MANURE MANAGEMENT FOR GREENHOUSE GAS MITIGATION IN JAPAN

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ABSTRACT

Considering the difficulty of mitigating environmental damage caused by climate change, all industries including agriculture should attempt to reduce greenhouse gas (GHG) emissions. Agricultural nutrients can enter other ecosystems via leaching, volatilization, and the waste streams of livestock and humans. The animal sector generates a huge amount of organic matter and nitrogen during feed production, feeding, and manure treatment. Methane is produced when organic materials with high moisture content decompose under anaerobic conditions during manure storage. Nitrous oxide is generated on farms as an intermediate product of nitrification and denitrification by microorganisms present in manure or wastewater and in soils, particularly following compost application. With the growing worldwide demand for animal products such as meat, eggs, and dairy, it is imperative that the animal industry develops methods to mitigate GHG emissions.Till date, the inventory data regarding different GHGs under various conditions from agricultural sector are unclear. To obtain the data required, we developed a system for the direct quantitative measurement of emissions from manure management facilities using a large dynamic chamber. The emission factor of each manure treatment system needs to be evaluated under the procedure and general conditions pertaining to each country because these factors may widely vary. Composting is the principal method for treating the solid fraction of swine manure in Japan. On the contrary, a wastewater purification system is necessary for continuous livestock production in urban farming, particularly for swine breeding. To achieve these ends, we have developed a number of mitigation measures. The cost-effectiveness of mitigation measures developed to regulate on-farm

GHG emissions needs to be evaluated. In present study that began this fiscal year, the economical introduction strategies of GHG regulation measures for domestic farming will be considered based on the Life-Cycle Assessment.

Keywords: Manure management, livestock waste, compost, wastewater treatment, low protein diet

INTRODUCTION

Livestock production systems are the leading sources of gaseous pollutants, including ammonia, methane, and nitrous oxide, which increase soil acidification and global warming. The recent annual report of the Food and Agriculture Organization (FAO, 2009) stated that animal industries contribute to 9% of anthropogenic CO_2 emissions, 37% of CH_4, and 65% of N_2O; when expressed as CO_2-equivalents, these components account for approximately 18% of anthropogenic greenhouse gas (GHG) emissions. Due to their effects on GHGs, animal production systems have been implicated in various local and global environmental problems. To ameliorate the adverse effects of these systems, the mitigation of these emissions should be prioritized, considering that animal production will continue to increase as the world population increases. Meanwhile, options for modifying current livestock-management methods without reducing productivity should be explored, developed, and implemented. For example, supplementing low-protein swine diets with amino acids can reduce nitrogen excretion by approximately 20% (Aarnink and Verstegen, 2007). However, the effects of supplemental low-protein diets on NH_3, N_2O, and CH_4 emissions remain unclear.

In FY2016, the total national GHG emissions reached 1307 Tg (National Greenhouse Gas Inventory Report of Japan, 2018), making Japan the fifth highest emitter of GHGs worldwide. This proportion of GHGs accounts for approximately 4.5% of the total global emission and represents an increase of 2.7% over the emission in 1990 (base year) under the Kyoto Protocol. Japan has set interim GHG reduction targets of 26% reduction below the emission levels recorded in 2013 by 2030 and 80% reduction below those recored in 1990 by 2050. In addition, the Japanese Cabinet submitted the Bill of Basic Law on Climate Change to the National Diet on 12 March 2010. Thus, there is an urgent need to incorporate GHG reduction measures in every category, including the agricultural industry.

CH_4 and N_2O generated from agricultural sector in Japan account for approximately 2% of the total national GHG emission. CH_4 emission due to enteric fermentation by livestock and GHG generated by the treatment of manure are the primary sources of GHGs from animal production in Japan.

CH_4 and N_2O from manure management accounted for 6.8 % and 11.8%, respectively, of the total domestic GHG emissions from agriculture, and together they accounted for approximately 0.6% of the annual national GHG emission. Therefore, the reduction of CH_4 and N_2O emissions using improved methods of manure treatment can potentially reduce overall GHG emissions from the agricultural sector in Japan.

MEASUREMENT SYSTEMS FOR GHG EMISSION FROM ON-FARM MANURE MANAGEMENT FACILITY

Framework of evaluation from manure management

There is still a lack of certainty concerning GHG emission data from different parts of the agricultural sector in Japan, and gas emission data from different livestock sources under various conditions need to be obtained. To this end, we developed a system for the quantitative measurement of emissions from manure management systems using a large dynamic chamber in an experimental study. With a small-scale apparatus, it was difficult to interpret the various changes in the gas emission rate in terms of actual on-farm manure management. In this report, we will introduce our initial measurement system to evaluate the emission materials produced by composting using a large chamber and describe some of the results using this system (Osada *et al.* 2001, Fukumoto *et al.* 2003). According to the results of this study, the emission factors of CH_4 and N_2O from composted manure varied significantly between livestock types, the moisture contents of the pile materials and ambient temperature (Tamura & Osada 2006, Shiraishi *et al.* 2006, Minato *et al.* 2013, Ohkubo *et al.* 2016).

Emission factors also vary depending on the manure treatment type. This is important information not only for inventory data but for the development of greenhouse gas regulations and technologies. In Asian countries, composting is widely used for the treatment of livestock waste. However, the exact amount of greenhouse gases generated from actual composting is not known. Not only the compost, but the emission factor of each treatment system should be evaluated under the procedure and general conditions used by each country, because these factors might also vary widely. It is important that each country has the measurement technique of GHG emission, not only for inventory data but for the development of greenhouse gas regulations and technologies (Maeda *et al.* 2010a,b,2013, Ohkubo *et al.* 2016).

Measurement system for compost (static pile)

In Japan, the composting process plays a central role in livestock waste treatment. Since much of the livestock waste is processed, greenhouse gas (GHG) generation is also recognized to be substantial. However, few experiments have been undertaken in Japan to quantify the amount of each GHG generated from the pile-type composting process, which is the most-representative composting system used in Japan. Various types of livestock waste were piled together with a moisture conditioner to form significant masses (around 300–1230 kg), and their respective CH_4 and N_2O emissions were determined during both the high-temperature and low-temperature seasons. The measurement system we devised consisted of a cylindrical chamber (3 m in diameter, 2.2 m in height, 13 m^3). Samples of inlet air (fresh air) were extracted from a height of 30 cm beside the chamber, and outlet air (exhaust air) was extracted just before entering the ventilation blower (Fig. 1). Gases at each sampling point were automatically carried to the analysis apparatus through a Teflon tube (4 mm diameter). CH_4 and N_2O concentrations in the exhaust air from the chamber were measured using an infrared photoacoustic detector (Innova trace gas monitor, type 1312, and multipoint sampler, type 1309; Lumasense Technol. Inc., Ballerup, Denmark) at 5 min intervals. Gas was dried by an electric cooler to improve the accuracy of the measurement values for methane and nitrous oxide. Air flow rate analyses were conducted weekly using an inclined manometer (Okano Factory) in the exhaust pipe according to the method of JIS B8330. Using the procedure described above, the air in the chamber was interchanged 10.2 times per hour and was highly stable (Fig. 1). The composting-manure emission factors of CH_4 (g per one-kilogram organic matter) and N_2O (g per one-kilogram nitrogen in composting material) varied significantly between livestock types. This should be important information not only for inventory data but also for the development of CHG regulations and technologies (Osada *et al. 2001*, Fukumoto *et al. 2003*).

Measurement system for slurry storage

Gas emissions from stored slurry generated by dairy cattle were the subject of this study. For this purpose, we developed a system for measuring the gases emitted from the surface of a slurry storage tank. We developed a system for measuring emissions from stored slurry by using a floating dynamic chamber. CH_4, CO_2, N_2O and NH_3 emitted from the storage tank of a dairy cattle farm in eastern Hokkaido were measured (Fig. 2).

Depending on the season, the temperature of the stored slurry varied from 15 to 22°C. CH_4 emission was 34–55 $g/m^2/day$, N_2O emission ranged from trace to 67 mg/m^2/day, and NH_3 emission was 0.5–0.7 g/m^2/day (Fig. 2). CH_4, CO_2 and NH_3 were probably generated during the winter as well, but, because the surface of the stored slurry was frozen, we were unable to obtain these measurements. N_2O emission from stored slurry was negligible in winter. All of the measured gas emissions showed seasonal variation and varied widely over the short term. Daily CH_4 emission (g/day) was strongly affected by the volume of slurry stored, the maximum daily ambient temperature, and the slurry temperature. N_2O and NH_3 emissions were influenced heavily by atmospheric humidity and solar radiation, respectively. To accurately calculate the gas generated annually from a specific slurry storage tank, measurements should be obtained continuously over a 24-h period for several days over at least two seasons (Minato *et al. 2013*).

Measurement system for wastewater treatment (aerobic treatment, purification)

The activated sludge process to remove nitrogen and reduce biochemical oxygen demand is reportedly cost-effective for swine wastewater treatment, and its use has thus increased in pig farming. N_2O is generated on farms as an intermediate product during nitrification and denitrification, while methane (CH_4) is also generated from organic matter degradation under anaerobic conditions by microorganisms in manure or wastewater. For the quantitative measurement of GHG emission from each tank at the wastewater treatment facilities in Chiba prefecture, the tank was sealed or covered with a small ventilation chamber, and fresh air (inlet air) and exhaust air (outlet air; head space of each tank) were collected through Teflon tubes. Fig. 3 provides a photograph and a schematic figure of the measuring chamber used in Chiba prefecture. CH_4, N_2O, and NH_3 were continuously measured by a multi-gas monitor (INNOVA 1412; LumaSense Technologies, Santa Clara, CA, USA).

The results of the total measurement period showed that the CH_4 and N_2O emission factors were 0.91% (kg CH_4 /kg volatile solids) and 2.87% (kg N_2O-N/ kg total N), respectively. The values were similar to those from a report from a 16-month-long nitrous oxide emission monitoring campaign at a full-scale municipal wastewater treatment in the Netherlands (Dealman *et al.* 2015). In contrast, the CH_4 emission factor calculated in the present study was rather high compared to prior laboratory measurements. We need to pay more attention to the measuring systems for both the ventilation and gas concentrations at full-scale wastewater purification facilities. The measurement strategies also need improvement to provide more environmentally sound measurements (Osada *et al.* 2017).

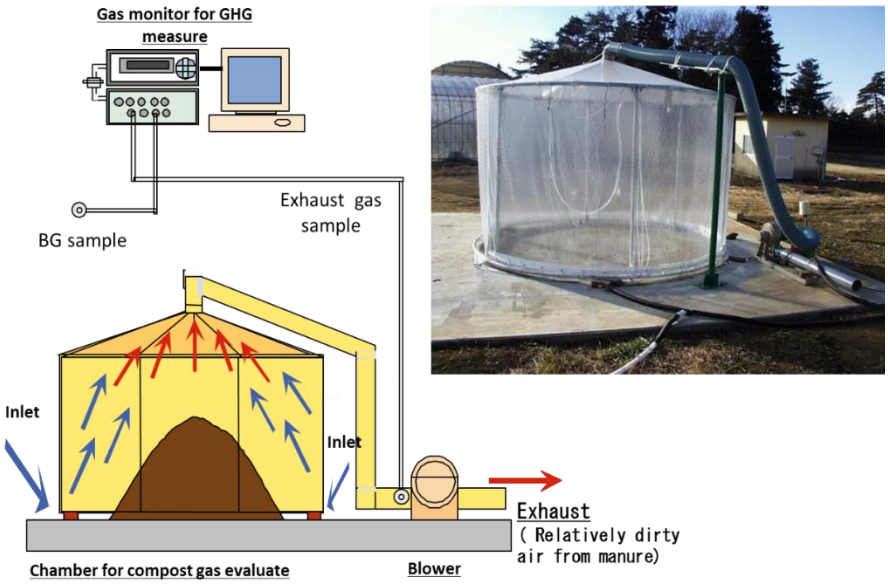

Fig. 1. System for measuring greenhouse gases from composting.

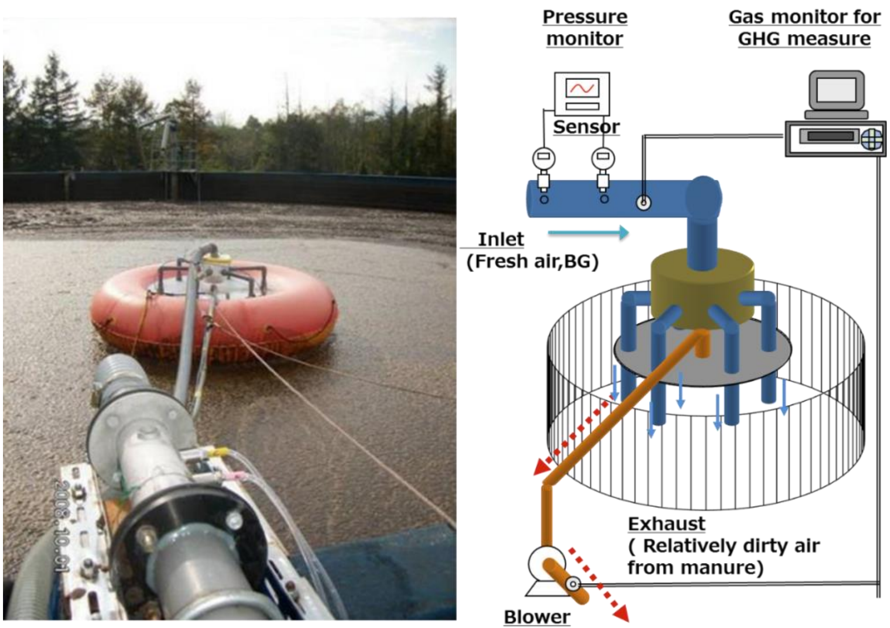

Fig. 2. System for measuring greenhouse gases from slurry storage.

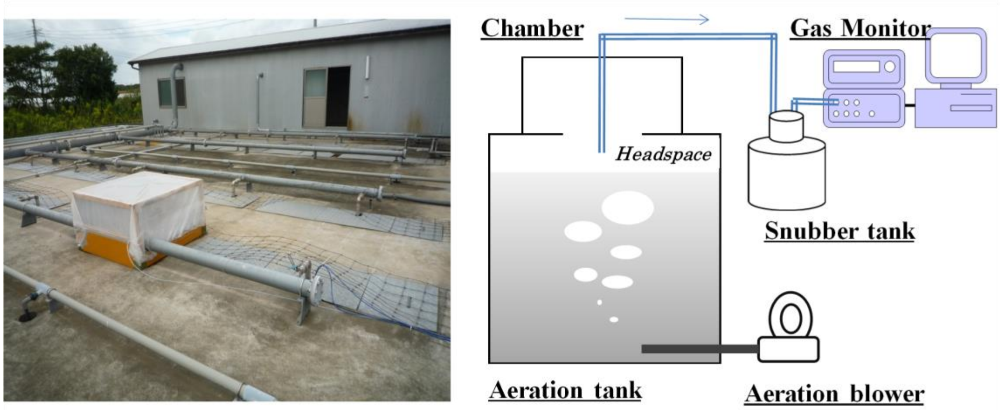

Fig. 3. System for measuring greenhouse gases from wastewater treatment plants.

MITIGATION OF GHG EMISSION FROM COMPOSTING SYSTEM

Trends of Japanese livestock industry and related environmental laws

The livestock industry in Japan has grown dramatically during the few decades since World War II, due to changes in dietary habit, with increased demand for livestock products. At present, the livestock industry has become the fundamental sector of Japanese agriculture, representing 34.4% (3,162,600 million yen) of the value of Japanese total agricultural output (FY 2016). In the Japanese livestock industry, the numbers of livestock animals are almost unchanged from year-to-year, despite the fact that the numbers of livestock farms decrease every year, resulting in a considerable increase in the number of animals on each livestock farm. For example, the average numbers of pig per farm in 1980 was 71, increasing to 2,056 in 2018 (29 times larger than that in 1980), while the numbers of pig farm decreased from 141,300 (1980) to 4,470 (2018). Intensive livestock production has caused the concentration of huge amounts of livestock waste in a limited area. The amounts of annual livestock excretion in 2018 are estimated to be approximately 79,000 thousand tons, which represents approximately one quarter of the total organic waste in Japan. Unsuitable handling or treatment of livestock waste could become the cause of serious environmental problems such as offensive odor generation and water pollution. In Japan, there are several environmental laws concerning livestock waste management such as Waste Management and Public Cleansing Law (enacted in 1970), Water Pollution Control Law (1970), Offensive Odor Control Law (OOCL,1971) and Law Concerning Special Measures for Conservation of Lake Water Quality (1984). Moreover, in 1999, the Law on the Appropriate

Treatment and Promotion of Utilization of Livestock Manure was enacted to encourage the recycling of livestock waste.

GHG generation in the composting treatment

Composting is the optimal treatment method for organic waste, and is recommended for the recycling of livestock waste. Livestock waste can be changed to a uniform organic fertilizer by composting treatment. However, composting of livestock waste is also one of the sources of anthropogenic GHG emissions. Livestock waste consists of urine, feces and other materials such as sawdust for bedding material, and its moisture content is usually too high to achieve good composting. Before the start of composting, it is important to control the moisture content of livestock waste by mixing it with a bulking agent to increase aerobic microbiological degradation. However, in practice, controlling the moisture content of livestock waste to a suitable level is often difficult because of the shortage of bulking agent, which will lead to unsuitable compost fermentation, meaning that the proportion of anaerobic decomposition of the organic matter increases. Therefore, gaseous components generated under anaerobic condition are increased, particularly CH_4. The greater the anaerobic proportion inside the compost pile, the greater the CH_4 emissions (Fukumoto *et al.*, 2003). Therefore, suitable composting treatment needs to be effective for reducing GHG emissions. The pathway of generation of CH_4 is simple, so that decreasing the anaerobic portion of composting material is an effective mitigation measure for CH_4 emission. On the other hand, nitrous oxide (N_2O) is a GHG with a high global warming potential which cannot be mitigated only by using suitable composting treatment, because N_2O is generated *via* both aerobic (nitrification) and anaerobic (denitrification) conditions. Conditions of both reduction and oxidation co-exist in the composting pile. Therefore, it is difficult to reduce N_2O emission by controlling the conditions of the composting process.

Generation of N_2O

Autotrophic nitrifying bacteria consist of ammonia-oxidizing bacteria (AOB), ammonia-oxidizing archaea and nitrite-oxidizing bacteria (NOB). In the nitrification process, ammonia is oxidized into nitrite by ammonia-oxidizing microbes, and NOB subsequently oxidize nitrite into nitrate. It is believed that N_2O is generated as a by-product during the oxidization process from ammonia to nitrite. On the other hand, denitrifying microbes reduce nitrate to produce nitrogen gas (N_2) *via* a series of intermediate nitrogen oxide products including N_2O. As another pathway of N_2O generation, there is nitrifier denitrification in which AOB reduces nitrite to N_2 via N_2O under certain circumstance of high N content, low organic C content, low O_2 pressure and low pH (Wrage *et al*., 2001).

In the composting process, nitrification is a prerequisite for N_2O generation because little nitrate nitrogen is contained in the fresh manure immediately after excretion. Usually, nitrifying bacterium grow in the stored livestock waste before the composting. However, because autotrophic nitrifying bacteria are mesophilic bacteria, the numbers of nitrifying bacteria would decline during the thermophilic phase of composting fermentation. After the thermophilic phase of composting had finished, nitrifying bacteria begin to multiply again. However, there are cases where the regrowth of NOB is delayed behind that of AOB in the composting process. In that case, the oxidation of nitrite into nitrate is inhibited, leading to the accumulation of nitrite in the composting material. Moreover, this phenomenon has important consequences because the nitrite accumulation enhances N_2O emission (He *et al*., 2001). In our studies, the nitrite accumulation during composting were often observed in swine-manure composting. The cause of nitrite accumulation was the delayed growth of NOB compared with AOB growth. Moreover, during the duration of nitrite accumulation, N_2O continued to be emitted. Therefore, it was considered that, to shorten the duration of nitrite accumulation would be effective in controlling N_2O emission. So, we attempted to shorten the nitrite accumulating period by a rapid recovery of complete nitrification in the swine-manure composting.

Effect of NOB addition on N_2O emission

To reduce N_2O emission caused by nitrite accumulation, the effect of the addition of a source of NOB during the swine-manure composting was examined in laboratory-scale composting experiments (Fukumoto *et al.*, 2006). As the NOB source, mature swine compost was chosen. Usually, well matured compost contains nitrifying bacterium to some extent, and it already existed on the livestock farm. The mature swine compost used in the experiment contained both AOB and NOB at high cell densities (10^5 to 10^6 cells per g compost). The material temperature rose to a high level during the first few weeks, sometimes exceeding 60ºC. During this period, large amounts of ammonia were emitted while N_2O emission was scarcely observed. The numbers of nitrifying bacteria in the composting material fell below the detection limit of incubation analyses, and most of the inorganic nitrogen compounds were occupied by ammonium in this period. Because NOB cannot survive at high temperatures, the timing of NOB addition was set at when the thermophilic phase of composting had finished.

After the thermophilic phase of composting had finished, mature swine compost containing NOB was mixed with the composting material. In the control (where there was no addition of mature swine compost), AOB started to grow initially. However, the growth of NOB was delayed, which resulted in prolonged nitrite accumulation and N_2O emission. On the other hand, the accumulation of nitrite was resolved relatively rapidly by the addition of NOB. As a result, the duration of N_2O emission was shortened. In the laboratory-scale composting experiments, the amount of N_2O emission decreased by 60% on average following addition of NOB during the swine-manure composting (Fig. 1). Moreover, in the later study, it was confirmed that NOB addition could also reduce nitric oxide (NO) emission (Fukumoto *et al.*, 2011). Therefore, it is thought that the plural environmental harmful gases emission would be mitigated by resolution of nitrite accumulation in the composting process.

Issues for practical use

The effect of NOB addition in decreasing N_2O emission was confirmed in the laboratory-scale composting experiments. Oukubo *et al*. (2016) examined its effect in the pilot-scale swine-manure composting. However, a negative effect, in that that the amount of N_2O was increased by addition of the NOB source, was observed in their experiment. They discussed that the cause of higher N_2O emission seemed to be due to an increase in the amount of N_2O generated in the denitrification process. This method can decrease N_2O emission induced by nitrite accumulation. However, this method cannot decrease N_2O emission *via* the denitrification process. To make it a usable practical method, it is important to minimize the N_2O generated from denitrification in the composting process, for which it is considered that a suitable composting treatment will be effective.

Recently, complete oxidation of ammonia to nitrate in one organism (complete ammonia oxidation: comammox) has drawn attention as a completely new route of nitrification. It has been revealed that *Nitrospira* species, which have been known to be NOB, have the all the enzymes necessary for complete nitrification (van Kessel *et al.*, 2015). As shown above, nitrite accumulation is an important cause of N_2O emission in the composting process. Therefore, if comammox could be applied to composting, it could be a decisive way to control N_2O emission, but further study is needed to confirm this model.

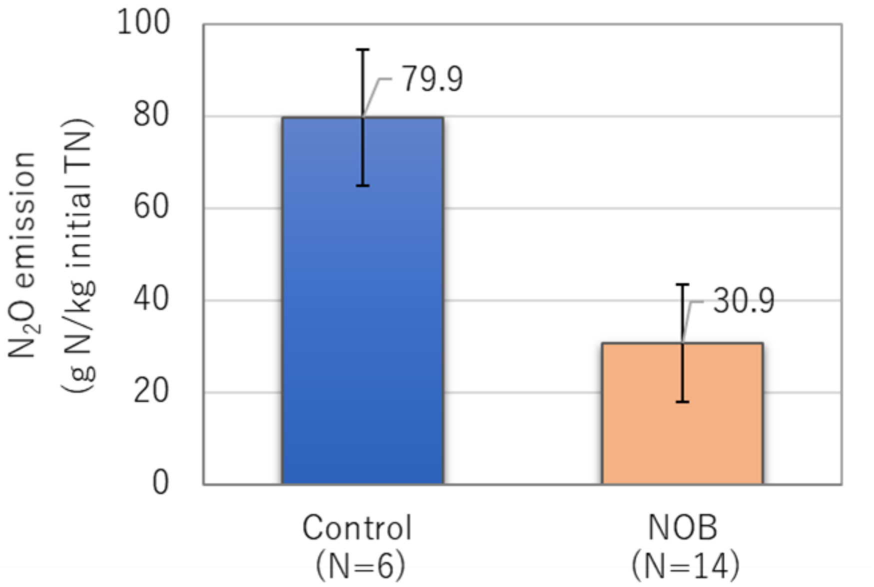

Fig. 4. Effect of NOB addition on N_2O emission in laboratory-scale swine-manure composting experiments. Error bars indicate standard deviation.

MITIGATION OF GHG EMISSION FROM WASTEWATER TREATMENT SYSTEM

Greenhouse gases such as CO_2, CH_4 and N_2O are emitted from wastewater treatment plants. N_2O, in particular, is a potent greenhouse gas, accounting for 7.9% of global anthropogenic greenhouse gas emissions in 2004, and having a global warming potential approximately 300-fold stronger than that of carbon dioxide (Intergovernmental Panel on Climate Change 2007). Kampschreur *et al.* (2009) reported that N_2O was emitted from various types of wastewater treatment. Online measurements suggest that N_2O emission is responsible for 0.01–90% of the total nitrogen load of influent.

N_2O is produced during biological nitrogen conversions in wastewater treatment plants. Most soluble nitrogen in wastewater exists as ammonium ions (NH_4^+). Under aerobic conditions, NH_4^+ is oxidized by autotrophic nitrifying bacteria into nitrite ions (NO_2^-) and nitrate ions (NO_3^-) by a reaction called nitrification. Nitrification is generally carried out by two groups of microorganisms, namely, NH_3-oxidizers that oxidize NH_4^+ to NO_2^-, and NO_2^--oxidizers that oxidize NO_2^- to NO_3^-. Although NO_2^- and NO_3^- are the main end products of nitrification, nitrifier denitrification (a pathway of nitrification) contributes to the production of N_2O by autotrophic NH_3-oxidizers (Wrage *et al.*, 2001). Subsequent to nitrification, under anoxic conditions, NO_2^- and NO_3^- are reduced to N_2 gas by heterotrophic or autotrophic denitrifying bacteria. This reaction is called denitrification. During denitrification, unlike nitrification, N_2O is a regular intermediate. If denitrification occurs completely, N_2O becomes N_2 gas and the release of N_2 gas to the atmosphere removes nitrogen from the reaction tank. Because N_2 gas is not a GHG, converting these ions into N_2 gas is important. An overview of reactions in which nitrification and denitrification is shown in Fig. 1. The overlapping boxes symbolize the possibility of a coupling between nitrification and denitrification. As nitrifier denitrification is a pathway of nitrification, the boxes for nitrification and nitrifier denitrification overlap, but separate into the different branches from nitrite (Wrage *et al.*, 2001). Ritchie and Nicholas (1972) reported that AOB produce N_2O through the reduction of NO_2^- with NH_2OH as an electron donor under aerobic as well as anaerobic conditions. Poth and Focht (1985) reported that N_2O production by AOB through nitrifier denitrification occurs only under conditions of oxygen stress. In the pathway of nitrifier denitrification, NO_2^- is reduced and NO_3^- is not formed.

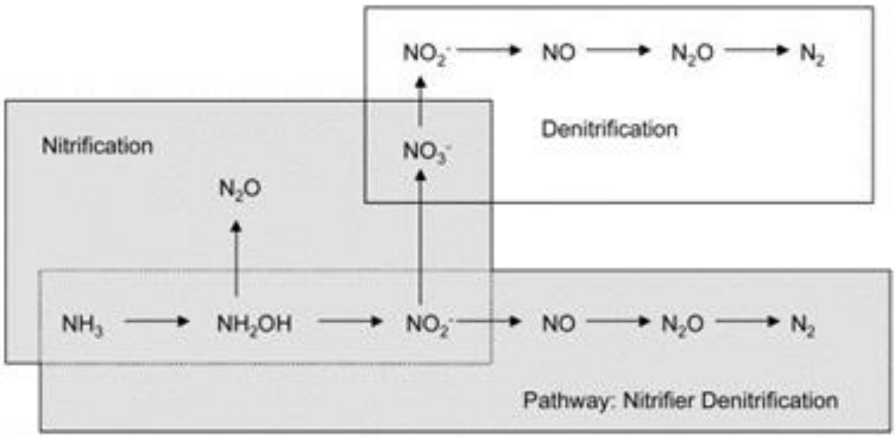

Fig. 5. Transformations of mineralized nitrogen (Wrage *et al.*, 2001).

To develop treatment methods that reduce the amount of N_2O generated in the process of converting NH_4+ within wastewater into N_2 gas, we focused on and examined the biofilm method. The microbial reactions in this method differ from those of the conventional wastewater purification treatment methods or the activated sludge (AS) method. A biofilm method uses carriers (materials that hold the microorganisms) to purify wastewater. In previous research, N removal from dairy farm wastewater treatment in an aerobic bioreactor packed with a perlite carrier, reported the efficient removal of N (Yamashita *et al.* 2011). The application of this perlite carrier method to swine wastewater treatment was expected to yield similar results. However, NO_3^- and NO_2^- were not efficiently denitrified, but instead both accumulated. This result would have been because bacteria of the aerobic denitrifying genus *Thauera* were present in the dairy farm wastewater and accumulated on the perlite carrier; in contrast, *Thauera* spp. was scarcely present in the swine wastewater and did not accumulate, thus leading to the absence of adequate denitrification. For this reason, if N is to be removed from swine wastewater by using a single-tank reactor, fixed-bed-type carriers should be used because they enable more efficient denitrification than do fluidized-bed-type perlite carriers because of the more efficient anaerobic growth within the tank of the former. We employed carbon fibers (CF) as carriers, because CF adhere strongly to microorganisms and are expected to hold them for longer and at higher concentrations than can be achieved with the AS method. Mitigation of nitrous oxide (N_2O) emission from swine wastewater treatment was demonstrated in an aerobic bioreactor packed with CF reactor (Yamashita *et al.* 2015, 2016). The CF reactor had a demonstrated advantage in mitigating N_2O emission and avoiding NOx (NO_3^- + NO_2^-) accumulation. The N_2O emission factor was 0.0003 g N_2O-N/g TN-load in the CF bioreactor compared to 0.03 g N_2O-N/g TN-load in the AS reactor. N_2O and CH_4 emissions from the CF reactor were 42 g-CO_2 equivalents/m^3/day, while those from the AS reactor were 725 g-CO_2 equivalents/m^3/day (Fig. 6). The dissolved inorganic nitrogen (DIN) in the CF reactor removed an average of 156 mg/L of the NH_4-N, and accumulated an average of 14 mg/L of the NO_3-N. In contrast, the DIN in the AS reactor removed an average 144 mg/L of the NH_4-N and accumulated an average 183 mg/L of the NO_3-N. NO_2-N was almost undetectable in both reactors (Fig.6). In the CF carrier experiment, a huge amount of biofilm was formed (29.0 mg dry-weight sludge/mg CF); this was equivalent to biofilms of ~50 g/10 L within the tank. In addition, there may have been AS as well as biofilms adhering to the CF within the tank, indicating that reasonable amounts of microorganisms were present and involved in purification. The CF method can be introduced by loading CF carriers into existing AS treatment equipment. No special equipment needs to be installed, and this reduces the initial investment required. The CF method is therefore likely to be adopted for use on livestock farms.

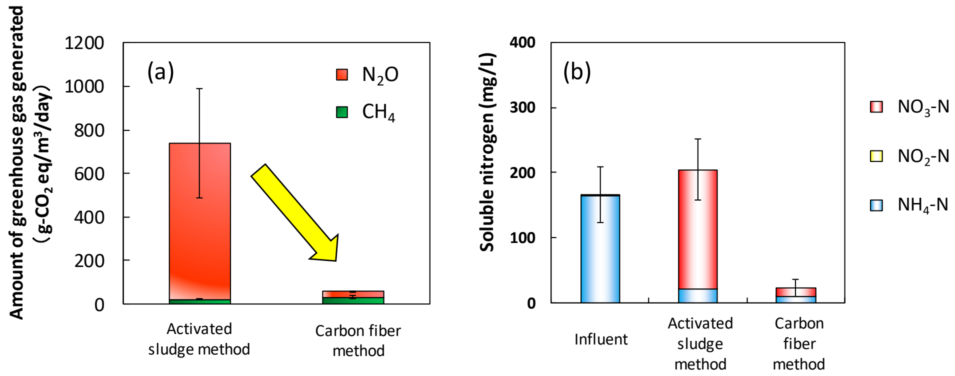

Fig. 6. Gas emissions and water quality in the activated sludge and carbon fiber bioreactors. (a) Amount of greenhouse gas generated from the bioreactors. (b) Water quality in the bioreactors.

POTENTIAL REDUCTION OF GHG EMISSIONS FROM MANURE MANAGEMENT BY USING A LOW-PROTEIN DIET SUPPLEMENTED WITH SYNTHETIC AMINO ACIDS

One possible measure to achieve reduction of GHG emissions from livestock production is by reducing the excretion by livestock of nitrogen, which is a source of N_2O emissions in manure management. Many studies of the feeding of a low-protein diet supplemented with crystalline amino acids (AA) to fattening pigs have been conducted and have reported a reduction in nitrogen excretion without sacrificing productivity (e.g. Otto *et al.* 2003b; Rotz 2004). Furthermore, the reduction of N_2O emissions from manure has recently been reported to be achieved by the low-protein diet technique (Osada *et al.* 2011). However, the use of a low-protein diet with AA involves additional GHG emissions resulting from AA manufacturing. The environmental impacts were therefore compared using the LCA method between two pig farming systems, one using conventional diets (CNV) and the other using the low-protein diets with AA (LOW). This section is based on Ogino *et al.* (2013), from whence further information can be obtained.

Materials and Methods

The first step of LCA is the definition of the functional unit (FU), the system boundaries and so on. The FU was defined as one marketed pig. For the comparative LCA of manure management, the CH_4 and N_2O emissions from the manure management of CNV were set as a baseline, and the system boundary of LOW included the CH_4 and N_2O emissions resulting from manure management and of changes in the GHG emissions from the processes of feed production including AA manufacturing and feed transport and the materials and energy consumed in the manure management process. For the cradle-to-farm gate LCA of pig farming, the evaluated system included the processes of feed production including AA manufacturing for LOW, feed transport, animal housing including the biological activity of the animal, and manure management. The diets for the growing stage (from 30 to 70 kg of liveweight) were designed based on Osada *et al.* (2011) while those for the fattening stage (from 70 to 115 kg of liveweight) were based on Kaji *et al.* (1997). The crude protein (CP) contents of LOW and CNV were 14.5% and 17.1% for the former study, respectively, and 10.8% and 14.0% for the latter study, respectively.

The second step of LCA is life-cycle inventory. The emission factors associated with pig farming considered in the analysis were collected from literature, LCA database, and so on. The emission factors used in this study were adopted because they were determined to be the most applicable to the defined conditions of the processes in the systems analyzed, such as the climate, animals, and styles of housing and waste treatment. The nitrogen content in excreted feces and urine for swine (expressed in g/day) was calculated as follows:

$$\text{Excreted N} = (\text{CP} - \text{RP} - \text{MP}) / 6.25$$

where CP is crude protein intake (g/day), RP is retained protein (g/day), and MP is milk protein for the lactating sow (g/day) calculated using the feeding standard (NARO 2005). The calculated nitrogen flow values per FU from feed to manure in LOW and CNV were as follows: 9.05 and 7.74 kg N from feed intake, 3.04 and 3.04 kg N used for weight gain, 1.67 and 1.59 kg N excreted into feces, and 4.35 and 3.11 kg N excreted into urine, respectively. The reduction in nitrogen excretion by the pigs resulting from the low-protein diets was determined to be 4.9% for feces and 40.6% for urine at the growing stage (Osada *et al.* 2011), and 7.0% for feces and 35.0% for urine at the fattening stage (Kaji *et al.* 1997). Further explanations on the life-cycle inventory and impact assessment methodologies are found in Ogino *et al.* (2013).

Results and Discussion

As a result of comparative LCA, the GHG emissions from manure management in LOW and CNV were 80 and 100 kg CO_2-equivalents, respectively. The lower direct and indirect GHG emissions from manure management contributed to lower total GHG emissions from LOW despite the higher emissions from feed production including AA manufacturing. The comparative LCA of the manure management of pig farming systems revealed that the use of a low-protein diet supplemented with AA resulted in 20% lower GHG emissions, even taking into account the negative effect of the changes in diet. While the GHG emissions from AA manufacturing were predictably higher than those from the production of the main feed ingredients, such as corn and soybean meal, the reduction in N_2O emissions from manure management, mainly from wastewater treatment, was much larger than the GHG increase due to the use of AA. The national GHG inventory, which provides a basis for policy-making related to GHG mitigation, categorizes the sources of GHG emissions based not on the life cycle of the products but on sectors (e.g. energy and agriculture), and each sector is broken down into activities or practices (e.g. mobile combustion and manure management). For the GHG emissions related to manure management, there is the category of manure management, which covers CH_4 and N_2O emissions from livestock manure management, and thus a comparative LCA of manure management enables quantification of GHG mitigation in this category in line with the structure of the national GHG inventory, taking into account negative effects. This is the significance of conducting the comparative LCA of manure management in this study as well as the cradle-to-farm gate LCA of pig farming. The GHG mitigation potential brought about by the low-protein diet technique was estimated to be 340 Gg year^{-1} using the GHG mitigation per head obtained in this study (19.9 kg CO_2-equivalents) and the annual number of marketed pigs (17.0 million head; MAFF 2010).

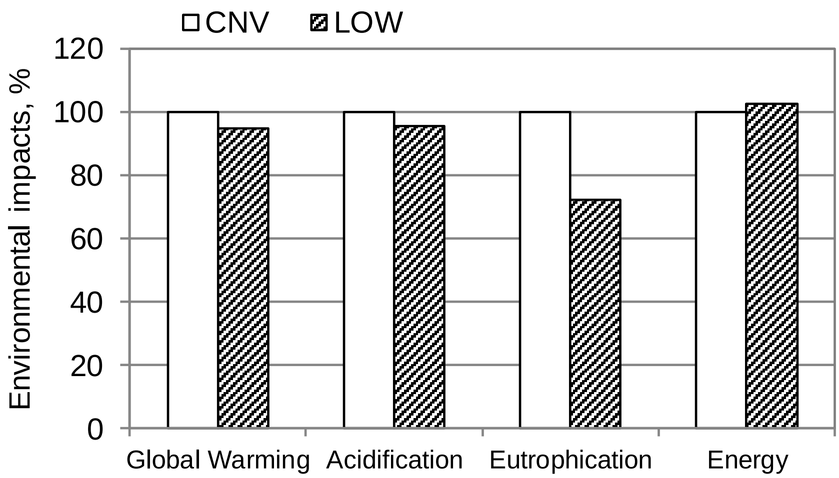

Fig. 7. Cradle-to-farm gate environmental impacts of pig farming systems. CNV, pig farming system using conventional diets; LOW, pig farming system using low-protein diets supplemented with amino acids. Values for CNV are expressed as 100%.

The results of LCA for four environmental impact categories over the whole life cycle of the pig farming systems (cradle-to-farm gate LCA) are shown in Fig. 7. The difference between LOW and CNV in terms of acidification had a tendency similar to the difference in global warming; LOW had a 4 to 5% smaller acidification potential than CNV. The eutrophication potential of LOW without maximizing GHG reduction was much smaller (by 28%) than that of CNV. Energy consumption was slightly (1-2%) larger in LOW than in CNV. The results of cradle-to-farm gate LCA of pig farming showed that LOW had lower GHG emissions than CNV throughout its life cycle (Fig. 7). The manure management process had the second highest GHG emissions (35% of the total) next to the feed production process in the pig life cycle, and thus the low-protein diet technique, which mainly reduces GHGs emitted from the manure management process, appears to be effective to reduce cradle-to-farm gate GHG emissions from pig farming. The eutrophication potential was markedly lower in LOW without maximum GHG reduction than in CNV, and this difference appeared to be because more than half of the environmental loads related to eutrophication were generated in the manure management process in CNV, and effluent nitrogen, which is a major source of eutrophication, was reduced by the low-protein diet technique. As the reason for the greater energy consumption in LOW, it was suggested that the low-protein diet technique mainly reduced N_2O emissions not relevant to energy consumption, while AA manufacturing consumed more energy than crop production per unit amount.

The results of LCA suggests that the low-protein diet technique reduces environmental impacts as a whole. The low-protein diet technique does not depend on the availability of the feedstock or the modification of waste treatment systems, and thus, theoretically, it can be used on all pig farms.

The reduction of GHG emissions from pig farming using a low-protein diet supplemented with AA has been reported for other countries or regions, such as France (Garcia-Launay *et al.* 2014), Brazil (Monteiro *et al.* 2016; 2017), Europe, and North and South America (Kebreab *et al.* 2016). Among these reports, larger reduction of GHG emissions has been observed when AA replaces soybean meal that is derived from South America and involves deforestation.

CONCLUSION

Composting is the most popular system for treating cattle manure in Japan. Restrictions on the level of GHG emissions vary depending on climate conditions and livestock species. We believe that efforts to reduce GHG begin by accurately measuring and presenting the emission status for each farm.

Nitrite accumulation is one of the important factors contributing to N_2O emission during the composting of livestock manure. One of the causes of nitrite accumulation during composting is the delayed regrowth of native NOB compared with AOB after the thermophilic phase of composting. To reduce N_2O emission during composting, the effect of the artificial addition of an NOB source (mature compost product) after the thermophilic phase of swine-manure composting was evaluated using laboratory-scale apparatus. By adding the NOB source, the duration of nitrite accumulation reduced, which resulted in the early cessation of N_2O emission. In the laboratory-scale swine-manure composting experiments, N_2O emission rate was reduced by 60% on average by adding the NOB source. However, a negative effect of the addition of the NOB source in the pilot-scale composting experiment was observed, which seemed to be due to an increase in N_2O generation *via* denitrification by the addition of nitrate nitrogen contained in the NOB source. Countermeasures are necessary to reduce N_2O generation from denitrification when this technique would be used in the actual composting treatment.

The CF method can be introduced by loading CF carriers into existing AS treatment equipment. No special equipment needs to be installed, and this reduces the initial investment required. The CF method is therefore likely to be adopted for use on livestock farms.

The results of the comparative LCA showed that the GHG emissions from manure management of LOW were 20% less than those of CNV. The results of cradle-to-farm gate LCA showed that LOW had lower GHG emissions, acidification potential, eutrophication potential and overall environmental impact, and slightly higher energy consumption, than CNV.

In terms of amino acid-balanced diets, the addition of crystalline AA is a cost-increasing factor, while the reduction of high-CP feed ingredients, such as soybean meal (a costlier option than low-CP feed ingredients like maize) is a cost-decreasing factor. Though the price of amino acid-balanced diets depends on the price ratio between high- and low-CP feed ingredients, as well as the level of added crystalline AA and price of AA, it is equal in price or moderately cheaper overall compared to the conventional diets.

For swine and chicken, the AA that will be lacking when reducing the CP content can be determined by comparing the amino acid content in the diet and the amino acid requirement of the livestock (in most cases, lysine and methionine are limiting AA for swine and chicken, respectively). In the case of cattle, unlike swine and chicken, since all AA are theoretically supplied from rumen microbes, we cannot determine which AA will be lacking by comparing the amino acid content in the diet and the amino acid requirement. However, we know empirically which AA are typically lacking, and thus amino acid-balanced diet could also be applied for cattle.

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