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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.

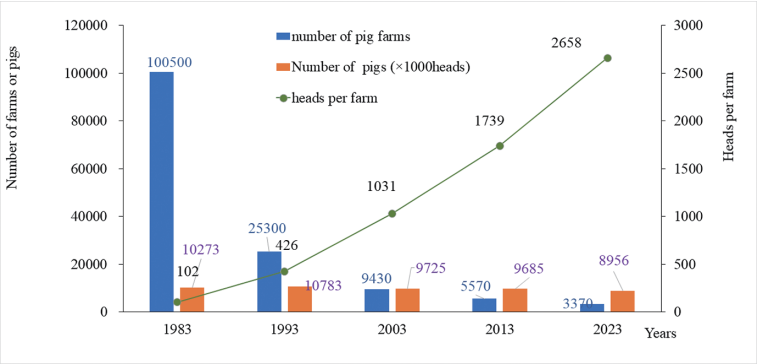
Keywords: *swine wastewater, nitrogen removal, innovative process, anammox, activated sludge process*

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)

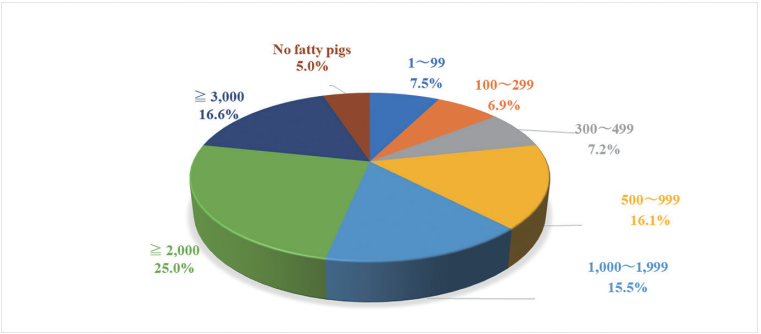


Figure 1. (a) Number of pig farms, total pig population, and average number of pigs per farm in Japan over the years; (b) percentage distribution of pig farm scales in 2023. Source: Author

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.

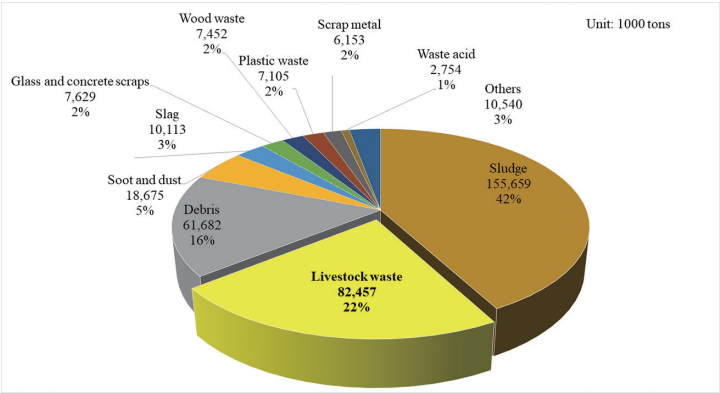


Figure 2 . Waste generated in Japan in 2023. Source: Author

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.

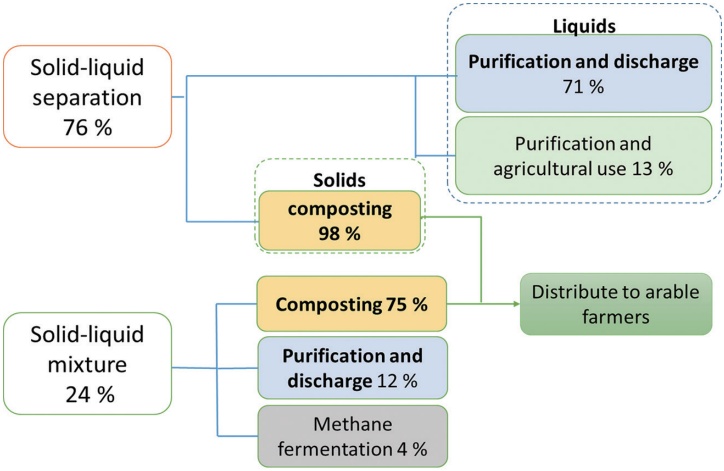


Figure 3. Pig waste disposal methods used in Japan. Source: Author

(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:

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

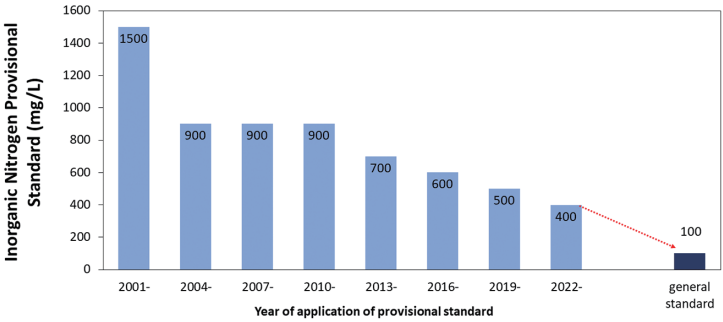


Figure 4. Inorganic nitrogen provisional standard over the years.
Source: Author

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.

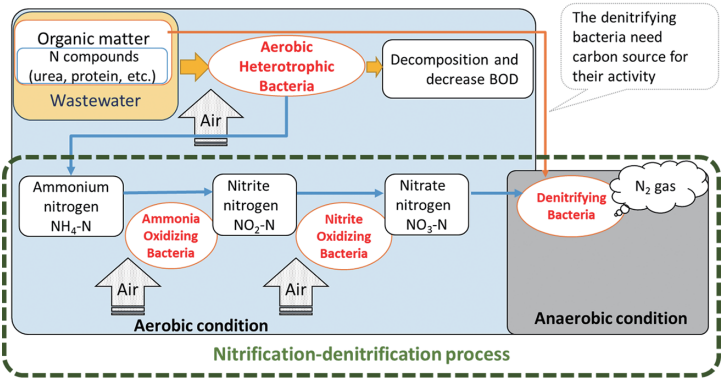


Figure 5. Schematic diagram of the activated sludge treatment process. Source: Author

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.

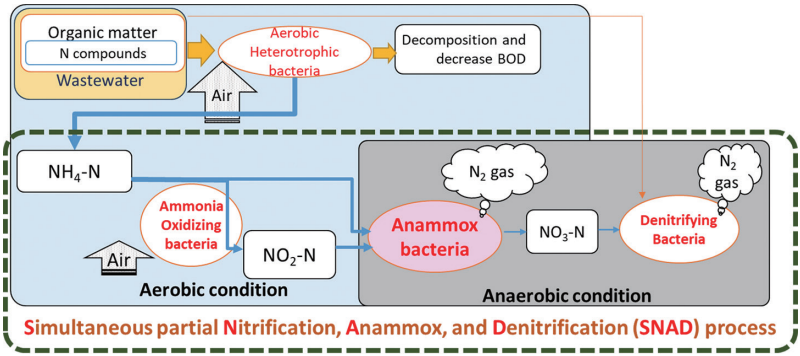


Figure 6. A novel nitrogen removal process using anammox bacteria. Source: Author

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.

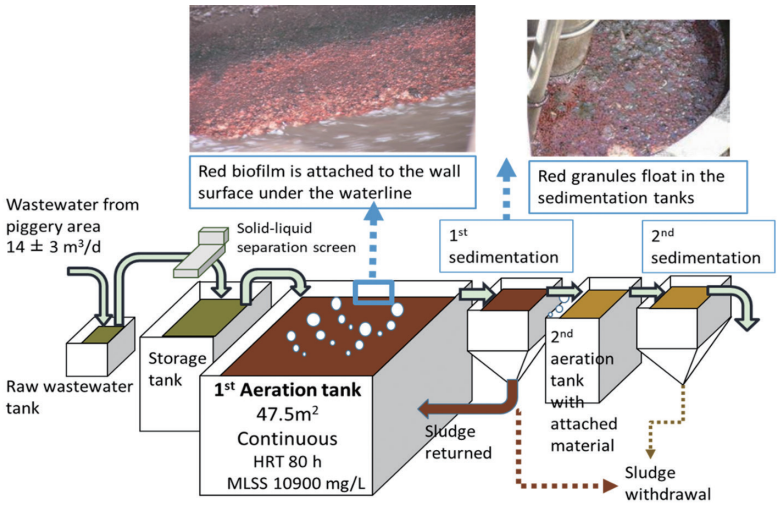


Figure 7. Diagram of a swine wastewater treatment plant accumulating anammox bacteria. Source: Author

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.

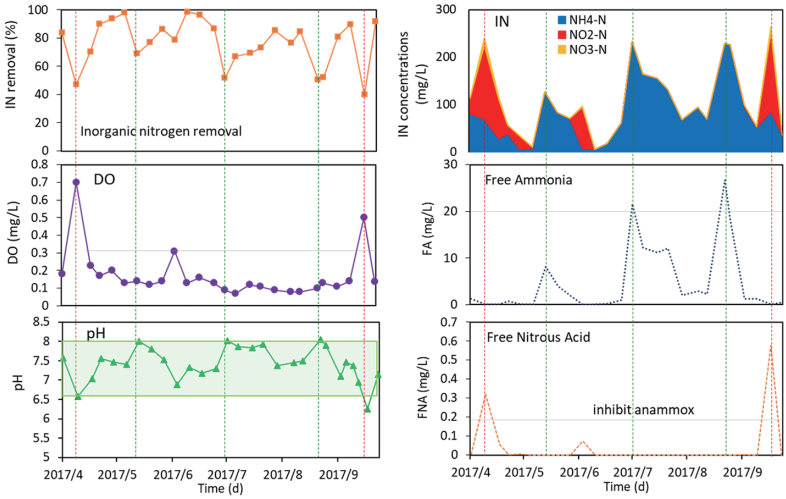


Figure 8. Factors affecting nitrogen removal. Source: Author

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.

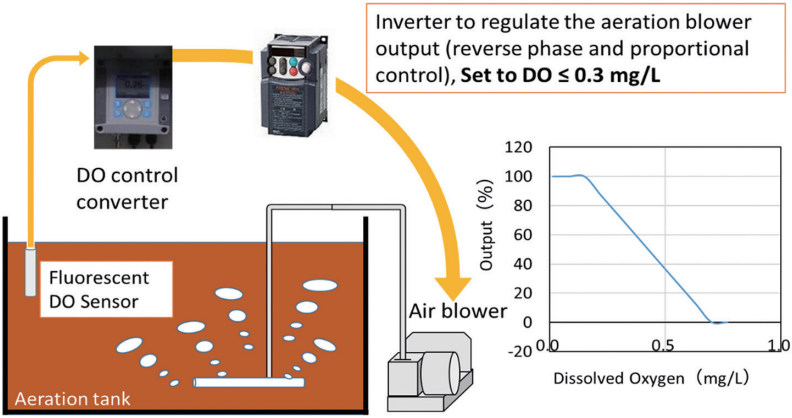


Figure 9. Schematic diagram of the aeration control system. Source: Author

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.

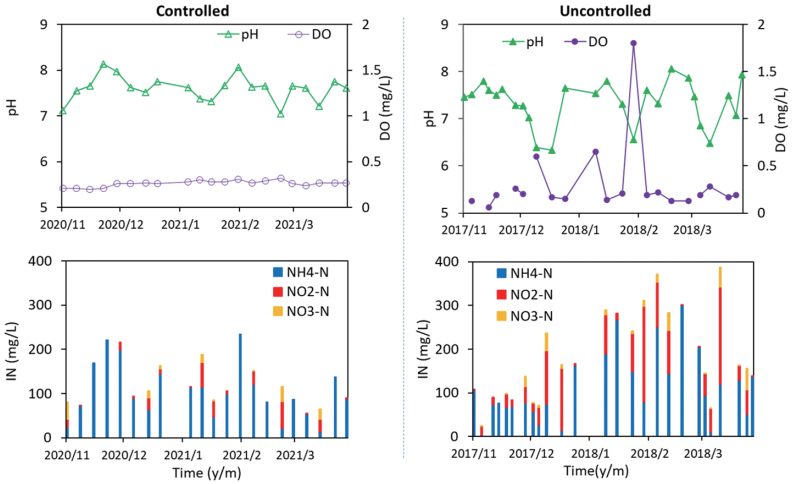


Figure 10. pH and DO, and inorganic nitrogen concentrations in the controlled and uncontrolled systems. Source: Author

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.

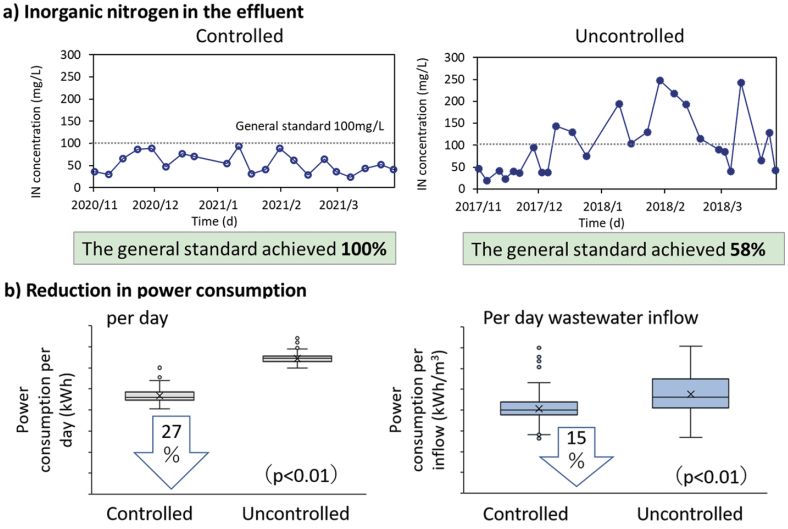


Figure 11. a) Inorganic nitrogen concentration in the effluent, b) Reduction in power consumption. Source: Author

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.

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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.