Environmental Pollution in Pig Farming in Vietnam: Challenges and Proposed Solutions

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Abstract: Environmental pollution from pig farming in Vietnam remains a pressing issue due to poor waste management practices. Many pig farms lack efficient systems for handling manure and wastewater, resulting in soil and water contamination and the release of harmful gases, such as methane and ammonia. This pollution is a serious threat to natural ecosystems, particularly in rural areas where regulations are insufficient and their enforcement is limited. The challenges in managing pollution include insufficient infrastructure, a lack of technical expertise, and economic constraints, especially for small-scale farmers. Many farmers struggle to adopt advanced or sustainable technologies due to high upfront costs and limited access to resources. Internationally, several countries have successfully implemented integrated waste management systems, such as biogas digesters and constructed wetlands, which help reduce pollution while enabling energy and nutrient recovery. Strong regulatory frameworks and financial incentives in these countries further promote sustainable practices. Drawing from the current state of environmental pollution in pig farming, the causes of pollution, and international best practices, targeted solutions have been proposed for Vietnam's pig farming sector.

Keywords: *Environmental pollution, pig farming, waste management, sustainable solutions*

1. Environmental Pollution from Pig Farming in Vietnam

Pig farming is a vital sector of Vietnamese agriculture that makes a significant contribution to food security and rural economic development. However, it also presents great environmental challenges, particularly in terms of pollution from waste generation and poor management practices. In recent decades, structural changes in production systems have intensified environmental pressures, even though the overall pig population has not increased dramatically (from 27.4 million in 2005 to 30.7 million in 2024). The industry has shifted from dispersed, smallholder-based production to more intensive, geographically concentrated commercial operations, often located near residential areas and water bodies. These changes, combined with higher nutrient inputs aimed at improving growth rates and productivity, along with inadequate waste treatment facilities, have led to substantially higher nutrient loads in manure and wastewater, increased waste generation per unit area, and overloaded treatment and disposal capacities. Consequently, environmental pollution has intensified, threatening water, air, and soil quality and posing serious health risks to nearby communities (Dinh and Cassou 2017; Ministry of Agriculture and Rural Development [MARD], Vietnam 2024).

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(1) Water Pollution

Water pollution is one of the most pressing environmental concerns associated with pig farming. The country's pig population has remained consistently large, with approximately 29.4 million pigs in recent years (28.1 million in 2021, 28.8 million in 2022, 30.1 million in 2023, and 30.7 million in 2024) (MARD 2024). Each pig generates 2.5 kg of feces and 5 liters of urine daily, which amounts to approximately 26.8 million tonnes of feces and 53.6 million cubic meters of urine annually. Unfortunately, the majority of pig farms do not separate solid and liquid waste. According to Le et al. (2020), between 75% and 98% of farms discharge manure and wastewater together, leading to the release of large volumes of highly polluted wastewater into the environment. Table 1 compares the concentrations of major pollutants in pig wastewater (Le et al. 2020; Phan et al. 2024) with Vietnam's effluent discharge standards, revealing that the pollutant concentrations at pig farms cannot meet the regulatory values without proper treatment.

Pig farming is also considered the largest source of liquid waste, contributing an average of 84% of the total slurry waste generated during the 2016–2020 period (Ngoc et al. 2024). Approximately 75% of this manure is produced by smallholder farms, with the remainder coming from commercial operations (Ngoc et al. 2024). In terms of pollution contribution, pig farming accounts for 30.3%, which is higher than other livestock species such as poultry (27.4%), cattle (23.7%), and buffalo (17.1%) (Dinh and Cassou 2017). In addition, according to government reports, pig farming is a significant source of pollution in several provinces, including Bac Giang, Dong Nai, and Ha Nam (Ministry of Natural Resources and Environment [MONRE], Vietnam 2021).

Table 1: Concentration of pollutants in pig wastewater (Le et al. 2020; Phan et al. 2024) and Vietnam effluent standards (QCVN 40:2011/BTNMT)

Parameter	Unit	Wastewater	Effluent standard (mg/L)	
			Column A	Column B
pH		6.78 – 7.26	6– 9	5.5– 9
TSS	mg/L	2,110 – 4,813	50	100
COD	mg/L	1,270 –5,028	75	150
BOD	mg/L	900 – 3,625	30	50
TN	mg/L	350 – 820	20	40
TP	mg/L	80 –150	4	6
Coliforms	MPN/100mL	1.4×10^6–5×10^8	3×10^3	5×10^3

Abbreviation: TSS, total suspended solids; COD, chemical oxygen demand; BOD, biochemical oxygen demand; TN, total nitrogen; TP, total phosphorus.
Column A specifies the pollution parameter values in livestock wastewater when discharged into water sources used for domestic water supply. Column B specifies the pollution parameter values in livestock wastewater when discharged into water sources not used for domestic water supply.

Wastewater from pig farms contains high concentrations of organic matter, nitrogen, and phosphorus. Comparative studies have confirmed that pig farms discharge higher levels of these pollutants than poultry or cattle farms (Cao et al. 2021). When wastewater is inadequately treated or directly discharged into rivers, lakes, and groundwater, it causes severe water contamination. The excess nutrients in wastewater from pig farms contribute to eutrophication, causing the proliferation of harmful algal blooms and subsequent oxygen depletion. The resulting disruption of aquatic ecosystems threatens the health and livelihoods of communities that depend on these water sources for drinking water and crop irrigation (Dinh and Cassou 2017).

Many researchers have confirmed that pig farming is a significant source of surface water pollution in Vietnam's agricultural regions (Chi et al. 2023; Dinh and Cassou 2017; Ngo et al. 2020; Tra et al. 2016; Vo 2022). The Red River and Mekong Delta regions, where pig farming is particularly concentrated, have been found to have dangerously high pollution levels in nearby surface water bodies, including ponds, lakes, rivers, and canals. Chemical oxygen demand (COD) values in these waters ranged from 17 to 1,030 mg/L, while biochemical oxygen demand (BOD) values ranged from 12 to 860 mg/L, far exceeding the Vietnamese surface water quality standards for Class B1 under QCVN 08-MT:2015/BTNMT, which set limits of 30 mg/L for COD and 15 mg/L for BOD (Ho et al. 2013; Tra et al. 2016; Vo 2022). In addition, coliform concentrations were over the permissible limit of 7,500 MPN/100 mL by 1.25 to 10.25 times (Chi et al. 2023; Dinh and Cassou 2017; Tra et al. 2016). The fact that spatial and temporal evidence show significantly higher pollutant concentrations in water bodies located downstream or adjacent to pig farms compared to upstream or unaffected sites further underlines pig farming as the source (Ngo et al. 2020; Tra et al. 2016; Vo 2022).

The presence of antibiotics and pathogens in wastewater further exacerbates health risks. A study in Ha Nam Province found that 6.3% of wastewater samples from pig pens contained fluoroquinolone residues, while 22.9% contained sulfonamide residues, with sulfamethazine concentrations averaging 27.8 µg/L. Almost all *Escherichia coli* concentrations (1.0×10^5 – 5.01×10^8 colony-forming units per 100 milliliters, CFU/100 mL) in the samples exceeded the Vietnamese regulatory limit for coliforms (< 5,000 CFU/100 mL). Additionally, *Salmonella spp.* (30 – 11,000 most probable number per 100 milliliters, MPN/100mL) was detected in 57.3% of samples, *Giardia lamblia* (4 – 400 cysts per 100 milliliters, Cyst/100mL) in 8.4%, and *Cryptosporidium parvum* (0 – 32 Cyst/100mL) in 5.2% (Pham et al. 2020).

Additionally, pig farming is also a significant source of heavy metal pollution. Elevated levels of zinc, copper, lead, and iron have been detected in pig manure, sediments, and wastewater channels that flow into rivers. This issue primarily stems from the use of contaminated groundwater and low-cost feed ingredients such as industrial by-products, spoiled or contaminated grains, and imported feeds that may not meet food safety standards (Do et al. 2023). As pigs consume these contaminated feeds, heavy metals accumulate in their bodies and are excreted mainly through feces. Also, the routine use of feed supplemented with copper and zinc to promote growth and prevent disease adds to this problem (National Center for Veterinary Hygiene Inspection II [NCVHI], Vietnam 2021). When manure containing high concentrations of heavy metals is improperly managed or applied as fertilizer, it contributes to long-term environmental pollution by contaminating soil and water. Approximately 70–90% of these metals are released into the environment, which reduces soil microbial activity, degrades crop productivity, and enables metal uptake by plants. Crops such as leafy vegetables and rice that are grown in contaminated soil often accumulate heavy metals, posing serious risks to food safety and human health (Do et al. 2023; NCVHI 2021). Furthermore, high concentrations of heavy metals in soil have been shown to disrupt enzyme systems in animals that are raised in such environments or those that consume the affected crops (Burton and Turner 2003; NCVHI 2021).

(2) Soil Contamination

Soil pollution is also a growing concern. Improper management of solid waste, including pig excrement and carcasses, can lead to nutrient overload and soil degradation. While pig manure is often used as fertilizer, its application varies by region. In the Red River Delta, composted manure is usually applied to crops, while in the South and mountainous areas, raw manure is often directly applied to fields (Nguyen T. H. 2024). When composting is not done correctly or manure is overused, this can result in nutrient imbalances, soil acidification, and the contamination of agricultural land. Moreover, pig feed often contains heavy metals and antibiotics, which can accumulate in their manure. Therefore, when this manure is used, these substances can build up over time, polluting the soil and threatening crops and human health (Cao et al. 2021).

(3) Air Pollution and Greenhouse Gas Emissions

Pig farming also contributes to air pollution, primarily through the release of ammonia (NH_3), methane (CH_4), and hydrogen sulfide (H_2S) during the decomposition of manure. These emissions cause foul odors, degrade the environment, and can even lead to respiratory issues in the populations of nearby communities. Nitrification of ammonia causes soil and water acidification, while methane is a potent greenhouse gas (GHG) with a much higher global-warming potential than carbon dioxide (CO_2), which accelerates climate change. Medium-sized pig farms alone emit an estimated 6 million tonnes of CO_2-equivalent annually (Pham and Kuyama 2017).

Vietnam's livestock sector, particularly pig farming, is a major contributor to the country's agricultural GHG emissions (Dinh and Cassou 2017; Van Dung et al. 2020), with emissions from pigs projected to reach approximately 5,913,000 tonnes of CO_2 equivalent per year by 2030 (Vietnam News 2024). Large manure pools in pig farms release substantial amounts of methane, posing a challenge to Vietnam's commitment to reducing methane emissions by 30% by 2030 under the UN Climate Change Conference (COP26) pledge (Vo 2022).

Additionally, ammonia emissions from pig waste significantly degrade air quality and pose health risks to nearby residents. Studies conducted in northern Vietnam have reported that ammonia concentrations in the ambient air near pig farms were 7 to 18 times higher than the permissible limit of 0.2 mg/m^3, while hydrogen sulfide concentrations exceeded the limit of 0.08 mg/m^3 by 5 to 50 times—both thresholds regulated under Vietnam's ambient air quality standard QCVN 06:2009/BTNMT, issued by the Ministry of Natural Resources and Environment. These excessively high levels were measured in areas surrounding intensive pig farming facilities and were found to be caused primarily by emissions from animal housing and manure storage (Dang et al. 2020; Hai Duong 2023; Nguyen T. H. 2017).

Several researchers have reported respiratory symptoms and other health issues among pig farmers and workers in intensive pig farming operations. For example, research in Vietnam and other countries has revealed an increase in cases of respiratory irritation, asthma-like symptoms, and reduced lung function associated with exposure to NH_3, H_2S, particulate matter, and bioaerosols from pig barns (Donham et al. 1995; May et al. 2012).

2. Challenges in Managing Environmental Pollution from Pig Farms

It is extremely challenging to control environmental pollution from pig farms in Vietnam because of rapid industrialization, inadequate infrastructure, and poor waste management systems. One of the most serious issues is wastewater management, as pig farms discharge large quantities of wastewater containing high levels of pollutants. Due to a lack of adequate treatment facilities, much of this wastewater is discharged directly into local water bodies, contaminating aquatic ecosystems and posing a threat to public health. Small-scale farmers contribute significantly to this issue, as they often lack the financial and technical capacity to install proper treatment systems (Chi et al. 2023).

The lack of solid/liquid separation is a significant issue that exacerbates wastewater pollution. In Vietnam, solid and liquid wastes are often not treated separately, resulting in higher concentrations of pollutants that put a greater strain on treatment methods (Chi et al. 2023; Le et al. 2020). Excessive water use in pig farming also adds to the problem. Farmers often rely on groundwater or surface water sources that are freely available, and this leads to very high consumption rates averaging 30–40 liters per pig per day in Vietnam, compared to 9.5–22.7 liters in Canada (Michael 2010) and 20–30 liters in Japan (Oki et al. 2003). This has the effect of diluting manure and urine, thus increasing wastewater volume and pollutant loads.

Biogas recovery systems, though widely used, have limited effectiveness. Small-scale farms often install digesters with capacities of 9–12 m^3, which become overloaded when farms exceed ten pigs. Consequently, excess wastewater is discharged into public drains or natural water bodies. Large-scale farms use biogas storage tanks with capacities of several thousand cubic meters, but the captured gas, including methane, is often underutilized or directly released into the environment, contributing to global warming (Nguyen T. H. 2024). Moreover, poor maintenance and improper operation further reduce the efficiency of these systems. In many cases, biogas facilities are installed mainly to comply with regulatory requirements, specifically the 2018 Law on Animal Husbandry and Decree 13/2020/ND-CP, which mandates that pig farms have a waste treatment system, rather than to actually function as effective waste treatment solutions (Nguyen T. H. 2024; Vu et al. 2007). Several factors contribute to this situation, including limited awareness among farm owners about the importance of wastewater treatment, high operational and maintenance costs, and difficulties in controlling and managing the systems effectively.

Weak enforcement of environmental regulations increases pollution problems in the pig farming sector. While Vietnam has enacted several regulations, such as the 2018 Law on Environmental Protection and Decree 13/2020/ND-CP, to address agricultural pollution, their actual implementation remains inconsistent, especially in the rural areas where most pig farms are concentrated. This is mainly due to the limited capacity and resources of local environmental agencies, overlapping responsibilities between ministries, and a lack of adequate legal deterrents (MONRE 2021). Many small-scale farmers are unaware of environmental regulations and do not understand the long-term consequences of improper waste disposal. In some cases, government support for the expansion of pig farming has prioritized economic development over environmental protection, further impeding effective pollution control (Nguyen T. H. 2024).

Limited technical and financial support from local authorities also contributes to the problem. Pham and Ho (2018) found that 85% of households had received no assistance at all from local authorities, clearly indicating ineffective local management and support for pig farms. Although there are training programs on waste treatment and sustainable pig farming, they are rarely implemented and have had limited impact. Many farmers do recognize the importance of waste treatment, but they are struggling to implement effective measures due to financial constraints and a lack of know-how.

The adoption of sustainable practices is also hindered by economic challenges, particularly for small-scale farmers who struggle to afford the high costs of waste treatment technologies and to comply with regulations. The high cost makes it difficult for them to invest in improved systems, leading to continued environmental degradation.

Furthermore, there is a widespread lack of education and awareness among farmers regarding sustainable livestock farming. Many of them continue to use traditional methods without understanding their long-term environmental consequences. This, combined with weak enforcement of regulations, is causing continued pollution and ecological damage. Meanwhile, the demand for sustainable pork products is low, and systems for tracing and certifying environmentally friendly products are still underdeveloped, limiting progress toward Sustainable Development Goal 12: Responsible Consumption and Production. Moreover, research on the environmental impacts of pig farming in Vietnam is limited, with a lack of comprehensive data on water contamination at the local level, which makes effective management and policy planning more challenging (Dang et al. 2020; Dinh and Cassou 2017).

The adoption of advanced waste management solutions depends on several factors, including the scale of production, the availability of land for a treatment system, access to agricultural extension services, income levels, and household labor resources. Large-scale farms are generally better equipped to implement waste treatment measures due to their greater financial and technical resources. However, some intensive livestock farms still have difficulty in fully treating their waste due to high production volumes and limited land for building treatment facilities (Dung 2022).

3. International Lessons in Mitigating Environmental Pollution from Pig Farming

Some developed countries have introduced effective measures to minimize the environmental impact of pollution caused by pig farming. Their experiences can be of great use to other nations, including Vietnam.

Denmark and Sweden are recognized as leaders in sustainable livestock farming, especially manure management. Their farms usually use anaerobic digestion systems to process pig manure. This process converts manure into biogas, a renewable energy source, and the captured methane is used for heating and electricity production, reducing GHG emissions and minimizing environmental pollution (European Biogas Association [EBA] 2022; Foged et al. 2012; Ministry of Agriculture, Nature, and Food Quality of the Netherlands [LNV] 2019, 2025). Based on Danish estimates, manure digestion can significantly mitigate greenhouse gas emissions by converting methane into usable energy and reducing nitrous oxide (N_2O) emissions during manure storage and field application. The process is estimated to avoid approximately 1,100 g CH_4 and 14 g N_2O per tonne of manure (Nielsen 2004). For instance, a biogas plant in northern Denmark (Haerup Biogas) produces about 40 GWh per year of energy from manure, supplying heat and power to the local area. In Sweden, by 2013, approximately 40 manure-digesting biogas plants were operational, collectively processing around 350,000 tonnes of cattle and pig slurry annually (Luostarinen 2013). Similarly, the Netherlands has pioneered the concept of nutrient recycling in agriculture, focusing on closing the nutrient loop between livestock waste and crop production. Pig manure undergoes treatment and is converted into organic fertilizer, which is safely reused on farmland. This approach reduces dependency on chemical fertilizers and prevents nutrient runoff into water bodies. Known as "circular agriculture," this integrated system enhances waste management while improving soil health (LNV 2019). According to reports, manure surpluses in agriculture, particularly those of nitrogen and phosphorus, have decreased significantly, largely due to the implementation of improved policies and advancements in agricultural practices. Specifically, nitrogen use efficiency in the Netherlands has increased from approximately 47% in the 1990s to 64% in 2023 (Compendium for the Living Environment 2024).

Germany complements these efforts by emphasizing sustainable feed practices and advanced wastewater treatment to reduce the environmental footprint of pig farming (Neumann et al. 2018; Pulz and Gross 2004). German farms are increasingly incorporating locally sourced and alternative feed ingredients, such as insects and algae, to lower the ecological costs of feed production. For example, on a German farm housing approximately 2,200 fattening pigs and 750 sows, about 3 tonnes of black soldier fly larvae (*Hermetia illucens*) are harvested daily, with a target production of 4.5 tonnes per day. A portion of these larvae is incorporated into the pigs' diet, enhancing immune response and resilience compared to conventional soy-based feed (Michel-Berger 2025). Furthermore, some farms utilize constructed wetlands to treat wastewater. These eco-friendly systems naturally filter effluents, thereby reducing water pollution and promoting sustainable wastewater management (Scholz 2015).

Building upon such European approaches, the US and Japan have established strict environmental regulations and standards for livestock farming, emphasizing waste management and pollution control. In Japan, the Ministry of the Environment enforces national guidelines to reduce odors, improve manure storage, and prevent water pollution caused by livestock operations. Farmers are encouraged to adopt odor-neutralizing technology and improve manure management methods to minimize the emission of ammonia. Japan also supports research into innovative pig farming methods, such as feed additives designed to reduce methane emissions (Ministry of Agriculture, Forestry and Fisheries, Japan 2018). In the US, states such as North Carolina have introduced comprehensive regulations requiring pig farms to manage their waste responsibly. These regulations mandate the use of manure storage lagoons, enabling manure to be treated before it is used as fertilizer. The measures aim to control runoff and mitigate environmental harm (Chastain and Henry 2015). These regulations and innovative treatment technologies have been implemented to improve the removal of pollutants. For example, a demonstration system combining a high rate of solids separation with water treatment achieved over 90% removal efficiency for odor, pathogens, nutrients, and heavy metals, and ammonium nitrogen (NH_4-N) concentrations in lagoon effluent were reduced by more than 95% (Aneja et al. 2024).

The successful practices described in this section have shown that sustainable pig farming is possible through the adoption of integrated waste management, renewable energy production, nutrient recycling, and regulatory oversight. By adopting similar methods, Vietnam could successfully address the environmental challenges posed by its growing pig farming sector, while promoting long-term agricultural sustainability.

4. Proposed Solutions and Sustainable Approaches

Addressing the dangers to health and threats to the environment caused by increasingly intensive pig farming in Vietnam requires a comprehensive plan that combines advanced technological solutions, strengthened policies and institutional frameworks, capacity development, and integrated farming practices that can reduce environmental impacts while supporting the transition toward sustainable pig farming.

(1) Policy and Institutional Improvements

Stricter environmental regulations and more effective enforcement are essential to reduce pollution from pig farms. Although the government issued Decree 14/2021/ND-CP in 2021, which establishes administrative sanctions and fines for violations of livestock waste treatment regulations, its effectiveness has been limited. Specifically, the decree lacks clear technical guidelines for waste treatment, provides inadequate mechanisms for regular monitoring and enforcement at the local level, and offers limited technical support to help small and medium-sized farms achieve compliance. As a result, many rural pig farms continue to discharge untreated or partially treated waste into the environment. Strengthening environmental laws, closing these regulatory gaps, and ensuring strict compliance are necessary steps for the government to play a more effective role in mitigating pollution from pig farming (Nguyen T. H. 2024; Hang 2023).

Furthermore, the government should consider implementing a reasonable wastewater tax or fee policy for pig farms to encourage efficient water use and improved wastewater management. Countries such as Germany, Austria, and the Netherlands have successfully implemented such measures, improving water conservation and reducing environmental pollution. Introducing a similar system in Vietnam could incentivize farmers to adopt more sustainable practices in managing water and waste. Although Vietnam's Environmental Protection Law provides a legal framework for wastewater fees, practical implementation remains limited. For example, Decree 53/2020/ND-CP imposes environmental protection fees on industrial wastewater but excludes many livestock farms due to difficulties in accurately measuring discharge volumes and limited monitoring capacity. To address these constraints, the government could consider simplified estimation methods based on farm size, number of animal units, or water consumption, which would eliminate the need for direct measurement. Additionally, investing in low-cost digital monitoring tools, such as flow sensors or smart water meters for pilot programs, could enhance data tracking and transparency. A phased enforcement strategy, beginning with large-scale farms, could further support the feasibility and gradual adoption of the policy (Nguyen T. H. 2024; Hang 2023).

In addition to regulatory measures, providing financial support and incentives for farmers to adopt sustainable practices is crucial. Subsidies or low-interest loans for technologies such as biogas digesters, constructed wetlands, and composting systems can help reduce the financial burden of transitioning to environmentally friendly methods (Hang 2023). Past donor-funded programs in Vietnam have offered subsidies for biogas systems, typically ranging from 1 to 3 million VND per household, but these reached fewer than 20% of small and medium-sized farms due to limited budgets and complex administrative procedures. To expand access, financial support programs should be scaled up and made more flexible, potentially through joint funding from national and local governments, development partners, and private stakeholders. Streamlining administrative procedures and leveraging digital platforms for applications and reporting could also lower access barriers for farmers (Nguyen T. H. 2024).

Moreover, introducing performance-based incentives, such as results-based financing, in which disbursements are tied to actual biogas production or verified reductions in waste, could enhance program effectiveness and accountability. While incentives such as tax breaks or preferential loans have been proposed, no large-scale implementation currently targets the livestock sector (Hang 2023). To make such incentives feasible, the government could establish a national green finance program tailored to agriculture, offering tax deductions for certified investments in environmental technologies and concessional loans through partnerships with development banks or climate finance mechanisms. In parallel, a farm accreditation system that recognizes and rewards environmentally responsible practices could help direct benefits toward compliant farms, increase transparency, and foster the wider adoption of sustainable technologies (Nguyen T. H. 2024; Hang 2023).

(2) Technological Solutions

Promoting research, application, and technology transfer in pig waste treatment is essential for developing solutions that are suited to different farm scales. Encouraging the reuse and recycling of waste from pig farming activities can further enhance sustainability in the sector (Hang 2023).

To date, anaerobic digesters are widely recognized as a promising technological solution for waste treatment and energy recovery in pig farms in Vietnam. These systems break down organic waste, such as manure, in an oxygen-free environment, generating biogas that can be used as a renewable energy source. However, the success of anaerobic digestion systems depends on several factors, including proper design and sizing relative to the farm's size, consistent feedstock quantity and quality, appropriate temperature and pH conditions, regular maintenance, and skilled operation. Inadequate management or lack of technical expertise often leads to system underperformance or failure. When effectively designed and managed, anaerobic digesters not only reduce waste volume and mitigate GHG emissions by capturing methane but also provide farmers with renewable energy for heating and cooking, reducing their reliance on fossil fuels (Nguyen T. H. 2024).

Another promising approach is the use of constructed wetlands for wastewater treatment. Constructed wetlands utilize aquatic plants, soils (substrate materials), and microorganisms to remove pollutants such as nitrogen, phosphorus, and organic matter from wastewater. These systems are cost-effective, environmentally friendly, and low-maintenance, as they replicate natural purification processes. Integrating constructed wetlands into pig farms facilitates the treatment of wastewater before discharge, preventing contamination and reducing environmental degradation (Nguyen T. T. 2024).

In addition to wastewater treatment, proper solid waste management, including composting and manure processing, is crucial. Composting transforms manure into nutrient-rich organic fertilizers, minimizing environmental pollution while improving soil fertility. Efficient manure management can reduce soil contamination, improve crop productivity, and limit the release of harmful gases such as ammonia and methane. By adopting these sustainable waste treatment technologies, pig farms can improve their environmental performance as well as gaining economic and energy benefits.

(3) Capacity Building and Awareness

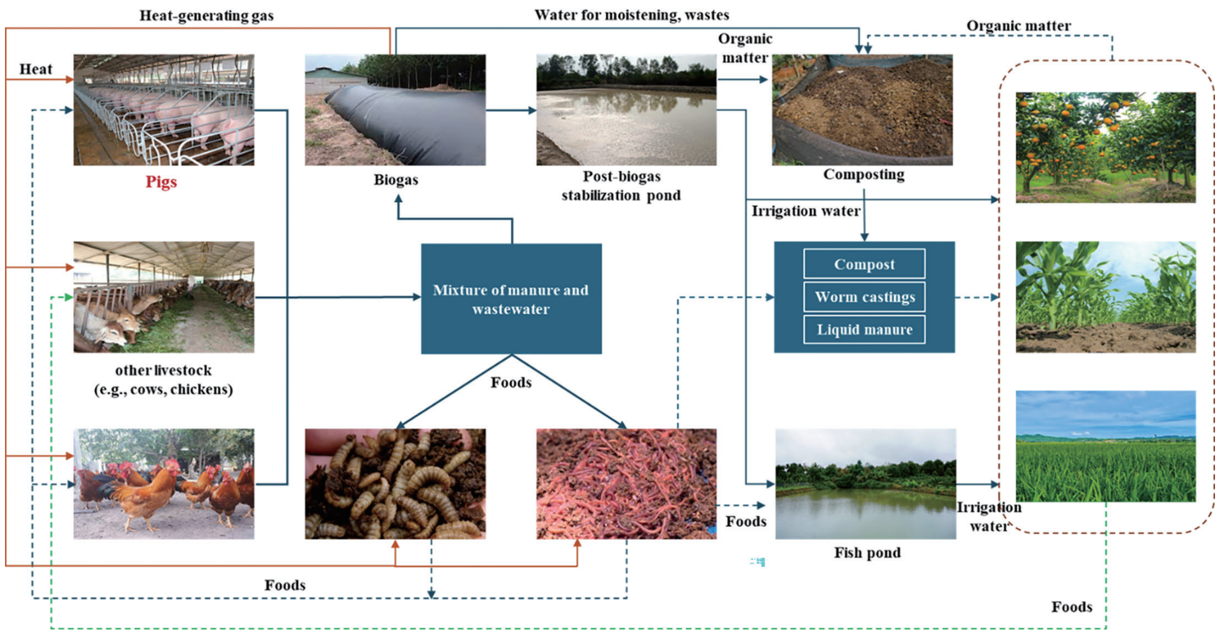
To implement sustainable environmental methods, it is essential to increase the farmers' understanding. Therefore, farmer education programs on waste management, pollution control, and the environmental impact of pig farming should be promoted and supported by government agencies, local authorities, non-governmental organizations (NGOs), and research institutions. These training programs could provide farmers with the knowledge and skills needed to adopt best practices, such as efficient waste management, proper manure storage, and the use of organic fertilizers.

To effectively promote sustainable pig farming, the Ministry of Agriculture and Rural Development should establish demonstration farms in collaboration with local agricultural extension centers, universities, and international development organizations. These demonstration farms should be located in major livestock-producing regions and equipped with technologies such as anaerobic digesters, constructed wetlands, and solid-liquid separators. In addition to showcasing the environmental and economic benefits of these systems, the demonstration farms should hold regular training sessions, technical workshops, and farmer-to-farmer exchange visits. Such direct exposure will help build farmers' confidence and strengthen their ability to adopt these technologies on their own farms.

(4) Integrated Farming Systems

Vietnam has initiated a promising approach for sustainable pig farming by adopting Integrated Farming Systems (IFS), which combine livestock and crop production to minimize waste and improve resource efficiency. Many Vietnamese farmers already practice informal forms of circular agriculture, where manure and crop residues are reused on-site to fertilize fields or feed other livestock. However, transforming these traditional, small-scale practices into a systematic and technically supported framework remains a significant challenge. Developing standardized guidelines, affordable technologies, and effective waste management strategies is essential to help smallholder farmers to fully benefit from these practices while minimizing environmental risks. In Vietnam, pig feed primarily consists of grains like corn and rice, along with soybeans and agricultural by-products such as bran and beer residue. While commercial complete feeds account for approximately 30–35% of total pig feed requirements, the majority (65–70%) comes from homemade feeds using locally available resources (Tran 2012; Vietstock 2024). This reliance on domestic feed sources presents a unique opportunity to design original solutions tailored to Vietnamese conditions, distinct from those used in Denmark, Sweden, or the Netherlands, where pig farming is highly industrialized and dependent on imported feed. Locally adapted IFS models can strengthen feed self-sufficiency, reduce fertilizer imports, and improve nutrient recycling within farms.

A central concept within IFS is the circular economy, where waste is considered a resource rather than a by-product. By recycling waste into organic fertilizers and converting pig waste into valuable inputs for other agricultural processes, farmers can close the nutrient cycle and reduce reliance on chemical fertilizers, thus increasing environmental sustainability by minimizing pollution, improving soil health, and supporting biodiversity. For example, a Vietnamese research group (Tran et al. 2024) proposed a waste-recycling pig farming model that aligns with circular and eco-friendly agricultural principles (Figure 1). In this model, pigs, as the primary livestock, produce manure and wastewater, which are systematically recycled. The solid manure is composted, and the wastewater containing unseparated manure is processed in a biogas recovery system to generate heat and is then stored in a post-biogas stabilization pond to reduce nutrient concentrations. Some of the treated wastewater is used to irrigate compost piles, encouraging microbial activity. In addition, organic waste supports the cultivation of worms and black soldier flies, which can serve as feed for other livestock. To further optimize resource efficiency, the model integrates chickens, cows, fish, and crops, utilizing by-products such as compost, liquid fertilizer, and worm manure. This model farm's primary product is pork, but it also produces beef, chicken, eggs, fish, and vegetables as additional outputs. By closing the nutrient loop, this model increases economic profitability and



reduces environmental treatment costs at the same time.

Figure 1. Food web diagram for a waste-recirculating pig farm. Adapted from Tran et al., 2024

(5) Adjusting the Ingredients in the Diet

Optimizing pigs' dietary intake can be an effective strategy for reducing environmental pollution by minimizing nutrient waste. A typical diet produces excesses of nitrogen and phosphorus in the pig manure, contributing to water pollution and ammonia emissions that are harmful to ecosystems. One solution is to lower the pig feed's crude protein levels while supplementing it with essential amino acids such as lysine and methionine, which will reduce the pigs' nitrogen excretion without affecting their growth. Similarly, adding phytase enzymes to feed enhances phosphorus absorption, decreasing its release into the environment. Pomar and Remus (2022) have shown that tailoring their food intake to meet the specific needs of growing-finishing pigs can reduce their nitrogen excretion by up to 30% and GHG emissions by 22% compared to conventional feeding methods. In addition, incorporating fiber-rich ingredients and agricultural by-products can improve the pigs' digestion process and reduce their methane emissions. The use of locally available feed alternatives can further decrease the carbon footprint of pig farming (Shurson 2025).

By putting these dietary adjustments into practice, farmers can improve nutrient efficiency, lower waste production, and ensure more sustainable livestock management practices, ultimately minimizing the environmental impacts of pig farming.

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