When sludge is periodically withdrawn from the first sedimentation tank, the water level in the aeration tank temporarily drops, revealing a red biofilm that forms on the tank walls. These red biofilms are indicative of the presence of anammox bacteria. In addition, red granules, composed of microbial aggregates, are occasionally observed in the sedimentation tanks, further confirming the accumulation of anammox bacteria.

The treated effluent, after passing through a second aeration tank and sedimentation tank for additional treatment, is discharged into a public water body, meeting the required environmental standards.

(3) Results

1) Characteristics of Influent and Effluent Wastewater

Table 3 presents the characteristics of influent and effluent swine wastewater. The average influent BOD was 1,104 mg/L, with the BOD volumetric load in the aeration tank at 0.32 kg/m^3/day, which is within the typical range for swine wastewater treatment plants. The average effluent BOD was 44 mg/L, and the BOD removal efficiency remained stable at 95 ± 4%.

The concentrations of total nitrogen and total inorganic nitrogen (TIN) in the influent were 629 mg/L and 457 mg/L, respectively. The average removal rates for total nitrogen and TIN were 75% and 68%, respectively. Despite the low BOD/TN ratio of 1.78, which is generally unfavorable for heterotrophic denitrification, the overall nitrogen removal efficiency was high. Notably, most of the nitrogen removal occurred in the first aeration tank.

Table 3. Characteristics of influent and effluent swine wastewater

	Unit	Influent	Effluent	Removal efficiency (%)
		Means ± S.D	Means ± S.D	
pH	-	8.36 ± 0.34	7.35 ± 0.49	-
BOD	mg/L	1104 ± 513	44 ± 27	95 ± 4
COD	mg/L	3984 ± 1484	409 ± 146	-
T-N*	mg/L	629 ± 198	154 ± 92	75 ± 14
T-IN**	mg/L	457 ± 128	146 ± 92	68 ± 17
BOD/T-N	-	1.78 ± 0.58	0.37 ± 0.24	
SS	mg/L	1743 ± 712	35 ± 14	

* T-N=Total nitrogen; ** T-IN=Total inorganic nitrogen

The results of the two-year survey (April 2016 to March 2018) also identified several factors influencing the accumulation of anammox bacteria, including dissolved oxygen (DO), pH, sludge retention time (SRT), inorganic nitrogen levels, and BOD removal. The dissolved oxygen concentration in the first aeration tank was low, at 0.31 mg/L, which is close to the optimal range for the SNAD process. The pH was within the neutral range, which also falls within the optimal range for anammox activity. The sludge retention time (SRT) was longer than 25 days, exceeding the doubling time of anammox bacteria, allowing sufficient time for bacterial growth. Ammonium and nitrite were detected simultaneously for most of the period, providing the necessary substrate for the anammox bacteria. The high BOD removal efficiency further confirmed the effectiveness of the wastewater treatment process. Overall, the accumulation of anammox bacteria was attributed to the combined influence of these factors.

2) Environmental Factors Reducing Nitrogen Removal

Figure 8 illustrates the environmental factors that contribute to fluctuations in nitrogen removal efficiency. The vertical dotted line marks the point where nitrogen removal efficiency decreased by 20 percentage points or more compared to the previous measurement. A red line indicates days when an increase in DO concentration and a decrease in pH below 6.5 were observed. Additionally, nitrite accumulation was noted. These factors led to the formation of free nitrous acid, which inhibits anammox activity. The green line represents days when no increase in DO concentration was observed. During this period, the pH rose above 8, and only ammonium was detected as nitrification stagnated. At the same time, free ammonia, which also inhibits anammox, was detected. These findings highlight the importance of maintaining a DO concentration below 0.3 mg/L and keeping the pH

within the range of 6.5 to 8.0 for stable nitrogen removal.

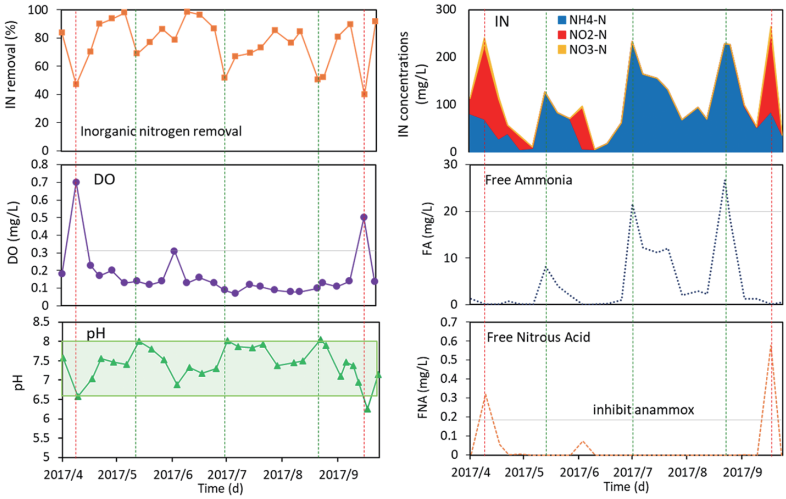


Figure 8. Factors affecting nitrogen removal. Source: Author

3) Stabilization of Nitrogen Treatment through Controlled Aeration

In processes utilizing anammox bacteria, controlling DO concentration is important. Therefore, our research team has developed an aeration control system aimed at optimizing the DO concentration in the aeration tank. Figure 9 illustrates a schematic diagram of the system. A fluorescent DO sensor is installed in the aeration tank to monitor the oxygen levels. The converter is programmed to decrease the air blower's output when the DO concentration increases and to increase the output when the DO concentration decreases. The blower output is controlled by an inverter to maintain the DO concentration below 0.3 mg/L. Simultaneously, the daily influent volumes are adjusted to keep the pH within the range of 6.7 to 8.0.

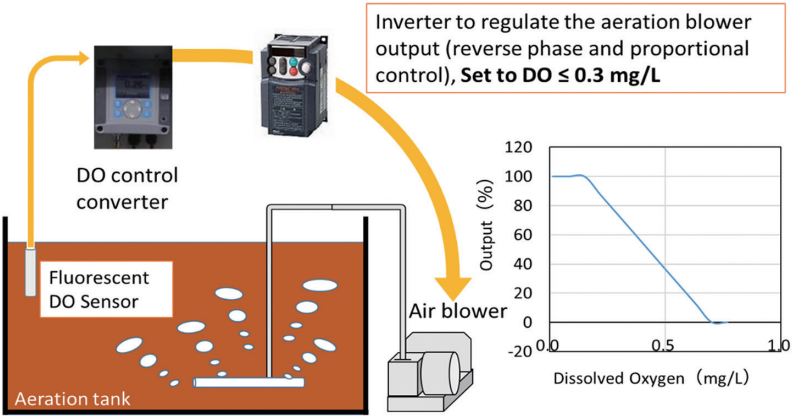


Figure 9. Schematic diagram of the aeration control system. Source: Author

Figure 10 shows the effectiveness of aeration control during the low-temperature period. A comparison was made between the uncontrolled area before aeration control and the controlled area after aeration control. In the controlled area, the DO concentration remained below 0.3 mg/L, and the pH stayed within the specified range. In contrast, in the uncontrolled area, the DO concentration fluctuated, and the pH decreased as the DO concentration increased. Regarding inorganic nitrogen concentration, nitrite accumulation was observed in the uncontrolled area as the DO concentration rose, whereas in the controlled area, no nitrite accumulation occurred, and the nitrogen concentration remained lower than in the uncontrolled area.

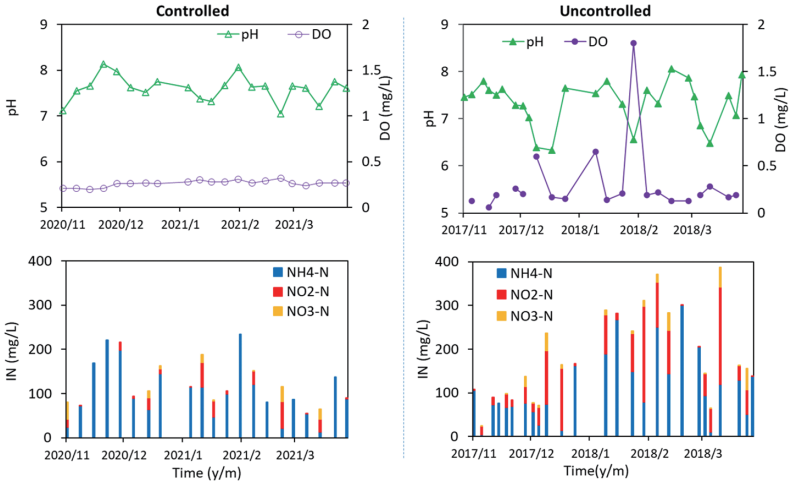


Figure 10. pH and DO, and inorganic nitrogen concentrations in the controlled and uncontrolled systems. Source: Author

Figure 11a shows the inorganic nitrogen concentrations adjusted to meet discharge standard values in the effluent. The controlled area achieved 100% of the general effluent standard, while the uncontrolled area reached only 58%. Figure 11b illustrates the impact of the aeration control system in reducing power consumption. Both the daily power consumption and the power usage per cubic meter of influent were significantly lower in the controlled area. These results confirm that the aeration control system not only improves the stability of nitrogen removal but also reduces the electrical energy required for wastewater treatment.

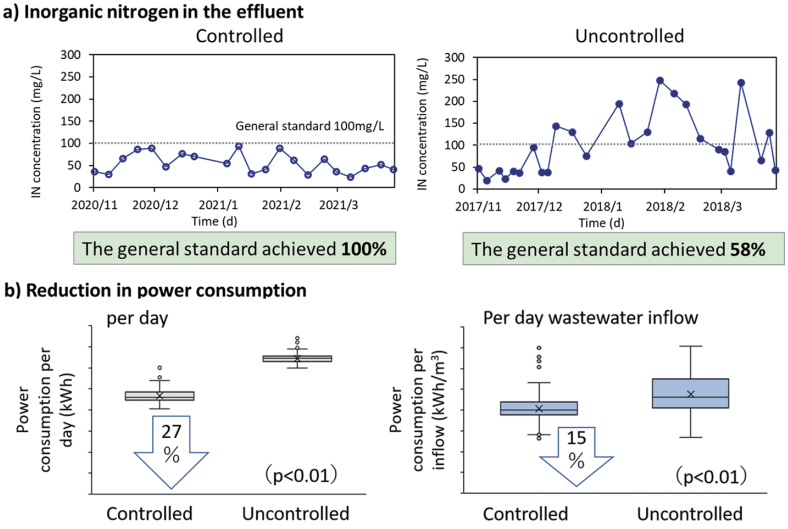


Figure 11. a) Inorganic nitrogen concentration in the effluent, b) Reduction in power consumption. Source: Author

4. Conclusion

Pig farming is an important sector in Japanese agriculture, but it faces the challenge of managing wastewater with high nitrogen content. Traditional treatment methods, such as activated sludge, are often costly and energy-intensive, particularly for nitrogen removal. In response, we have developed a more cost-effective wastewater treatment system that utilizes the spontaneous accumulation of anammox bacteria to remove nitrogen from swine wastewater. Our findings demonstrated that this approach is viable for wastewater treatment, achieving high nitrogen removal efficiency. Furthermore, stable and effective nitrogen removal can be achieved by controlling the aeration process and maintaining a DO concentration below 0.3 mg/L. This innovative process is expected

to be widely adopted in livestock wastewater treatment facilities due to its energy-efficient and low-cost nature.

References

Chen, H., S. Liu, F. Yang, Y. Xue and T. Wang. 2009. The Development of Simultaneous Partial Nitrification, ANAMMOX and Denitrification (SNAD) Process in A Single Reactor for Nitrogen Removal. *Bioresource Technology*, 100(4), 1548–1554.

Ishimoto, C., T. Sugiyama, T. Matsumoto, H. Uenishi, Y. Fukumoto and M. Waki. 2020. Full-Scale Simultaneous Partial Nitrification, Anammox, and Denitrification Process for Treating Swine Wastewater. *Water Science and Technology*, 81(3), 456–465.

Qiao, S., T. Yamamoto, M. Misaka, K. Isaka, T. Sumino, Z. Bhatti and K. Furukawa. 2010. High-rate Nitrogen Removal from Livestock Manure Digester Liquor by Combined Partial Nitritation-anammox Process. *Biodegradation*, 21(1), 11–20.

Suto, R., C. Ishimoto, M. Chikyu, Y. Aihara, T. Matsumoto, H. Uenishi, T. Yasuda, Y. Fukumoto and M. Waki. 2017. Anammox Biofilm in Activated Sludge Swine Wastewater Treatment Plants. *Chemosphere*, 167, 300–307.

Waki, M., T. Yasuda, Y. Fukumoto, F. Béline and A. Magrí. 2020. Numerical Assessment of Nitrogen Removal from Swine Wastewater in Activated Sludge Systems: Comparison between Continuous and Intermittent Aeration. *Bioresource Technology Reports*, 11, 100492.

Wang, L. and D. Li. 2024. Current Status, Challenges, and Prospects for Pig Production in Asia. *Animal Bioscience*, 37(4), 742–754.

Chapter 5
Challenges of Recycling Swine Wastewater in Vietnam to Approach a Circular Economy

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Abstract: This research presents a comprehensive synthesis and detailed analysis of existing literature on swine wastewater management in Vietnam, aiming to promote sustainable agricultural practices through wastewater recycling. The primary goal is to reduce waste generation and enhance the sustainable utilization of water resources by integrating livestock wastewater into other economic activities. The study identifies major challenges in reusing livestock wastewater, drawing on both scientific evidence and practical considerations. Key issues include variations in farm characteristics, such as size and operational scale, as well as climatic conditions that influence wastewater treatment processes. Additionally, the analysis evaluates existing wastewater treatment technologies and their effectiveness in addressing the unique characteristics of swine wastewater. Current regulations and policies related to livestock waste management are also reviewed to identify gaps and barriers to the implementation of circular economy practices in agriculture. To address these challenges, the research proposes specific policies and regulatory frameworks aimed at fostering the safe and effective reuse of swine wastewater and livestock waste. These recommendations include incentivizing the adoption of advanced and cost-effective wastewater treatment technologies, establishing clear guidelines for wastewater recycling practices, and enhancing monitoring and enforcement mechanisms to ensure compliance with environmental

standards. Moreover, tailored policies that consider the diversity of farm operations and regional climatic differences are suggested to improve the feasibility of implementation. By providing actionable insights, this study contributes to the development of sustainable livestock farming practices in Vietnam, aligning with global efforts to achieve environmental protection, resource conservation, and a circular economy in agriculture.

Keywords: *reusing livestock effluent, swine wastewater, circular economy, sustainable agriculture*

1. Introduction

In recent years, the circular economy has emerged as a promising approach to minimizing waste and promoting the sustainable use of natural resources (Morseletto 2020; Murray et al. 2017). Within the agricultural sector, livestock wastewater is increasingly recognized as a valuable resource that can significantly contribute to the circular economy by facilitating nutrient recycling and reducing environmental pollutant loads. This recognition is particularly critical in the context of extreme weather events, water scarcity, and the global push to enhance water use efficiency. The reuse of wastewater, including livestock wastewater, represents a vital strategy for mitigating water depletion while supporting sustainable agricultural practices (Jaramillo and Restrepo 2017).

However, the implementation of livestock wastewater recycling is influenced by several factors. These include farm characteristics, local environmental conditions, the availability and efficiency of wastewater reuse technologies, and the regulatory frameworks governing wastewater management. Moreover, recycling livestock wastewater involves inherent risks, such as potential food safety concerns and broader environmental impacts, which must be carefully addressed to

ensure sustainable practices (Lahlou et al. 2021).

In Vietnam, livestock farming, particularly swine farming, serves as a cornerstone of the agricultural economy. The country ranks sixth globally in terms of swine population, producing approximately 3 million tons of pork annually. This thriving sector generates nearly 60 million cubic meters of nutrient-rich wastewater daily. Recycling this wastewater offers immense potential for nutrient recovery, environmental protection, and resource efficiency. However, it also poses significant challenges, including technical, economic, and regulatory barriers, as well as public health and ecological concerns.

This research explores these challenges, drawing on empirical evidence and insights from studies conducted by the authors and other researchers specializing in livestock waste management in Vietnam. It aims to provide a comprehensive understanding of the opportunities and constraints surrounding swine wastewater recycling, emphasizing its role in advancing sustainable agricultural practices and contributing to the circular economy.

2. Study Methodology

This research primarily employs a literature review methodology to identify the challenges associated with reusing livestock wastewater for crop cultivation. The main data sources include the Vietnam Journal of Science Online, ResearchGate, Google Scholar, and ScienceDirect. Additionally, the study utilizes the online database of legal documents (http://vbpl.vn) for policy analysis. Statistical data from the General Statistics Office of Vietnam regarding the current status of the livestock industry and other relevant figures are also incorporated. The collected information is synthesized and presented using charts, tables, analytical matrices, and evaluations to provide a comprehensive overview and achieve the research objectives.

3. Results and Discussions

(1) The Need to Reuse Swine Wastewater in Vietnam

The livestock sector plays a vital role in Vietnam, providing essential food products and contributing significantly to the country's economic and social development. Over the past decade, Vietnam's population has grown at an average annual rate of 1.03%, increasing from 89.8 million in 2012 to 98.56 million in 2021. During this period, the country's per capita income rose from USD 1,540 to USD 4,000 per year (GSO 2022). This population and economic growth have driven a rising demand for livestock products such as meat, eggs, and milk.

According to the Ministry of Health, the average daily meat consumption per person increased from 51 g/day in 2000 to 84 g/day in 2010, reaching 134.5 g/day in 2020. Urban residents tend to consume more meat compared to their rural counterparts. Notably, pork remains the most widely consumed meat in Vietnam, with swine farming dominating the livestock sector. Pork output consistently surpasses that of other types of livestock, accounting for over 45% of the country's total meat production over the years (GSO 2022).

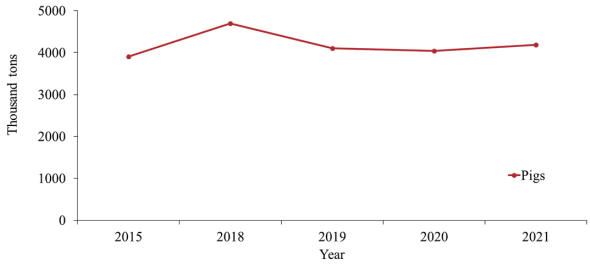


Figure 1: Pork production in Vietnam from 2015 to 2021. Source: GSO 2022

Along with the increase in meat production, there have been significant changes in the number of swine in Vietnam. From 2010 to 2021, the average growth rate of agricultural production value in the livestock sector was 5%–6%, making it a crucial contributor to the agricultural economy (Cao et al. 2022).

While the growth of the livestock sector brings substantial economic benefits to Vietnam, it also increases pressure on waste management, particularly wastewater. Dinh (2017) estimated that over 80 million tons of manure are generated annually by the livestock sector, with swine farming contributing the largest share at 30.3%. Swine farming is also considered a high-water consumption sector. Results from the LCASP project survey of 281 livestock facilities in 10 provinces indicated that the average water usage per swine is 42.5 liters per day (Nguyen et al. 2020). In Binh Dinh, the water usage coefficient for swine farming was as high as 74.5 liters per swine per day. The study also found that household-scale swine farming has a higher water usage coefficient, averaging 44.8 liters per swine per day, compared to 33.9 liters per swine per day for farm-scale swine farming. Another estimate from the General Department of Environment indicates that the wastewater generation coefficient for swine farming is approximately 20 liters per swine per day, whereas the coefficient for buffalo and cattle farming is only 12.5 liters per animal per day (MONRE 2018). The estimated wastewater generation based on these coefficients is calculated as shown in Table 1.

Table 1: Estimation of wastewater volume generated from swine and buffalo raising in the period 2010–2022

Year	Buffalo (in thousand heads)	Estimated wastewater (l/day)	Swine (in thousand heads)	Estimated wastewater (l/day)
2010	8.685	108.566.000	27.373	547.466.000

2011	8.148	101.857.500	27.056	541.120.000
2012	7.822	97.775.000	26.494	529.880.000
2013	7.716	96.452.500	26.264	525.288.000
2014	7.755	96.946.000	26.761	535.228.000
2015	7.891	98.640.000	27.750	555.014.000
2016	8.016	100.200.000	29.075	581.506.000
2017	8.146	101.832.500	27.406	548.134.000
2018	8.228	102.850.000	28.151	563.038.000
2019	8.447	105.598.750	19.615	392.310.000
2020	8.563	107.041.250	22.027	440.558.000
2021	8.574	107.178.750	22.688	453.774.000
2022	8.570	107.125.000	24.684	493.680.000

Swine farming generates the largest volume of wastewater compared to other types of livestock farming in Vietnam. Swine waste contains high levels of organic matter, nutrients, and microorganisms. The pollutants in swine wastewater include BOD_5, COD, total nitrogen (TN), total coliform (CF), and total phosphorus (TP). Poor management and inadequate treatment of this waste are major contributors to pollution in areas surrounding swine farming operations, as highlighted by previous studies (Ho 2017; Tien et al. 2009). In this context, promoting the recycling of livestock wastewater is regarded as a promising solution to mitigate pollution by utilizing the nutrients present in the wastewater.

However, since the early 2000s, changes in the scale and techniques of livestock farming and waste treatment have significantly affected the use of wastewater in livestock facilities. The proportion of facilities utilizing wastewater for other activities remains low. According to a survey of 720 livestock facilities conducted by Tien et al. (2009), more than 70% of households directly discharged liquid waste and wastewater into the environment across various types of livestock

farming. Similarly, a study by Son et al. (2014) in Hung Yen, which covered 42 livestock facilities of different scales, found that 38% of farms used manure and wastewater for crop fertilization, while 52% used liquid manure as fish feed. A more recent survey by Giang et al. (2021), involving 123 swine farming facilities with herds of 50 or more in four provinces—Hanoi, Thai Binh, Ha Tinh, and Dong Nai—reported that only 50% of facilities reused livestock wastewater. This percentage varied significantly by region, with Hanoi at 18%, Dong Nai at 43%, Ha Tinh at 73%, and Thai Binh at 66%. These findings indicate that the rate of livestock wastewater reuse in Vietnam remains relatively low.

There are numerous challenges to reusing livestock wastewater for crop cultivation in Vietnam. The following sections will examine the main challenges related to farm conditions, the quality of treated livestock wastewater, and the legal regulations governing wastewater reuse for crop cultivation.

(2) The Available Farmland for Wastewater Reuse in Crop Cultivation on Livestock Farms in Vietnam

According to the findings of various researchers, farm characteristics, particularly the availability of production land, are significant factors influencing the decision-making processes of households (Belayneh 2023; Tey and Brindal 2022; Wittstock et al. 2022).

Table 2: Average area statistics of swine farms in Vietnam

No.	Locations	Statistic
1	National average area	Livestock farms with an area of less than 5,000 m² account for 65%-70% of the total. Farms with an area of more than 10,000 m² comprise only 10%-15% of the total. Livestock farms in Vietnam have an average area of 3,000-5,000 m², whereas in Thailand, the average is 6,000 m² (JICA 2013)

2	Hung Yen Province (Van Giang)	Based on a survey of 42 livestock farms, the garden-pond-cage (VAC) system farms have an average area of 11,648 m², pond-cage (AC) farms have an average area of 12,657 m², VC farms have an average area of 1,673 m², and C farms have an average area of 461 m². Additionally, 33% of the interviewed farms are located within residential areas (Son et al. 2014).
3	Ha Noi (Gia Lam, Ung Hoa, Son Tay)	The survey results from 41 swine farms show that those under the VAC system have an average area of 20,735 ± 6,026 m², while those under the VC system have a lower average area of 5,098 ± 1,106 m² (Ho et al. 2016).
4	Dong Nai Province	The area among FDI farms, cooperatives, joint-stock companies, and household farms differs significantly. FDI farms have an average area of 44,000 m², cooperative farms have an average area of 38,000 m², joint-stock companies have an average area of 44,000 m², and household farms have an average area of 5,800 m² (Le 2017).
5	Hung Yen, Hai Duong, and Bac Ninh Province	A survey of 90 livestock farms in Hung Yen, Hai Duong, and Bac Ninh shows that the average area of a farm was 4,833 m². Among them, swine farms in Hung Yen had an average area of 4,875 m², farms in Hai Duong had an average area of 5,545 m², and farms in Bac Ninh had an average area of 4,082 m² (Vu et al. 2007).
6	Bac Giang Province	The survey of 125 swine farms, including both household-scale and large-scale farms, shows that the average area of the swine farms ranges from 150 to 10,800 m². The distance from swine barns to residential areas ranged from 10 to 500 meters (Ngo et al. 2021).
7	Dong Nai, Ha Tinh, Thai Binh and Ha Noi	The survey of 123 small, medium, and large-scale farms shows that the average area of swine farms in Hanoi was 5,796 ± 10,098 m², in Thái Bình was 4,723 ± 9,898 m², in Ha Tinh was 42,446 ± 45,377 m², and in Dong Nai was 27,955 ± 31,106 m² (Giang et al. 2021).

Research indicates that farm size positively impacts the implementation of environmental protection measures by farmers. Livestock farms require a suitable land area to recycle waste for cultivation. However, the land available on most livestock farms in Vietnam presents limitations for waste reuse. The 2020 Agricultural and Rural Survey, involving over 9,000 agricultural households nationwide, found that the average production area per household is approximately 5,000–6,000 m², with each household managing 2.8 plots of land on average (GSO 2021). Swine farming facilities generally have smaller production land areas compared to other types of agricultural operations. Son et al. (2014) reported that 65%–70% of swine farms occupy areas smaller than 0.5 hectares, while only 10%–15% cover more than 1

hectare. However, there are significant regional differences in farm size and farming scale. Livestock farms in the Red River Delta and Mekong Delta tend to have smaller areas compared to those in the midland, mountainous, central coastal, and Central Highlands regions. Statistical results from various studies show that livestock farms are generally small and located within residential areas.

The farm size in Vietnam is considerably smaller compared to many other countries in the region and worldwide. According to Lowder et al. (2016), 70% of farms in the wealthiest countries have an area greater than 20 hectares, while 70% in the poorest countries have an area greater than 5 hectares. Additionally, in Vietnam, agricultural land is often fragmented and located far from livestock farming areas. This spatial separation significantly affects the construction and installation of waste treatment facilities, as well as the reuse of livestock waste for other economic activities, particularly the use of livestock wastewater in crop production.

(3) Actual Demand for On-Farm Irrigation Water in Vietnam

Recycling wastewater in livestock areas is particularly critical in regions experiencing water scarcity. In such areas, recycling wastewater generated from livestock activities helps reduce pollution and addresses the issue of irrigation water shortages (Elahi et al. 2017; Jaramillo and Restrepo 2017). However, irrigation water scarcity is not a pressing issue across all ecological regions of Vietnam, especially during the rainy season.

Studies have shown that the periods when farms generate the most wastewater coincide with the rainy season in Vietnam. Due to its tropical monsoon climate, the country experiences abundant rainfall, which is distinctly seasonal. Most regions receive between 1,400 and 2,400 mm

of rainfall from May to October. This period also brings high average temperatures nationwide, ranging from 25 to 30°C, during which farms consume substantial amounts of water for cleaning and cooling. Hinh (2017) reports that in the North, livestock households use an average of 30–40 liters of water per swine per day during the summer, while in the South, the average is 15–30 liters per swine per day for cooling. Additionally, livestock households in Vietnam use an average of 5–10 liters of water per swine per day for cleaning, with cleaning frequencies being higher in the summer than in the winter. During the rainy season, the water supply often exceeds demand, which reduces the potential for using livestock wastewater for irrigation.

Farm economic activities have become less diverse after a period of agricultural development focused on specialization, combined with limited land availability. Many farms now concentrate solely on livestock production, lacking other activities such as crop cultivation and aquaculture. This situation reduces the demand for irrigation water, even when wastewater is generated and available. As a result, many livestock farms discharge excess wastewater into the environment when biogas digesters and storage tanks become overloaded, leading to environmental pollution around livestock farms.

Another reason for the low demand for reusing swine wastewater is that irrigation services are heavily subsidized, leading to a low price for irrigation water. On the other hand, swine wastewater must be treated adequately to comply with current national technical standards for irrigation water, which adds additional costs to wastewater usage. Additionally, extra costs such as labor and transportation may be incurred if the livestock farm is far from the cultivation area. Therefore, farmers often find more cost-effective alternatives for swine wastewater disposal.





Figure 2: Collection of Livestock Wastewater for Crop Cultivation in Van Duc Commune, Gia Lam, Hanoi. Source: Author

(4) Quality of Swine Wastewater after Treatment

Swine wastewater in Vietnam primarily includes excrement, urine, pen wash water, cooling water, and effluent from biogas tanks and other treatment systems. Although it contains high levels of TN and TP, it also harbors numerous pathogens, parasite eggs, and bacteria. Therefore, if livestock wastewater is not properly treated or is lost during reuse processes, it becomes a source of pollution for the surrounding environment and poses risks to human and animal health.

Recently, due to the efforts of local authorities to address environmental pollution in livestock farming, most livestock facilities in Vietnam have implemented waste treatment measures. The most commonly adopted solution is the construction of biogas tanks. According to statistical data from various studies, the adoption rate of biogas tanks increased from 57% in 2010 to over 90% a decade later (Cao et al. 2011; Giang et al. 2021; Ngo et al. 2021). Except for large-scale farms, most biogas tanks in Vietnam have a capacity of less than 15 m^3 (Hinh 2017).

However, studies evaluating the quality of livestock wastewater

have shown that the effectiveness of these treatment measures is very limited. According to a study by Tien et al. (2009), treated livestock wastewater still had very high levels of coliform. The coliform levels in household and farm livestock waste exceeded permissible limits by 278 times and 630 times, respectively. A study by Cao et al. (2021) which evaluated the quality of livestock wastewater from 130 swine farms, 80 poultry farms, and 40 cattle farms in Hanoi, revealed that livestock waste exceeded the national quality standards for livestock wastewater (QCVN-62) and was not safe for irrigating certain crops. The study found average concentrations of BOD_5 at 660.2 ± 400.6 mg/l, COD at 1107.7 ± 701.6 mg/l, TN at 56.7 ± 58.7 mg/l, TP at 118.7 ± 75.5 mg/l, TSS at 248.2 ± 94.7 mg/l, and CF at 8.8e+04 ± 7.1e+04 MPN/100ml. These results indicate that many parameters of swine farming wastewater exceed the current limits of national technical standards for permissible discharge into the environment, with BOD_5 levels exceeding the allowable limit by 6.6 times, COD by 3.7 times, TSS by 1.6 times, and Coliform by 17.6 times. However, the analysis also showed significant variations in wastewater quality among swine farming facilities. Over 85% of samples had BOD_5, COD, TSS, and CF levels exceeding standards, except for TN, which exceeded standards in 22% of samples (Cao et al. 2021).

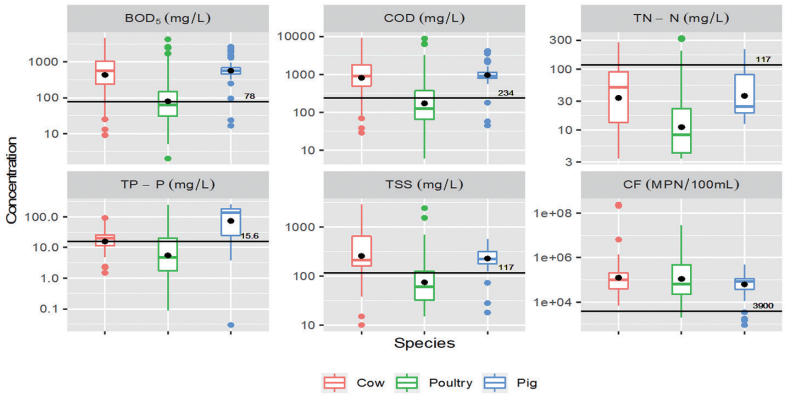


Figure 3: Quality of wastewater from swine, cow and poultry farms in Ha Noi. Source: Cao et al. 2021

In 2021, a study on wastewater reuse in swine farms in Hanoi, Thai Binh, Ha Tinh, and Dong Nai found that the Coliform concentration in swine wastewater after treatment exceeded the standard threshold. The average coliform value from wastewater samples was 49,000 ± 88,000 MPN/100mL, which is 66 times higher than the standard for livestock wastewater and far exceeds the allowable limits for crop irrigation water according to the QCVN01-195:2022/BNNPTNT standard (Giang et al. 2021). Therefore, proper treatment to ensure the quality of swine wastewater for safe use in crop irrigation presents a major challenge in Vietnam. A study by Dung et al. (2020) concluded that most biogas tanks on livestock farms in Vietnam are ineffective in reducing greenhouse gas emissions and treating husbandry waste. Other studies provide further evidence of environmental pollution around livestock areas, supporting this claim. Some studies have proposed a solution for treating liquid farm waste by combining biogas tanks with a bio-pond system. After biogas treatment, the wastewater would remain in the

ponds for 3-4 months to eliminate pathogens and break down organic matter into nutrients that plants can easily absorb, while the remaining sludge can enrich the soil. However, this solution requires a large area and significant investment, making it unsuitable for most small-scale livestock farms in Vietnam. Therefore, finding an appropriate wastewater treatment technology that meets current livestock farming conditions and ensures treated water quality for irrigation and other purposes is a pressing need in Vietnam to achieve sustainable livestock wastewater reuse.

(5) Legal Regulations for Recycling Swine Wastewater

Implementing the recycling of swine wastewater, as well as other types of waste, is currently in the process of establishing a comprehensive legal framework. The recycling of livestock waste, including wastewater, is emphasized in the revised Environmental Protection Law of 2020 and the Livestock Production Law enacted in 2019, along with related guiding documents. The principles regarding the use of livestock waste from these documents can be summarized as follows:

- Livestock farming must be integrated with crop production and other sectors to form a circular economic chain in agriculture.
- Livestock waste, agricultural by-products, and valuable resources must be efficiently utilized.
- The treatment and use of livestock waste and agricultural by-products are the shared responsibility of the entire society.
- Maximizing the use and efficiency of agricultural by-products and livestock waste to achieve sustainable development, reduce greenhouse gases, and protect the livestock farming environment.

- Aligning with the Livestock Development Strategy for the period 2021-2030, with a vision to 2045.

In addition to the policies, regulations, and guidelines mentioned above, several other policies aim to facilitate livestock farms, including household-scale operations, in implementing measures for waste treatment and utilization. These policies provide support in the form of financial aid, installation of facilities, technical guidance for waste treatment, land and tax incentives, and access to credit for large-scale livestock enterprises. The key documents are summarized as follows:

- Decision No. 50/2014/QD-TTg dated September 4, 2014, by the Prime Minister regarding policies to enhance the efficiency of household-scale livestock farming for the period 2015–2020.
- Decree No. 55/2015/ND-CP by the government on credit policies for agricultural and rural development.
- Directive No. 26/CT-TTg dated October 6, 2015, by the Prime Minister on accelerating the implementation of the agricultural sector restructuring scheme towards enhancing added value and sustainable development.
- Decree No. 57/2018/ND-CP, which replaces Decree No. 210/2013/ND-CP dated December 19, 2013, concerning mechanisms and policies to encourage businesses to invest in agriculture and rural areas.

However, livestock wastewater presents a unique challenge as it is difficult to immediately generate value from it. Furthermore, the recycling of livestock wastewater faces significant challenges, as discussed above. To effectively and sustainably implement the recycling of livestock wastewater, additional policies and regulations

are necessary. According to the authors, the key policies and regulations that need further development include:

- Specific policies for recycling livestock wastewater: Tailored policies are needed for small and medium-sized livestock farms, which are prevalent in Vietnam and remain a crucial segment in the current livestock development strategy. These farms are characterized by their small scale, proximity to residential areas, and distance from other agricultural production zones. The regulatory framework and monitoring systems for environmental protection and waste recycling for this group are still limited (Dinh 2017; Hinh 2017).
- Land use policies: While there are existing regulations and policies prioritizing land use for large-scale livestock farms, additional policies are needed to address land sharing for recycling livestock waste within communities. This would help mitigate the limitations related to land availability.
- Tools for evaluating circular economy practices: The development of tools to assess the implementation of circular economy principles in managing livestock wastewater and other waste is crucial. However, as with many economic sectors in Vietnam, these tools are still underdeveloped.
- Technical guidelines for nutrient-rich wastewater: it is essential to create technical guidelines for livestock farms to use the appropriate amounts of wastewater for irrigation. Incorrect dosage or loss of wastewater during irrigation can have adverse environmental impacts and hinder overall sustainability goals.
- Effectiveness of biogas digesters: Studies indicate that biogas digesters are not highly effective in treating liquid livestock waste, particularly in removing harmful organisms and ensuring

the safety of irrigation water. Therefore, future policies should prioritize scientific research on effective treatment technologies for this waste component, specifically tailored to the common characteristics of livestock farms in Vietnam.

- Cost pressures and regulations: The low cost of water for agricultural production in Vietnam contributes to the pressure on managing livestock wastewater. This leads farmers to use more water in livestock farming and to dispose of wastewater rather than recycling it due to cost-benefit considerations. To encourage farmers to practice wastewater recycling, mandatory regulations and specific incentive policies are needed to enhance their awareness of their responsibilities in wastewater reuse.

4. Conclusion

Based on analyses from practical observations and conducted studies, this paper highlights the critical necessity of reusing swine wastewater in Vietnam to achieve the goal of circularity in the agricultural sector moving forward. If effectively recycled, Vietnam could save a significant amount of water each day, which is rich in nutrients and valuable for other production purposes. However, the study also identifies several challenges that must be addressed to achieve sustainable reuse of wastewater in this crucial industry.

The major challenges stem from the typical production characteristics of swine farming: small production areas, proximity to residential areas but distance from agricultural production zones, and high water usage in swine care. Additionally, there are challenges related to the quality of wastewater and the availability of wastewater treatment technologies that meet irrigation water standards. The cost of treating and using swine wastewater may also exceed that of using

water from the national irrigation system. Moreover, the hot and humid climate with seasonal heavy rainfall reduces the demand for wastewater use, particularly during the rainy season. Alongside these challenges, policies and regulations concerning the reuse of swine wastewater and livestock waste in general still need to be developed and refined.

References

Belayneh, M. 2023. Factors Affecting the Adoption and Effectiveness of Soil and Water Conservation Measures among Small-Holder Rural Farmers: The Case of Gumara Watershed. *Resources, Conservation & Recycling Advances*, 18, 200159.

Cao, D. P., D. V. Tran, T. L. Nguyen, N. H. Duong, T. T. H. Tran, S. T. Hoang, and T. T. H. Nguyen. 2022. Báo cáo thường niên về NN&PTNT 2021_Hướng đến phát triển nền nông nghiệp có khả năng chống chịu cao từ kinh nghiệm ứng phó với đại dịch Covid-19 (Annual Report on Agriculture and Rural Development 2021: Towards Developing Highly Resilient Agriculture from Experience in Responding to the COVID-19 Pandemic). <http://www.iae.vn/Data/upload/files/HV%20Nong%20nghie%20VN_Bao%20cao%20thuong%20nien%202021_NN%20ung%20pho%20dai%20dich%20covid%2019%20(1)-%C4%91%C3%A3%20n%C3%A9n.pdf> (accessed on 15 September 2024). (in Vietnamese)

Cao, S. T., H. P. Tran, H. T. T. Le, H. P. K. Bui, G. T. H. Nguyen, L. T. Nguyen, B. T. Nguyen and A. D. Luong. 2021. Impacts of Effluent from Different Livestock Farm Types (Pig, Cow, And Poultry) on Surrounding Water Quality: A Comprehensive Assessment Using Individual Parameter Evaluation Method and Water Quality Indices. *Environmental Science and Pollution Research*, 28, 50302–50315.

Cao, T. S., D. A. Luong, D. T. Vu and T. L. T. Ho. 2011. Đánh giá mức độ ô nhiễm nước mặt tại các trang trại chăn nuôi lợn trên địa bàn tỉnh Hưng Yên (Surface Water Pollution Assessment at Difference Pig-farms in Hung Yen Province). *Journal of Science and Development*, 9, 393–401. (in Vietnamese)

Dinh, T. X. 2017. *An Overview of Agricultural Pollution in Vietnam: The Livestock Sector*. Washington, D.C.: World Bank.

Dung, P., D. Hoan, J. Arango, T. Nghia, N. Kien, A. Arevalo and S. Douxchamps. 2020. Greenhouse Gas Emissions from Piggery and Biogas Digesters in the North of Vietnam. *Vietnam Journal of Agricultural Sciences*, 3(4), 843–853.

Elahi, E., M. Abid, L. Zhang and G. M. Alugongo. 2017. The Use of Wastewater in Livestock Production and Its Socioeconomic and Welfare Implications. *Environmental Science and Pollution Research*, 24(21), 17255–17266.

Giang, H. T. N., T. T. L. Huong, N. T. An, M. Yabe, N. T. Thang, V. N. Hieu and C. T. Son. 2021. Recycling Wastewater in Intensive Swine Farms: Selected Case Studies in Vietnam. *Journal- Faculty of Agriculture Kyushu University*, 66, 115–121.

General Statistics Office of Vietnam (GSO). 2021. Results of the Mid-term Agricultural and Rural Survey in 2020. from General Statistics Office <https://www.gso.gov.vn/du-lieu-va-so-lieu-thong-ke/2021/06/thong-cao-bao-chi-ve-ket-qua-dieu-tra-nong-thon-nong-nghiep-giua-ky-nam-2020/>

———. 2022. *Vietnam Statistical Yearbook 2021*. Hanoi: Statistics Publisher.

Hinh, N. T. 2017. Thực trạng xử lý môi trường chăn nuôi tại Việt Nam và đề xuất giải pháp quản lý (Current Status of Livestock Waste Treatment in Vietnam and Proposed Solutions). *Journal of Environment*, 6, 28–29. (in Vietnamese)

Ho, T. L. T., T. S. Cao, P. K. H. Bui and H. N. Nguyen. 2016. Comparison of Two Pig-Farming Systems in Impact on the Quality of Surface and Groundwater in Hanoi, Vietnam. *International Journal of Agricultural Innovations and Research*, 5(1), 11–19.

Ho, T. B. L. 2017. Đánh giá chất lượng nước thải chăn nuôi heo sau biogas tại thị xã Tân Uyên và huyện Bắc Tân Uyên tỉnh Bình Dương (Assessing the Quality of Pig Farming Wastewater after Biogas in Tan Uyen Town and Bac Tan Uyen District, Binh Duong Province). *Thu Dau Mot University Journal of Science*, 32, 135–142. <https://scholar.dlu.edu.vn/thuvienso/bitstream/DLU123456789/254646/1/28069-529-94038-1-10-20170416.pdf> (in Vietnamese)

Jaramillo, M. F. and I. Restrepo. 2017. Wastewater Reuse in Agriculture: A Review about Its Limitations and Benefits. *Sustainability*, 9(10), 1734.

Japan International Cooperation Agency (JICA). 2013. Agricultural Transformation & Food Security 2040: Asean Region with Focus on Vietnam, Indonesia, and Philippines: Regional Food Security Study. <https://openjicareport.jica.go.jp/807/807/807_100_12145538.html>

Lahlou, F.-Z., H. Mackey and Y. Al-Ansari. 2021. Wastewater Reuse for Livestock Feed Irrigation as A Sustainable Practice: A Socio-Environmental-Economic Review. *Journal of Cleaner Production*, 294, 126331.

Le, T. M. H. 2017. Phát triển mô hình trang trại chăn nuôi heo theo hướng hội nhập quốc tế ở Đồng Nai (Developing a Large Farm Scale in Pig Farming Towards International Integration in Dong Nai). (Doctor Thesis of Doctorate in Economics), University of Economics and Law, Vietnam National University, Ho Chi Minh City. (in Vietnamese)

Lowder, S., J. Skoet and T. Raney. 2016. The Number, Size, and Distribution of Farms, Smallholder Farms, and Family Farms Worldwide. *World Development*, 87, 16–29.

Ministry of Natural Resources and Environment of Vietnam (MONRE). 2018. *Báo cáo Hiện trạng Môi trường Nước Quốc Gia 2018: Môi trường nước các lưu vực sông* (*The National Environmental Report 2018: Water Quality in River Basins*). (in Vietnamese)

Morseletto, P. 2020. Targets for A Circular Economy. *Resources, Conservation, and Recycling*, 153, 104553.

Murray, A., K. Skene, and K. Haynes. 2017. The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, 140(3), 369–380. <doi:10.1007/s10551-015-2693-2>

Ngo, A. T., G. T. H. Nguyen, D. H. Nong and L. See. 2021. Simulating the Spatial Distribution of Pollutant Loads from Pig Farming Using an Agent-Based Modeling Approach. *Environmental Science and Pollution Research*, 42037–42054.

Nguyen, T. T., S. Sommer, T. B. N. Tran, T. S. Nguyen, V. T. Tran and T. H. Le. 2020. Báo cáo tổng kết gói thầu số 27: nghiên cứu công nghệ chăn nuôi lợn tiết kiệm nước (Summary Report of Package 27: Research on Water-Saving Pig Raising Technology.) <https://lcasp.org.vn/uploads/news/2019_07/goi-thau-27.pdf> (in Vietnamese)

Son, C. T., N. T. H. Giang and H. T. L. Tra. 2014. Đánh giá tình hình xử lý chất thải tại các hệ thống trang trại chăn nuôi lợn trên địa bàn huyện Văn Giang, tỉnh Hưng Yên (Evaluation of Waste Treatment Situation at Pig Farming Systems in Van Giang District, Hung Yen Province). *Journal of Soil Science*, 59–64. (in Vietnamese)

Tey, Y. S. and M. Brindal. 2022. A Meta-Analysis of Factors Driving the Adoption Of Precision Agriculture. *Precision Agriculture*, 23, 353–372.

Tien, P. D., N. D. Dieu, H. V. Loc and B. T. T. Dan. 2009. Đánh giá thực trạng ô nhiễm môi trường trong chăn nuôi (An Evaluation of the Situation of Environmental Pollution in Animal Production). *Journal of Animal Husbandry*, 4(9), 10–16. (in Vietnamese)

Vu, D. T., T. C. Lai, V. D. Nguyen, and V. B. Dang. 2007. Chất lượng nước dùng trong trang trại chăn nuôi lợn ở vùng đồng bằng sông Hồng (Quality of Water Used at Pig Farms in The Red River Delta). *Journal of Science and Development*, VI(3), 279–283. (in Vietnamese)

Wittstock, F., A. Paulus, M. Beckmann, N. Hagemann and M. C. Baaken. 2022. Understanding Farmers' Decision-Making on Agri-Environmental Schemes: A Case Study from Saxony, Germany. *Land Use Policy*, 122, 106371.

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.

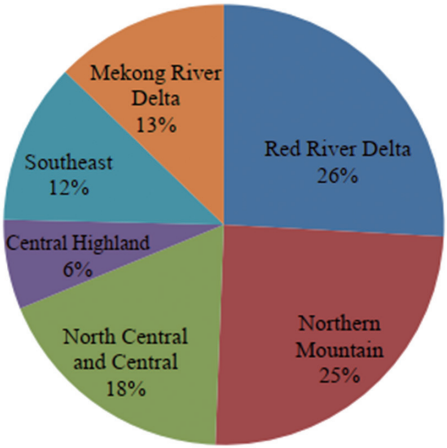


Figure 1. Total pig production by area in 2017. Source: Dao 2021

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

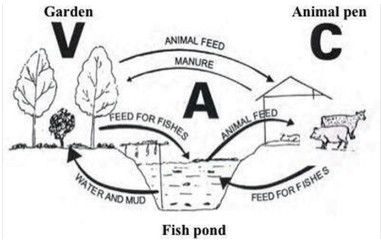
Solid waste treatment	
1. Pig manure treatment	
Biogas	80.72%
Composting	15.66%
Feeding fish	13.25%
2. Treatment of inorganic waste	
Treated together with household waste	93.98%
Buried in a dug hole	3.61%
Collected and sent for recycling	2.41%
Liquid waste treatment	
VAC	10.84%
Biogas	79.52%
Discharge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

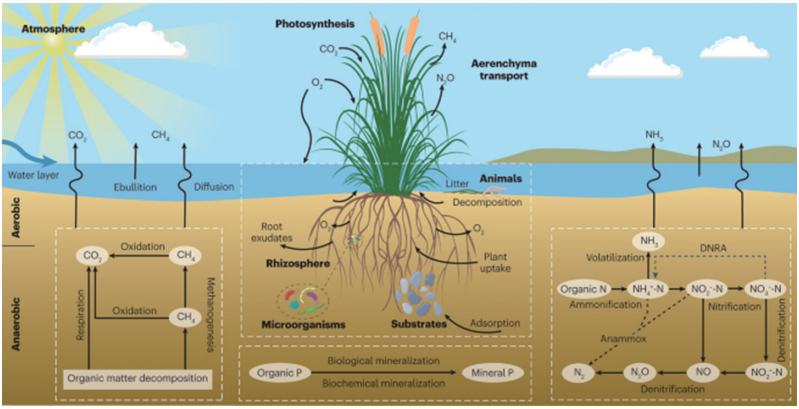


Figure 3. Biogeochemical mechanisms in constructed wetlands.
Source: Wu et al. 2023

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.

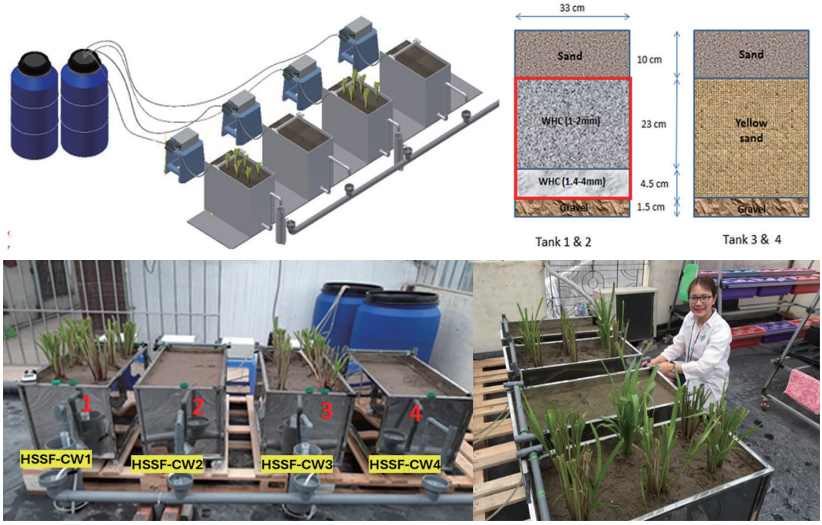


Figure 4. CW systems. Source: Author

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.

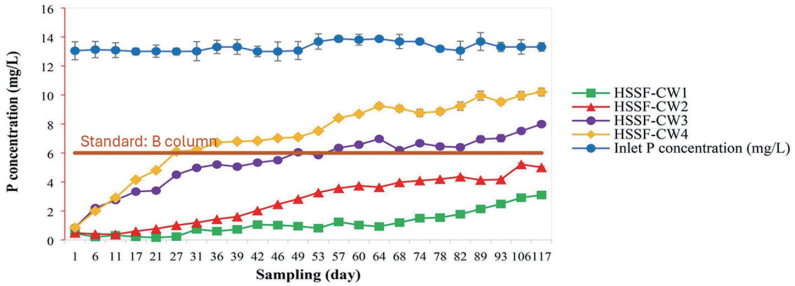


Figure 5. The inlet and outlet P concentration during the experimental period. Source: Nguyen et al. 2020.

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%.

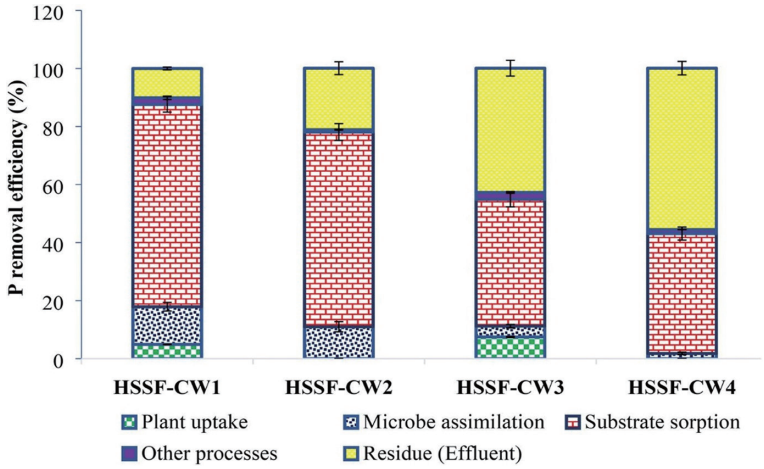


Figure 6. P removal routes in each CW system during the experiment. Source: Nguyen et al. 2020

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.

ONLINE ISBN 978-4-910550-16-9
PRINT ISBN 978-4-910550-17-6

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