Doctoral Thesis

Flow of Manure Nutrient, Floor Space Allowance and Nitrogen Fertilization Practice (Rice Farming) in Integrated Crop-Animal Farming System

경축순환농업체계의 가축분뇨 양분흐름, 단위사육면적 및 질소시비법(답작) 분석

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Abstract

Flow of Manure Nutrient, Floor Space Allowance and Nitrogen Fertilization Practice (Rice Farming) in Integrated Crop-Animal Farming System

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An integrated crop-animal farming (ICAF) refers to a management system that establishes a sustainable agricultural environment and ecosystem by reusing the by-products between the livestock farms and the crop farms in the agricultural system. Understanding the balance of nutrients from the generation of livestock manure to the land-application of plant-soil system is considered to be one of the important factors in establishing the ICAF system. However, it is not easy to understand the relationship of each factor and find a balance point because the complex processes are linked in the ICAF system. Therefore, this dissertation analyzed the nutrient flow and dynamics from livestock manure production to land-application in South Korea. The nutrient flow of pig manure in the ICAF system was analyzed by applying appropriate FSA considering pig productivity. In addition, a suitable method of using chemical fertilizer and treated swine slurry was proposed. As a result, the following conclusions were obtained.

First, the ICAF system in South Korea is still inadequate and has been suffering from the disposal of livestock manure and agricultural waste in many areas.

Therefore, it was necessary to closely examine the ICAF status of the relatively active areas (Nonsan and Namwon) and to find out the ICAF system considering the characteristics of the poor ICAF areas (Yeongcheon and Jinju). In Jinju, the urbanization rate was relatively high. Therefore, the ICAF system was considered to be suitable for the two-track model that co-promotes the compost/liquid fertilizer facility and the energy facility. In the case of Yeongcheon, it would be appropriate to install three to four decentralized public recycling facilities at midsize (around 30 tons) in *myeon* where a cluster of livestock farms was located. However, according to scenario predictions, the recycling rate of livestock manure in the area had increased but the over-supply of nutrients had not decreased. Comparing the nutrient requirement of the crop with the amount of nutrient input to the cropland, it can be seen that 113 kg ha^{-1} of N and 146 kg ha^{-1} of P_2O_5 were over-supplied annually. In Jinju, 12 kg ha^{-1} yr^{-1} of P_2O_5 was expected to have an oversupply in comparison with the amount of nutrients required for crops. Even if the ICAF system is built in consideration of local characteristics, the use of large amounts of livestock manure and indiscriminate application of chemical fertilizers exceeding the capacity of agricultural land remains a problem.

Second, the appropriate level of floor space allowance (FSA) is probably the most important factor in managing this large-scale pig farms. In particular, the pig farming industry in South Korea prefer to pursue profit by maximizing the production of pigs in a limited space as much as possible. As a result, farmers (producers) are guaranteed a certain level of productivity, but livestock, farm managers, and people around the farm cannot avoid the negative impact. In this dissertation, the average survival rate (SR) of growing pigs tended to increase with increasing FSA. Generally, fattening pigs in South Korea were being raised in a small space. Therefore, it was found that if the FSA of "0.8 ~ 1.0 m^2 $head^{-1}$" is increased to "1.1 ~ 1.27 m^2 $head^{-1}$", it contributed to raise the average SR. The days at a slaughter weight of 110 kg (d-SW) of fattening pigs also showed a tendency to decrease with increasing FSA. It is considered that the fattening pigs raised in moderately wide space (1.27 ~ 1.54 m^2 $head^{-1}$) were helpful for the increase of the growth rate due to the stress reduction. A slight increase in the FSA can have a positive impact on productivity, while also solving environmental problems. As FSA increased, the amount of nutrients (N, P_2O_5 and K_2O) from livestock manure was reduced. In the case of N, 20%, 27%, 37% and 48% of N were reduced in 1.0 m^2 $head^{-1}$, 1.1 m^2 $head^{-1}$, 1.27 m^2 $head^{-1}$ and 1.54 m^2 $head^{-1}$, respectively, compared to the N value of 0.8 m^2 $head^{-1}$. Other nutrients (P_2O_5 and K_2O) were also reduced at a similar rate. According to the nutrient flow calculation method of the four regions (Namwon, Nonsan, Yeongcheon and Jinju), increasing the FSA from 0.8 to 1.54 m^2 $head^{-1}$ resulted in a reduction of surplus N up to 60%. In the case of P_2O_5, 5% ~ 16% was reduced as the FSA increased, and the deviation by region excluding Jinju was not large. Jinju showed the highest surplus P_2O_5 reduction (61%) compared to other regions probably due to the large cropland area per livestock unit (LU).

Third, the use of proper N fertilizer in rice farming is an essential factor in the success of farming. The N fertilization practices using organic fertilizers (livestock manure) with chemical fertilizers are being used as part of sustainable agriculture. When using anaerobically-aerobically treated swine slurry (TSS) and chemical fertilizer (AS) in combination, it is preferable to use the chemical fertilizer less than 3:1 ratio since the recovery of inorganic N was constant regardless of the mixing ratio of AS. In the oxidized topsoil of paddy soils, NH_4^+ was converted to NO_3^- by the effect of nitrification process. As a result, it was predicted that the soil

$\delta^{15}N$ level increased as the $^{14}NH_4^+$ decreased. Total ^{15}N recovery (crop + soil) was 42%, 43% and 54% in HTSS + LAS (3:1 ratio of TSS and AS), LTSS + HAS (1:2 ratio of TSS and AS) and AS (chemical fertilizer only), respectively. The N fertilization practice with low AS and high TSS rates was recommended for sustainability and cost savings. However, N losses, especially through the coupled nitrification-denitrification process, can diminish the benefits that HTSS+LAS offers.

In the introduction of this dissertation, the current status and problems of the overall livestock production in South Korea were described. In chapter 2, two regions (Yeongcheon and Jinju) operated as individual recycling facilities and two regions operated by public recycling facilities (Namwon and Nonsan) were selected to investigate the dynamics of livestock manure nutrients. The potential nutrient supply and nutrient requirements of crops were analyzed. Chapter 3, in conjunction with the content of Chapter 2, examined the appropriate FSA that satisfies both productive and environmental aspects. Chapter 4 discussed the land-application of livestock manure for the next phase of the livestock manure disposal and treatment process (discussed in chapter 2). The N behavior of paddy soils using TSS + AS mixed fertilization practices was investigated. Conventional land-application studies on livestock manure were based primarily on fertilizer value and crop productivity of compost / liquid fertilizer. This thesis is different in that it can analyze the N behavior of the soil-crop system more accurately by using ^{15}N and proposed appropriate TSS and AS fertilization practices compared with existing methods. In particular, anaerobically-aerobically treated pig slurry was used as a fertilizer resource in paddy soils. This is a study on the follow-up process of renewable energy of livestock manure and can be regarded as an academic contribution of this thesis. It is hoped that guidelines on the land-application of livestock manure in various agricultural sectors such as horticulture, upland, fruit trees, grass land as well as paddy soil will be created on the direct / indirect extension of this thesis.

Keywords : Livestock manure, Nutrient flow, Floor space allowance, Integrated crop-animal farming, 15-Nitrogen stable isotope, Treated swine slurry

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CHAPTER 1. GENERAL INTRODUCTION

1.1. Background of research

Reliance on livestock to satisfy human demand for animal products is increasingly high. For producers, concentrated animal feeding operation (CAFO) is a cost-effective way to meet the increasing demand for animal products due to population growth. This production system is also good for consumers because consumers can easily purchase the right-price livestock products from the market. As long as there is no complaint, the current system will be maintained. However, concerns are growing about CAFO as the immorality of the system and the consumption trend requiring a healthy diet became widely known to the public through the media. Especially, South Korea has limited land area to operate the livestock industry. Therefore, the approach from the environmental aspect is emphasized unlike European animal welfare approach (Hovi et al., 2003; Borell and Sørensen, 2004; Chung et al., 2014). As a national consumption of livestock products increases along with meat intake (**Table 1.1**), the scale of domestic animal farming also increases, simultaneously increasing the amount of livestock manure.

Table 1.1. Pork supply and demand status in South Korea[①]

Item		2008	2009	2010	2011	2012	2013	2014	2015
Supply	Self-production (1,000 tons)	709	722	764	574	750	853	830	842
	Importation (1,000 tons)	509	479	524	370	275	185	274	358
	Total (1,000 tons)	1,218	1,201	1,288	944	1,025	1,038	1,104	1,200
Demand (1,000 tons)		927	916	940	938	926	1,048	1,118	1,205
Total consumption (1,000 tons)		927	916	940	938	926	1,048	1,118	1,205
Self-sufficiency ratio (%)		58.2	60.1	59.3	60.8	73.2	82.2	75.2	70.2
Per capita consumption (kg)		19.1	19.1	19.2	19.0	19.2	20.9	21.8	23.7

① Adapted from 'Agricultural Business Management Assistant: Pig management', RDA, 2016.

In South Korea, livestock manure generated from swine houses is a particularly serious problem compared to other animal species. Swine manure is higher in water content than the manure of other animals. Of course, water content varies with stages of growth, feed materials, breeding management and manure management② but the water content of swine manure is generally at least 96%, while the remaining 4% is composed of solids (MWPS-18, 2004; Suresh, 2009).

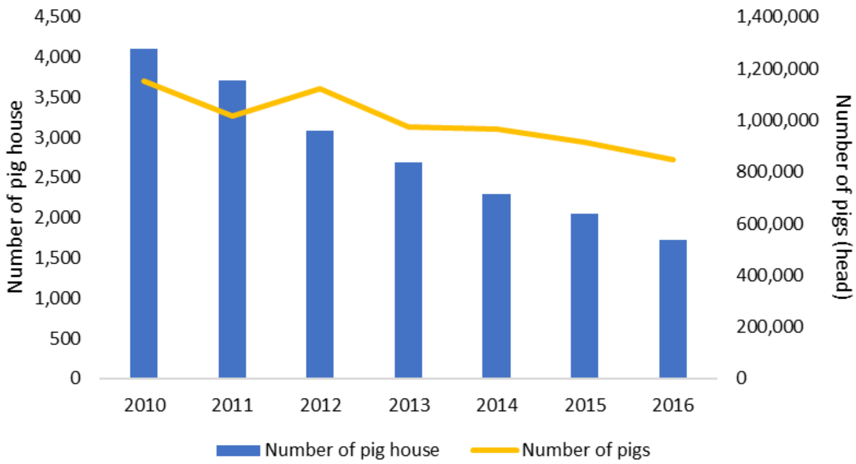

Fig 1.1. Number of pig houses and pigs in small-scale farms (<1,000 pigs) in South Korea from 2010 to 2016

The number of small-scale pig farms under 1,000 is showing a decreasing trend in South Korea (**Fig 1.1**). Small-scale farms cannot properly control the generation of odors, which makes them subject to complaints (a more detailed

② In South Korea, the manure management of pigs is generally accomplished by collecting feces and urine into slurry pits and then treating them by solid-liquid separation process. Therefore, according to the handling system of the manure, pig manure is a slurry type and has a high moisture content. Beef cattle use bedding materials, which results in lower water content and higher solids content (Source: Ohio State University Extension Bulletin 604, 1992 Edition.).

in case study 1.1.1). The economic difficulties of small-scale farms also make it impossible to invest in improving the farm environment. On the other hand, large-scale farms tend to increase (**Fig 1.2**). If a large quantity of swine slurry is generated in a confined space, the capacity of the area can easily be exceeded. This causes soil and water pollution, which leads to civil complaints by the residents and even evasion of pig farming in the long term.

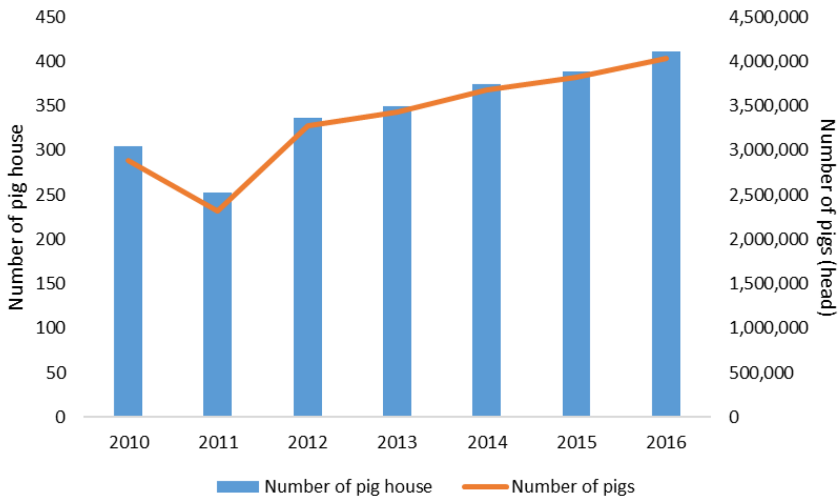

Fig 1.2. Number of pig houses and pigs on large-scale farms (over 5,000 pigs) in South Korea from 2010 to 2016

1.1.1. Case study: The nitrogen loss through ammonia gas volatilization

A total of 12 pig houses in South Korea were investigated twice in summer and winter season. The first field survey was conducted in January ~ February 2013, and the second field survey was conducted in July ~ August. In this case study, the above-mentioned small-scale farms were investigated for the status of odor production. Based on the field survey, the type of pig house was classified as follows: a winch curtain and scraper system for the first-generation pig house (**Fig 1.3**), an open window slurry pit system for the second-generation pig house (**Fig 1.4**), and a non-circulating enclosed slurry pit system for the third-generation pig house (**Fig 1.5**). Odor-causing pig houses including 1st, 2nd and 3rd generation have been faced with realistic operational limitations. Most municipalities are not allowed to build or renovate swine farms due to odor problem. Recently, a circulating enclosed slurry pit pig house[③] (a non-discharge system that recirculates all the generated pig manure into a pig house) has been developed and popularized. This pig house has the advantage of being capable of structurally reducing odor and producing good quality liquid fertilizer. The produced liquid fertilizer can be used as fertilizer in nearby cropland. Large-scale farms with more than 3,000 pigs showed a tendency to introduce a circulating enclosed slurry pit pig house (a fourth-generation pig house) in South Korea.

Fig 1.3. First generation pig house type in Korea (winch curtain and scraper pig house, field survey in 2013)

③ Korea Pork Producers Association recommended ‘a circulating enclosed slurry pit pig house’ as a pig house system capable of reducing odor in the 'Results of product and facility verification of odor reduction in pig farm in 2016' report.

Fig 1.4. Second generation pig house type in Korea (open window slurry pit pig house, field survey in 2013)

Fig 1.5. Third generation pig house type in Korea (non-circulating enclosed slurry pit pig house, field survey in 2013)

Ammonia analysis in the pig house showed the highest value in farm #6, followed by farm #9 and farm #2 (**Fig 1.6**). Sampling was performed by dividing the inner corridor of the pig house into front, middle, and back. Each sample was repeated twice to obtain an average value. Ammonia levels in the pig house of Farm #6 ranged from 20 to 30 ppm, which indicates that the ventilation was poor. In fact, farm #6's ventilation system was the winch curtain type, but it was not fully opened and was found to rely more on forced ventilation by the fan. It is considered that the ammonia gas generated from the inside was not discharged out due to the structural problem of the pig house. This situation could be interpreted in two ways. One is that inadequate ventilation of the fan prevented air in the pig house from exhausting smoothly through the winch curtain. Conversely, the air was exhausted directly through the vent without circulating inside the pig house due to excessive fan ventilation.

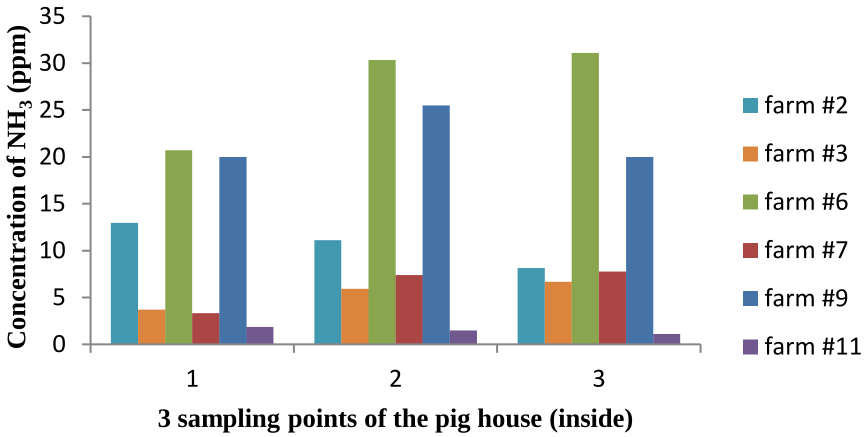

Fig 1.6. Ammonia gas concentration (ppm) of pig house (inside)

For farm #9, the ammonia level was the second highest at 20 to 25 ppm, and structural problems similar to farm #6 were found. Farm #9 was a winch curtain type pig house. Compared to other pig houses, the farm #9 had relatively old facilities. The pig house was located in the mountains and the temperature difference between day and night was severe. Thus, the one side wall was completely closed despite the winch curtain type. This was the farm owner's decision to reduce temperature-caused mortality rather than ventilation. It is necessary to find the appropriate point of ventilation and temperature considering the geographical characteristics of the pig house. The N loss via volatilization may also depend on the floor type of the pig house. Slat floor and sawdust floor showed N loss of 25% and 50%, respectively. At the storage process, about 10% additional N loss was observed (Rotz, 2004). Stone et al. (1975) reported that total N (TN) was not significantly affected, although about

35% of ammonium N was lost under constant temperature and humidity conditions. Other study showed that 47-77% of the initial N was volatilized as ammonia gas and a small amount (<5%) of N was volatilized as NOx gas (Martins and Dewes, 1992). Sommer (2001) reported that about 28% N loss occurred in the composting process of livestock manure. It is reported that the amount of TN was not changed even though N was volatilized by ammonia gas, because organic matter in compost was decomposed for a certain period to supply N (Seo, 1988). The concentrations of volatile ammonia gas in composting process were analyzed at nine livestock manure recycling facilities (S1~S9) located in four cities of Nonsan, Namwon, Yeongcheon and Jinju. Ammonia gas volatilized from the compost pile or stack of compost pile with mechanical agitation was sampled using air sampler, vacuum cabinet, flux chamber and Tedlar bag. The flux chamber was placed on the compost pile and the volatilized air was collected for 20 minutes. Vacuum pump was used to collect the gas that was fed into the Tedlar bag of the connected vacuum chamber at a rate of 2 ml L^{-1} (**Fig 1.7**).

Fig 1.7. Flux chamber-Vacuum cabinet: collecting odor samples in compost using Tedlar bag

Ammonia levels in the composting facilities ranged from 4 to 420 ppm (**Fig 1.8**). This value was lower than the maximum ammonia concentration of 1,000 ppm produced by pig manure composting reported by Kuroda et al. (1996) and was lower than the highest ammonia concentration of 2,500 ppm produced by chicken manure composting reported by Tanaka et al. (1983). S2 showed the highest ammonia concentration, which is the result of the structural causes of the compost facility. S2 was the only compost facility that was closed and operated by mechanical stirring.

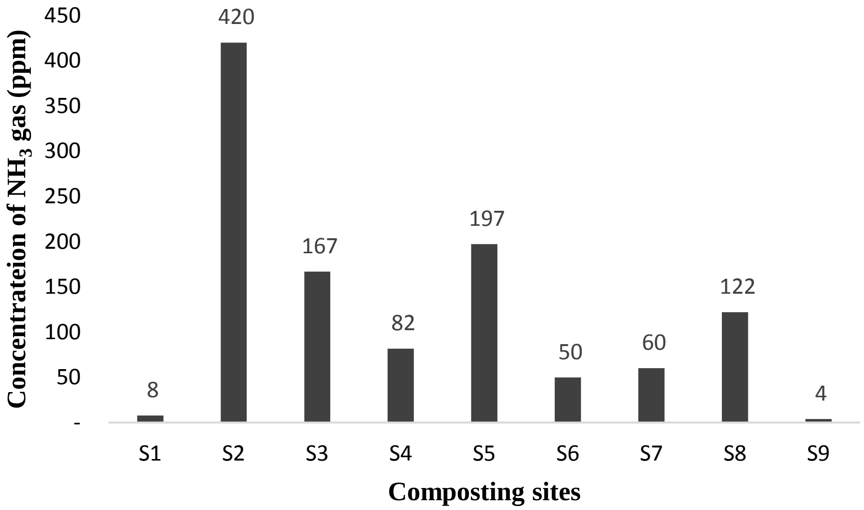

Fig 1.8. Ammonia gas concentration (ppm) of compost process

The volatilization of ammonia gas occurs when ammonium N contained in livestock manure is converted by the following reaction (Meisinger and Jokela, 2000).

Reaction 1: $CO(NH_2)_2 + H^+ + 2H_2O \rightarrow 2NH_4^+ + HCO_3^-$

Reaction 2: $NH_4^+ \leftrightarrow NH_{3\ gas} + H^+$

Urea [$CO(NH_2)_2$] is converted to ammonium N via hydrolysis in the presence of water and urease. Ammonia gas can easily be generated inside and outside of the pig house by the above reactions. Thus, small-scale pig farms tend to abandon their farm operations because they are generally unable to control odor complaints and treat pig manure appropriately. This circumstance makes large-scale pig farms (CAFOs) to survive because they can operate expensive odor reduction facilities and swine slurry treatment systems. However, if the farm is not properly managed, CAFOs can also cause severe ammonia gas production because of the high stocking density of animals. In addition, the high amount of swine slurry production from the CAFOs are not easy to recycle as fertilizer due to physical factor (limited land area) and social factor (distrust of liquid fertilizer performance). Various livestock manure treatment systems have been tried in South Korea to solve these problems.

1.1.2. The livestock manure treatment system in South Korea

Swine manure treatment methods can be roughly divided into solid fertilization, liquid fertilization, and waste-to-energy by methane fermentation (**Fig 1.9**). Solid and liquid fertilization act as a plant nutrient source and soil conditioner by returning to the soil, while the waste-to-energy method has the ability to convert waste from livestock manure into a thermal or electrical energy source. It is necessary to choose the appropriate method according to local conditions and circumstances (To be discussed in detail in Chapter 2).

Fig 1.9. Livestock manure to energy method: underground anaerobic digestion system for methane fermentation (AEBE laboratory)

Recently, various government departments are supporting a budget for obtaining energy sources using biomass to secure renewable energy④. In this regard, a bio-energy production system using only livestock manure is not economically feasible. It also can cause a problem of disposal of the waste generated from methane fermentation. Therefore, simply imitating developed countries can be an economical and environmental burden because South Korea imports most organic resources from overseas (Kang and Han, 2013). The government policy for promoting the use of liquid fertilizers is currently expanding the areas where spray the liquid fertilizers. Though the domestic livestock manure treatment methods in practice vary by region, they generally consist of four systems, including public recycling facilities (**Fig 1.10** and **Fig 1.11**), individual compost (**Fig 1.12**) and liquid fertilization facilities (**Fig 1.13**),

④ The Ministry of Environment and the Ministry of Agriculture and Forestry are interested in renewable energy projects using organic waste resources such as livestock manure. The list of research projects is as follows: Ministry of Environment. 'A study on bioenergy recovery and composting technique for pig slurry'. Korea Environmental Industry & Technology Institute. 2014; Rural Development Administration. 'Recovery of bioenergy from renewable animal and food waste'. National Institute of Agricultural Science. 2009.

public treatment facilities, and individual purification treatment facilities. Livestock manure that is brought to public recycling facilities or individual compost and liquid fertilization facilities is converted to liquid and solid fertilizers (composts) through the recycling process after solid-liquid separation. After that, the liquid fertilizer and compost are returned to the cropland in each region, along with chemical fertilizers. On the other hand, livestock manure that is brought to public treatment facilities or individual purification treatment facilities is discharged into a water system (**Fig 1.14**).

Fig 1.10. Public recycling facilities (liquid fertilization, the photographs were taken in 2012 by the local animal manure field survey in South Korea)

Fig 1.11. Public recycling facilities (solid fertilization, the photographs were taken in 2012 by the local animal manure field survey in South Korea)

Fig 1.12. Individual solid fertilization facilities (the photographs were taken in 2012 by the local animal manure field survey in South Korea)

Fig 1.13. Individual liquid fertilization facilities (the photographs were taken in 2012 by the local animal manure field survey in South Korea)

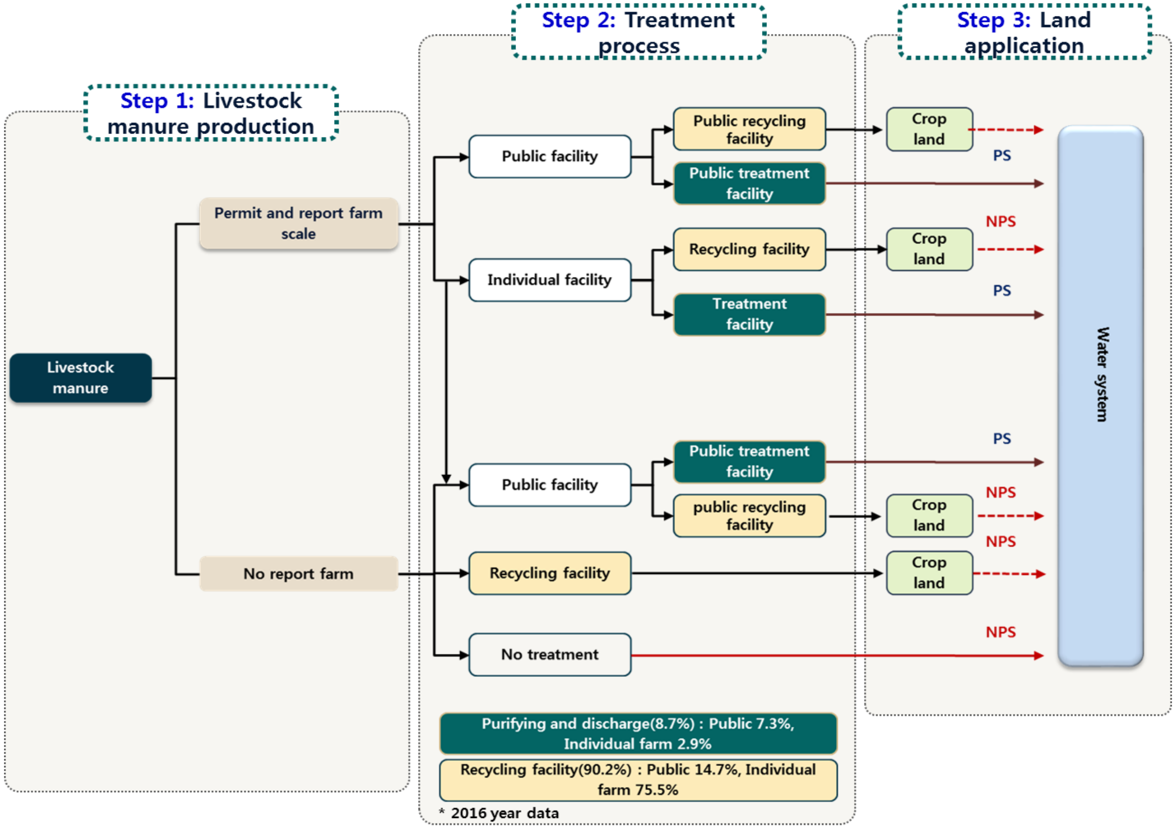

Fig 1.14. The livestock manure treatment systems in South Korea

Liquid fertilizers have been used with chemical fertilizers for cultivation of rice, vegetable crops, fruit trees, and grass in South Korea. However, there are still negative opinions in the field because of the lack of review of an accurate analysis of soil, nutrient requirements of vegetation, fertilizer application level according to component analysis of liquid fertilizers, and spraying facilities and methods (RDA, 2010). The TS (total solids) and TVS (total volatile solids) values of raw swine slurry were different (**Table 1.2**). The TN of the raw swine slurry was not significantly different from 3.8 to 5.4 g kg^{-1}. The pH was in the range of 7.2 ~ 7.9, which is neutral or weakly alkaline. The TS and TVS values of the effluent after biological treatment (aerobic or anaerobic treatment) were significantly reduced. The TP (total phosphorus) and TN values were also reduced. The pH of swine slurry after treatment was not largely changed. However, the pH was changed to slightly acidic (pH 5.2) according to the treatment method (coupled with aerobic and anaerobic process). Solid fertilization is a way to add bulking agents like sawdust and chaff (rice husk) to livestock manure with high water content (RDA, 2010). The livestock manure mixed with bulking agents is fermented for some time to decompose organic matter. The amount of water is adjusted through the process of adequate composting before finally returning it to the soil. Recently, some solid fertilizers did harm the crops and caused an odor due to nutrient component shortage and immature compost.

Table 1.2. Physicochemical characteristics of raw swine slurry and treated swine slurry (effluent)

	Total solids (TS)	Total volatile solids (TVS)	Total phosphorus (TP)	Total nitrogen (TN)	pH	Treatment	Reference
	---------------------------- g kg^{-1}			---------------------------			
Raw slurry	53	36	1.5	4.4	7.9	-	Melse and Verdoes, 2005
	45	32	3.4	5.4	7.4	-	Suresh et al., 2008
	40	28	2.8	4.6	7.2	-	Suresh and Choi, 2011
	52	39	-	3.8	-	-	Boopathy, 1998
	25	19	1.8	4.1	7.7	-	In this study
Effluent	9	3	0.03	0.41	8.2	Nitrification and denitrification	Melse and Verdoes, 2005
	8	-	0.3	1.7	7.4	Anaerobic digestion	Zhu et al., 2009
	16	7	-	1.9	7.1	Anaerobic digestion	Boopathy, 1998
	16	9	0.9	0.7	5.2	Anaerobic/aerobic treatment	In this study

As it is difficult to secure adequate bulking agents in particular, the government's efforts are required to secure an adequate amount of bulking agents from overseas (Kang and Han, 2013). Previous study[5] reported that not a lot of solid and liquid fertilizers can be additionally returned to soil in respect of the nutrient quota system, because an excessive amount of N and P is stored in the soil in Korea (Song et al., 2012). The land-application of livestock manure should be broadly approached as a whole, considering the expansion of self-sufficiency rate of food, conservation of soil environment, environment-friendly utilization of organic waste generated in South Korea. Conversion of the nutrient supply plan for the soil from the regional concept to the national concept is expected to increase the demand for livestock manure recycling considerably.

1.1.3. Effects of livestock manure on soil and water pollution

There are problems to be solved in order to operate the integrated crop-animal farming (ICAF) system. First, the production of livestock manure exceeds the capacity of cropland (Kim et al., 2015). This means that even if livestock manure is converted to a fertilizer source through a treatment facility, there is a shortage of available agricultural land. Second, Korea has a large regional variation in livestock manure production due to regional biases of livestock farms (Kim et al., 2015). Third, there is a difference in perception of livestock manure between livestock farmers and crop farmers. Because of the

[5] Directions for introducing total maximum nutrient loading system of cultivated land. 2015. KREI. (http://webbook.me.go.kr/DLi-File/091/025/002/5591216.pdf)

lack of awareness of the fertilizer value of liquid manure, it is difficult to find crop farmers that can use liquid fertilizers (Song et al., 2012). The amount of livestock manure was only 1% of the total sewage and wastewater production, but the water pollution load accounted for 37.0% (Ministry of Environment, 2012). The proportion of livestock and soil contributing to nonpoint pollutants (BOD and TP basis) was 91% to 95% (Jang, 2013). Due to the aforementioned problems, livestock manure is more likely to act as an environmental pollutant source than a fertilizer source (Brennan et al., 2012; O' Flynn et al., 2013; Laurenson and Houlbrooke, 2014).

Especially, liquid fertilizer derived from pig manure has a high potential to cause environmental pollution due to lack of use area (agricultural land). The concentration of N in the liquid fertilizer varies greatly depending on the treatment process and raw manure composition (**Table 1.2**). Therefore, liquid fertilizer is used on agricultural land by estimating the fertilizer rate based on N (RDA, 2010). In other words, the N concentration analysis is necessary before using liquid fertilizer (Laboski et al., 2006). If the N analysis is neglected, the possibility of accumulation of nutrients in soil (Steinfeld et al., 2006; Liu et al., 2012; Kumaragamage et al., 2016) and possibility of water pollution (Kim et al., 2013; King et al., 2017) becomes high. In general, surplus N is lost through leaching and run-off from cropland (Oenema et al., 2007; Sommer et al., 2013). Oenema et al. (2007) reported that about 4% of the N excreted in barns was lost via leaching and run-off. Tabbara (2003) reported that the compost and liquid fertilizer runoff from agricultural lands depends mainly on rainfall and cropping conditions (i.e., cropping system, fertilizer rate, water management, soil management, etc.). The extent of runoff is determined by precipitation and rainfall intensity (Shepherd et al., 2012; Wallace et al., 2013).

The rainfall in Korea tends to be concentrated between June in early summer and early September. If the amount of precipitation exceeds the potential evapotranspiration, the run-off water occurs. In other periods, irrigation is needed due to lack of water. It is important to manage the compost and liquid fertilizer efflux that take into account these non-periodic, intermittent and short-term rainfall characteristics. Soil erosion occurs due to high rainfall intensity, and the soil particles flow into the water system. The soil particles which include livestock manure nutrient cause runoff along with soil loss on the surface (Sommer et al., 2013). On the other hand, leaching is a process in which nutrients escape through pores in the soil with the water flow (**Fig. 1.15**). Studies on the effects of these factors (weather conditions, crops species, cultivation conditions, soil characteristics etc.) on the dynamics of fertilizer components (mainly N and P) and their quantification are insufficient in South Korea.

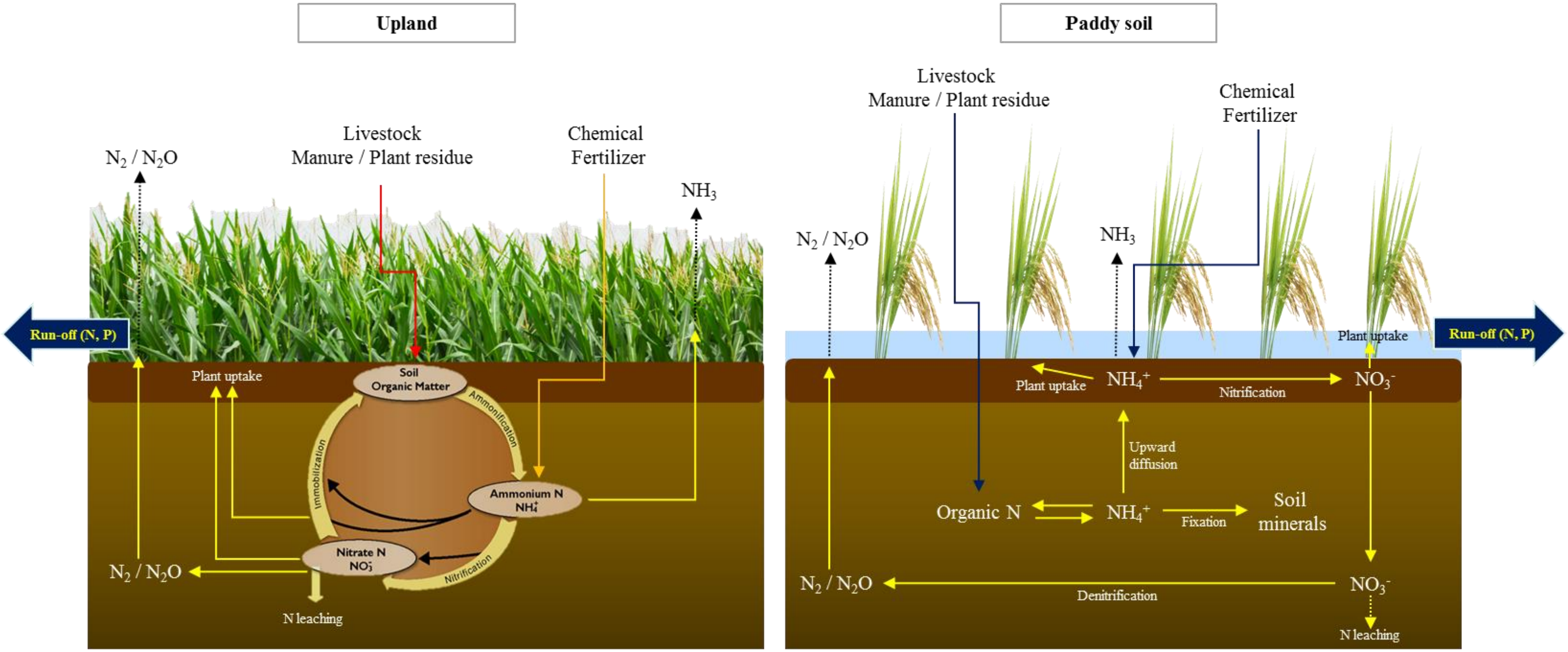

Fig 1.15. Nitrogen cycle in upland and paddy soil [6]

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[6] Adapted from Bijay-Singh, Singh VK. Rice Production Worldwide: Chapter 10. Fertilizer management in rice. Springer. Pp. 217-253; http://fyi.uwex.edu/discoveryfarms/files/2010/10/nitrogen-cycle1-300x256.jpg

Although most of the processed livestock manure is returned to cropland through the recycling process, it still contains many problems such as odor emission, incorrect use, lack of social awareness of liquid fertilizer, improper treatment, soil and water pollution. Therefore, this dissertation analyzed the nutrient flow from livestock manure production to land-application in South Korea. Understanding the balance of nutrients from the generation of livestock manure to the land-application of soil-crop system is considered to be one of the important factors in establishing the ICAF system. In chapter 2, two regions (Yeongcheon and Jinju) operated as individual recycling facilities and two regions operated by public recycling facilities (Namwon and Nonsan) were selected to investigate the dynamics of livestock manure nutrients. The potential nutrient supply and nutrient requirements of crops were analyzed. In chapter 3, the appropriate pig's floor space allowance (FSA) in terms of productivity was examined in conjunction with the livestock manure environmental problems mentioned in chapter 2. Chapter 4 discussed the land-application of livestock manure (treated swine slurry) for the next phase of the livestock manure disposal and treatment process (discussed in chapter 2). A well-managed chemical N fertilization practice combined with anaerobically-aerobically treated swine slurry (TSS) is necessary to improve sustainability and N use efficiency in rice farming. Therefore, the dynamics of N derived from chemical N fertilizer with and without TSS in paddy soil-plant systems were investigated.

1.2. Research objectives

The objectives of this study were:

1. To analyze the nutrient flow based on an analysis of the relationship between the potential nutrient supply and the nutrient requirement for crops when livestock manure is returned to cropland
2. To determine the effect of FSA on pig productivity and performance, and to evaluate the nutrient flow of livestock manure in soil-crop systems based on the proposed FSA
3. To estimate the contribution of applied fertilizer N to the N turnover in the rice paddy soil with different N fertilization practices that are manipulated by the quantity of anaerobically-aerobically treated swine slurry and chemical N fertilizer
4. To compare the rice response to the applied N derived from each of N fertilization practices

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CHAPTER 2. NUTRIENT FLOW OF LIVESTOCK MANURE IN AN INTEGRATED CROP-ANIMAL FARMING SYSTEM

2.1. Abstract

An integrated crop-animal farming (ICAF) system has emerged as a sustainable agricultural system that recognizes livestock manure from livestock farming as a fertilizer resource and returns it to cropland. However, the ICAF system in South Korea has not been universalized, and it is easy to find regions that have difficulties in processing and recycling livestock manure. The objectives of this study were (1) to suggest the customized ICAF system reflecting the regional characteristics and (2) to analyze the livestock manure nutrients flow in terms of three primary elements as N, P, and K. The field investigation and survey were conducted from June to September of 2012. The field investigation and interview involved a total of twelve recycling facilities, including two in Nonsan, three in Namwon, three in Yeongcheon and four in Jinju. The questionnaire consisted of 54 farms in Namwon, 51 farms in Yeongcheon, and 44 farms in Jinju. Nonsan was not surveyed. The mass balance analysis was used to suggest and evaluate the ICAF systems for two sites (Jinju and Yeongcheon). Jinju's public recycling facilities were expected to be more effective as a 'two - track model' as well as a role of compost/liquid fertilizer processes. In the case of Yeongcheon, it would be appropriate to install three to four decentralized public recycling facilities at midsize (around 30 tons) in *myeon* where a cluster of livestock farms was located. Comparing the nutrient flow of the scenarios where the public recycling facilities were

applied to the existing treatment, it was found that N, P_2O_5 and K_2O did not differ greatly before and after applying the model in Jinju. This was the result of the high recycling rate of livestock manure (98%) in Jinju. In Yeongcheon where the ICAF model was applied, N, P_2O_5, and K_2O were generated from livestock manure in a similar amount as well. The N, P_2O_5 and K_2O values of Yeongcheon after applying the model increased by 3.2%, 1.1% and 3.9%, respectively. However, comparing the nutrient requirement of the crop with the amount of nutrient input to the cropland, it can be seen that 113 kg ha^{-1} of N and 146 kg ha^{-1} of P_2O_5 were over-supplied annually. In Jinju, 12 kg ha^{-1} yr^{-1} of P_2O_5 was expected to have an oversupply in comparison with the amount of nutrients required for crops. Since Jinju and Yeongcheon may cause eutrophication problems, P_2O_5 supply should be considered as an essential factor in building ICAF system.

Keywords: Integrated crop-animal farming, nutrient mass balance, compost, liquid fertilizer

2.2. Introduction

The resource recycling system, which uses livestock manure generated from animal farms as a fertilizer resource of cropland, that is to say the integrated crop–livestock farming (ICAF) system, has emerged as a key factor for sustainable agriculture (Peyraud et al., 2014). Various ICAF systems from farm level to regional level are considered a way to solve problems like environmental pollution (Bell et al., 2014), biodiversity loss (Lemaire et al., 2014), and nutritional imbalance (Lemaire et al., 2014) resulting from animal farming practices. Because the ICAF systems in South Korea are in poor condition, there are many regions which have trouble in treating and recycling livestock manure. It is necessary to find appropriate plans and models according to regional characteristics by understanding the status of domestic ICAF system. A thorough examination of the ICAF systems of regions which are relatively poor is also required. Though the domestic livestock manure treatment methods in practice vary with region, they generally consist of four components, including public recycling facilities, individual compost and liquid fertilization facilities, public treatment facilities, and individual purification treatment facilities (RDA, 2010). Livestock manure that is brought to public recycling facilities or individual compost and liquid fertilization facilities is converted to liquid and solid fertilizers (composts) through the recycling process after solid-liquid separation.

After this process, the liquid fertilizer and compost are sprayed on cropland in each region, along with chemical fertilizers. On the other hand, livestock manure that is brought to public treatment facilities or individual purification treatment facilities is discharged into rivers. It is important to trace the flow of the nutrients (N, P, K) derived from composts, liquid fertilizers and chemical fertilizers to make chemical fertilizers more environmentally and economically efficient and recycle the components of fertilizers by returning them to cropland. More specifically, it is necessary to understand the characteristics of livestock manure generation based on the field survey data and the status of treatment facilities. Quantitative interpretation of the inflows, outflows and crop uptake processes of N, P and K originated from treated livestock manure is a necessary process for proper use of livestock manure as a fertilizer in cropland (Powell et al., 2005). Therefore, this study was designed to (1) propose a customized ICAF model that considers regional characteristics and (2) analyze the nutrient flow related to the proposed models based on an analysis of the relationship between the potential nutrient supply and the nutrient requirement for crops when livestock manure is returned to cropland.

2.3. Methods

For this study, two regions (Yeongcheon and Jinju) that implement ICAF system at their own facilities and two regions (Namwon and Nonsan) that entrust the treatment to public recycling facilities were selected to activate the ICAF system through comparative analysis of the current status of these areas. Interviews were conducted targeting agricultural and livestock farms to investigate and analyze the human, social, and economic aspects related to ICAF system by using a questionnaire survey which was intended to understand how the farmers were aware of the system. Interviewers gave a full explanation to interviewees to make them understand the purpose of the survey and interviewees answered individually in order. First, the interviewer obtained an interviewee's consent for a face-to-face survey (**Fig 2.1**). For consistency, orientation was given to participants to explain details about the intent, purpose, and process of the survey. Regions which participated in the interview and survey are listed in **Table 2.1**. The field investigation and survey were conducted from June to September of 2012. The field investigation and interview involved a total of twelve recycling facilities, including two in

Nonsan, three in Namwon, three in Yeongcheon and four in Jinju. The questionnaire consisted of 54 farms in Namwon, 51 farms in Yeongcheon, and 44 farms in Jinju. In the case of Nonsan, two field investigations (interview) without survey were conducted.

Table 2.1. Date of interview and survey investigation in sampling sites

Site	**Farms and recycling facilities**	**Type of research**	**Date**
Nonsan	Facility 1	Interview	2012.07.03.
	Facility 2	Interview	2012.07.03.
	No livestock farms and crop farms	-	-
Namwon	Facility 3	Interview	2012.06.26.
	Facility 4	Interview	2012.06.26.
	Facility 5	Interview	2012.07.11.
	21 livestock farms and 33 crop farms	Survey	2012.08.13.～2012.08.15.
Yeongcheon	Facility 6	Interview	2012.07.10.
	Facility 7	Interview	2012.07.10.
	Facility 8	Interview	2012.07.10.
	30 livestock farms and 21 crop farms)	Survey	2012.10.26.～2012.10.27.
Jinju	Facility 9	Interview	2012.07.17.
	Facility 10	Interview	2012.07.17.
	Facility 11	Interview	2012.07.17.
	Facility 12	Interview	2012.07.17.
	19 livestock farms and 25 crop farms	Survey	2012.09.20.～2012.09.22

Fig 2.1. Data collection through on-site interviews and surveys (Namwon, Nonsan, Yeongcheon, and Jinju)

2.3.1. Amount of livestock manure

Livestock manure produced in the regions is separated and treated at recycling facilities to be converted to liquid fertilizer (LF) and solid fertilizer (SF) to be sprayed on crops later. Forage crops are used to feed animals, which means that nutrients absorbed into forage crops return to animals. An expression using estimated variables which can affect fertilizer component balance based on these livestock manure recycling facilities is as follows: The amount of manure produced from swine farms can be calculated using the number of swine on each farm and the average annual manure amount. The amount of livestock manure was calculated using the value recalculated in 2008 with the application of the livestock manure production per unit (Notification No. 1999-109 of the Ministry of Environment, 07.08.1999). This can be represented by equation (2.1). The total amount of manure produced (T) in a region i was calculated by multiplying the number of livestock (f_{ai}) by production unit (mp).

$$\begin{pmatrix} T_1 \\ T_2 \\ \vdots \\ T_n \end{pmatrix} = \begin{pmatrix} f_{a_1} f_{b_1} f_{c_1} f_{d_1} \\ f_{a_2} f_{b_2} f_{c_2} f_{d_2} \\ \vdots \; \vdots \; \vdots \\ f_{a_n} f_{b_n} f_{c_n} f_{d_n} \end{pmatrix} \begin{pmatrix} mp_a \\ mp_b + sd_b \\ mp_c + sd_c \\ mp_d \end{pmatrix} \tag{2.1}$$

f_{a1} : number of pig

f_{b1} : number of cow

f_{c1} : number of dairy cow

f_{d1} : number of poultry

mp_a : the amounts of pig manure production (ton/yr/head)

mp_b : the amounts of cow manure production (ton/yr/head)

mp_c : the amounts of dairy cow manure production(ton/yr/head)

sd_b : the amounts of cow manure + saw dust (ton/yr/head)

sd_c : the amounts of dairy cow manure + saw dust (ton/yr/head)

mp_d : the amounts of poultry manure production (ton/yr/head)

From the above matrix, if you add all T_i ($T_{manure} = \sum_i^n T_i$), you can obtain the total amount of livestock manure which is brought to recycling facilities or treated on livestock farm.

2.3.2. Recycling status of livestock manure

The status of livestock manure treatment by region (**Table 2.2**) was as follows: In Nonsan, individual solid fertilization facilities, individual liquid fertilization facilities, individual purification treatment facilities, public treatment facilities, and public recycling facilities for treatment entrustment handled livestock manure at rates of 46%, 5%, 4%, 10%, and 35%, respectively. Most livestock manure (81%) in Nonsan was recycled by public recycling facilities and individual solid fertilization facilities. In Namwon, individual solid fertilization facilities (43%), public recycling facilities for treatment entrustment (41%), individual liquid fertilization facilities (14%), and individual purification treatment facilities (2%) handled livestock manure. As in Nonsan, most livestock manure in Namwon (84%) was treated by individual solid fertilization facilities and public recycling facilities for treatment entrustment. Since there was no public treatment plant, livestock manure in this area has been discharged to rivers through individual purification facilities. In Yeongcheon, which lacked a public recycling facility, most livestock manure was recycled as solid and liquid fertilizer at individual recycling facilities (18% and 66% respectively; 84% in total), and the rest was discharged into rivers after the purification process at individual facilities (7%) or public treatment facilities (9%). The amount of swine manure was highest among those of livestock in Yeongcheon, and most of it was treated at individual liquid fertilization facilities. In Jinju, which, like Yeongcheon, lacked a public recycling facility, most of the livestock manure was treated as compost or liquid fertilizer at individual farming facilities, and especially the proportion of liquid fertilizer was high. It can be understood from the characteristics of the livestock scale. Approximately 113,751 tons of manure per year were produced in about 60,000 pigs which is much higher than those from other animals (**Table 2.5**). Livestock manure treatment facilities used in this region included individual solid fertilization facilities (15%), individual liquid fertilization facilities (83%) and individual purification treatment facilities (2%), and there was no public treatment facility. The number of livestock, animal species, amount of livestock manure produced, the status of livestock manure treatment and crop species as well as urbanization rate[⑦] were included among regional characteristics to be considered when proposing ICAF models. In this study, the Namwon and Nonsan were selected based on activated ICAF system among four target areas. The ICAF model was proposed considering the regional characteristics of

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[⑦] http://www.index.go.kr/egams/stts/jsp/potal/stts/PO_STTS_IdxMain.jsp?idx_cd=1200&bbs=INDX_001&clas_div=A; the 'urbanization rate' is derived from the ratio of 'urban population in the usage area' among the 'total population' in the region. In addition, population, population density, Gross Regional Domestic Productions (GRDP), GRDP of agriculture, forestry and fishery (GRDP-AFF), Internet supply level, and water and sewage supply level are key indicators of urbanization. In this study, the Internet supply level and water and wastewater supply level were excluded from the review because they are leveled in most regions of South Korea.

Yeongcheon and Jinju areas where the ICAF system was relatively inferior. The expected nutrient flow was analyzed by applying the model to Yeongcheon and Jinju.

Table 2.2. Treatment status of livestock manure at four regions in South Korea

Region	Treatment status of livestock manure				
	ISFF [b]	ILFF	IPTF	PTF	PRF
	---------------------------- tons yr^{-1} --------------------------------				
Nonsan	331,958 [a] (46%)	36,082 (5%)	28,866 (4%)	72,165 (10%)	252,577 (35%)
Namwon	308,851 (43%)	100,556 (14%)	14,365 (2%)	0	294,485 (41%)
Yeongcheon	126,210 (18%)	462,770 (66%)	49,082 (7%)	63,105 (9%)	0
Jinju	39,043 (15%)	216,036 (83%)	5,206 (2%)	0	0

[a] The values indicate the amount of livestock manure (tons yr^{-1})
[b] ISFF: individual solid fertilization facilities
ILFF: individual liquid fertilization facilities
IPTF: individual purification treatment facilities
PTF: public treatment facilities
PRF: public recycling facilities

2.3.3. Flow analysis of nitrogen, phosphorus, and potassium derived from livestock manure

Korean-cattle and poultry manure which are brought from or occur on livestock farm are generally treated as low water content. In general, water content of cattle manure is reduced by mixing in bedding, and poultry manure is originally low in water content (70–80%), so it is usually used to make solid fertilizer after being treated with solids (MWPS-18, 2004). On the other hand, swine manure is separated into liquid and solid fertilization after the solid-liquid separation process because its water content is as high as 96% (MWPS-18, 2004; Suresh, 2009). T_{LF} (Total liquid fertilizer) is the total amount of liquid fertilizer and can be calculated by multiplying swine slurry by the portion of liquid (p) after solid-liquid separation. In this study, the value of p was 0.09.

$$T_{LF} = p \sum_i^n a_i \qquad (2.2)$$

In general, solids of swine manure, cattle and poultry manure with lower water content are used together to produce solid fertilizers. Sawdust and chaff (rice husk) are generally added for moisture adjustment in the first process, pre-treatment. However, according to the field investigation, they were not added to swine manure because the water content of swine manure will be proper if it is well-separated.

$$T_{SF} = (1-p) \sum_i^n a_i + \sum_i^n b_i + \sum_i^n c_i + \sum_i^n d_i + SD \qquad (2.3)$$

Here, SD is the amount of sawdust supplied annually. Based on equation (2.1), $a_i = f_{a_i} m p_a$, which means the annual amount of livestock manure generated from livestock farm i.

T_{LF} is the annual amount of liquid fertilizer of the region, and T_{SF} is the annual amount of solid fertilizer of the region. Generally, if the amount of element X is known depending on the type of manure, the total amount of element X generated can be calculated as follows.

$$\begin{pmatrix} T_{1,X} \\ T_{2,X} \\ \vdots \\ T_{n,X} \end{pmatrix} = \begin{pmatrix} f_{a_1} f_{b_1} f_{c_1} f_{d_1} \\ f_{a_2} f_{b_2} f_{c_2} f_{d_2} \\ \vdots \; \vdots \; \vdots \\ f_{a_n} f_{b_n} f_{c_n} f_{d_n} \end{pmatrix} \begin{pmatrix} mp_a (X_{a,l} + X_{a,s}) \\ mp_b X_b + sd_b X_{sd} \\ mp_c X_c + sd_c X_{sd} \\ mp_d X_d \end{pmatrix} \quad (2.4)$$

X_{sd}: the amount of nutrient contained in sawdust

$X_{a,b,c,d}$: the amount of nutrient contained in each livestock manure

Table 2.3. The amount of nutrient (N, P_2O_5, K_2O) in livestock manure[⑧]

Species	Nutrient	Feces (%)	Urine (%)	Average (%)
Korean-cattle[1]	N	0.50	0.68	0.59
	P_2O_5	0.60	0.07	0.34
	K_2O	0.18	0.60	0.39
Dairy cow	N	0.33	1.02	0.68
	P_2O_5	0.49	0.27	0.38
	K_2O	0.49	0.27	0.38
Pig	N	0.96	0.80	0.88
	P_2O_5	0.83	0.09	046
	K_2O	0.42	0.53	0.48
Layer chicken	N	1.39		1.39
	P_2O_5	0.62		0.62
	K_2O	0.68		0.68
Broiler chicken	N	1.19		1.19
	P_2O_5	0.29		0.29
	K_2O	0.50		0.50
Duck	N	1.29		1.29
	P_2O_5	0.46		0.46
	K_2O	0.59		0.59

[1] Korean-cattle: Hanwoo + beef cattle

* This data is adapted from 'The study to re-establish the amount and major compositions of manure from livestock', RDA. 2008.

⑧ The fertilizer nutrients (N, P_2O_5 and K_2O) in livestock manure was based on the data provided by RDA. In this paper, the mean values of feces and urine were used in the equations. The fertilizer nutrient values in beef cattle, cows and pig manure are divided into feces and urine. In the case of poultry, feces and urine are integrated and present as a single value. Therefore, the average value was used for the overall consistency of the study.

The amounts of the main elements in livestock manure (**Table 2.3**) from each livestock farm can be represented as follows: $N_{a,l}$ is N content in liquid fertilizers, and $N_{a,s}$ is N content in solid fertilizers from swine manure. Likewise, P_a is phosphorus content and K_a is potassium content.

$$\begin{pmatrix} T_{1,N} \\ T_{2,N} \\ \vdots \\ T_{n,N} \end{pmatrix} = \begin{pmatrix} f_{a_1} f_{b_1} f_{c_1} f_{d_1} \\ f_{a_2} f_{b_2} f_{c_2} f_{d_2} \\ \vdots \ \vdots \ \vdots \\ f_{a_n} f_{b_n} f_{c_n} f_{d_n} \end{pmatrix} \begin{pmatrix} mp_a(N_{a,l}+N_{a,s}) \\ mp_b N_b \\ mp_c N_c \\ mp_d N_d \end{pmatrix} ;\ \mathrm{N} \qquad (2.5)$$

$$\begin{pmatrix} T_{1,P} \\ T_{2,P} \\ \vdots \\ T_{n,P} \end{pmatrix} = \begin{pmatrix} f_{a_1} f_{b_1} f_{c_1} f_{d_1} \\ f_{a_2} f_{b_2} f_{c_2} f_{d_2} \\ \vdots \ \vdots \ \vdots \\ f_{a_n} f_{b_n} f_{c_n} f_{d_n} \end{pmatrix} \begin{pmatrix} mp_a(P_{a,l}+P_{a,s}) \\ mp_b P_b \\ mp_c P_c \\ mp_d P_d \end{pmatrix} ;\ \mathrm{P} \qquad (2.6)$$

$$\begin{pmatrix} T_{1,K} \\ T_{2,K} \\ \vdots \\ T_{n,K} \end{pmatrix} = \begin{pmatrix} f_{a_1} f_{b_1} f_{c_1} f_{d_1} \\ f_{a_2} f_{b_2} f_{c_2} f_{d_2} \\ \vdots \ \vdots \ \vdots \\ f_{a_n} f_{b_n} f_{c_n} f_{d_n} \end{pmatrix} \begin{pmatrix} mp_a(K_{a,l}+K_{a,s}) \\ mp_b K_b \\ mp_c K_c \\ mp_d K_d \end{pmatrix} ;\ \mathrm{K} \qquad (2.7)$$

Therefore, the amount of element X in liquid fertilizers from swine manure is as follows:

$$T_{LX} = r_{x,l} p X_{a,l} mp_a \sum_i^n f_{a_i} = r_{x,l} p X_{a,l} \sum_i^n a_i \qquad (2.8)$$

And the amount of element X in solid fertilizers is as follows:

$$T_{SX} = r_{a,s}[(1-p)X_{a,s}mp_a \sum_i^n f_{a_i} + (X_b mp_b) \sum_i^n f_{b_i} + (X_c mp_c) \sum_i^n f_{c_i} + (X_d mp_d) \sum_i^n f_{d_i}] \quad (2.9)$$

Here, $r_{a,l}$ is a correction factor in the process of treating liquids from swine manure, and $r_{a,s}$ is a correction factor in the process of treating solids from swine manure. It is now assumed that the amount of liquid or solid loss is always the same regardless of the type of manure. Therefore, all correction factors are represented by r from here. In this study, N loss in the process of aerobic treatment of liquid fertilizers was about 32%. N loss varied with swine house environments. Two swine houses with bedding system lost 25% and 50% of their N, respectively (Rotz, 2004). An additional 10% of the N was lost in the storing process, which means that 30% of the N was lost during the process at the swine house on average. Data from the field investigation showed similar figures, and applying them in calculating N loss resulted in about 34% loss (data not shown). Therefore, other values were calculated, assuming that 32% of N is volatilized in the process of liquid fertilization on average. For composting process, N loss was set as about 29%. Sommer's experiment (2001) reported that about 28% of the N was lost in the process of solid fertilization of livestock manure. It assumes that if the processed solid and liquid fertilizers are sprayed directly onto the soil surface when applying them to cropland, 33% and 20% of the N will be lost from liquid and solid fertilizers, respectively (Rotz, 2004; University of Minnesota Extension Fact Sheet, 2006). In the process of livestock manure recycling, the utilization rates of P and K were both 90-100%

(Midwest Plan Service, 1993). In this study, 90% was used as the correction factor of P and K by applying the minimum utilization rate. The annual nutrient requirements for the region can be calculated using the cultivation area by crop and N, P, and K required per area by crop. If the annual requirement of nutrient X is T_{RX} (ton yr^{-1}), the cultivation area of crop y is a_y (ha), and the requirement of nutrient X per area of crop y is $m_{X,y}$ (kg 10a^{-1}),

$$T_{RX} = \sum_y^n (a_y m_{x,y} \div 10 \times 1000) \tag{2.10}$$

Using the total annual requirements of nutrients X (T_{RX}) and the total amount of nutrients supplied through composts and liquid fertilizers (T_{TX}), it is possible to determine whether additional fertilizer is applied or whether environmental burden is caused by excessive input of nutrients contained in composts and liquid fertilizers. If the additional requirements of nutrient X in chemical fertilizers is A_X,

$$A_X = \begin{cases} T_{RX} - T_{TX} & (T_{RX} \geq T_{TX}) \\ & 0 \end{cases} \tag{2.11}$$

If the environmental impact is B_X when nutrient X is excessive, this can be represented by the following equation (for the environmental impact, only N and P taken into account, not K):

$$B_X = \begin{cases} T_{TX} - T_{RX} & (T_{TX} \geq T_{RX}) \\ & 0 \end{cases} \tag{2.12}$$

2.4. Results and Discussion

2.4.1. Proposal of ICAF models

After reviewing the characteristics of livestock and agricultural farms of Jinju in the survey and interview, it was found that there were a few small livestock farms, while there were enough cropland which are targets for spraying with solid and liquid fertilizers. There was experience and awareness of the resource utilization at the livestock farming level. The liquid fertilizer distribution center was used to collect and distribute livestock manure, and the public recycling facility was temporarily suspended due to complaints during site selection and construction. And in Jinju, the population and population density were higher compared to the other regions. The urbanization rate, which was as high as 92%, compared to about 60% of other cities, was decided after comprehensive reviews of the population, population density, economic conditions, and social indicators (**Table 2.4**). Furthermore, GRDP-AFF accounts for 7.4% of GRDP. Given the economic contribution, public opinion on the need for livestock and public recycling facilities was also less favorable than other regions. Thus, the relatively high urbanization level of Jinju made it difficult to establish an ICAF system as a general model. In addition, it seems to be a major factor that makes it difficult to manage aggressively such issues as the establishment of a public recycling facility and the support of livestock farmers. Therefore, in Jinju, it would be more effective to promote a public recycling facility with the waste-to-energy model, not with the solid and liquid fertilization model. Public waste-to-energy recycling plant means a facility that can produce energy like biogas and solid fuel using 70 tons or more of livestock manure per day (70%), etc., and recycle it as solid and liquid fertilizers and others[9]. This facility can be a solution for solving civil complaints about handling livestock manure in Jinju where the urbanization level is high. By treating livestock manure as well as food waste together, it is necessary not only for the local community, but also for all the citizens to establish themselves as the relevant subject. Previous research also showed that the mixing method of livestock manure and food waste could reduce the civil complaints and technically improve energy production efficiency (Lee et al., 2014).

[9] http://www.mafra.go.kr/cms/util/contentsFileDown.jsp?board_id=19&FILE_NAME=2011.

Table 2.4. Urbanization rates of four regions (Yeongcheon, Jinju, Nonsan and Namwon)

Indicator	Yeongcheon	Jinju	Nonsan	Namwon
Population (people)	107,701	333,256	131,565	89,898
Population density (people/km^2)	117.0	467.5	236.8	119.4
Urbanization rate (%)	62.7	92.2	58.0	63.2
GRDP-AFF/GRDP [1] (%)	10.7	7.4	14.0	17.9

[1] GRDP: Gross Regional Domestic Productions; GRDP-AFF: GRDP of agriculture, forestry and fishery

☞ This data is adapted from the research report 'Development of Integrated Animal-Crop Farming Models Reflecting Their Regionality', 2012. MIFAFF

Yeongcheon had a relatively large number of livestock farms, while a number of agricultural farms were relatively small. In other words, it would be difficult to secure farms to be sprayed with liquid fertilizers if ICAF system is activated. In this region, there was a lack of resource recycling experience and awareness at the livestock farm level. Rather, there was more interest and experience in the treatment of purification and discharge of livestock manure. Given this situation, Yeongcheon's direction of purification and waste-to-energy reflects on-site problems to some degree and was regarded as a reasonable solution. Despite these conditions which make resource recycling inappropriate in this region, one notable characteristic was the fact that YC's livestock farms were clustered in a few *myeon*. In other words, the possibility of installing three to four medium-sized (about 30 tons) decentralized public recycling facilities in *myeon* where livestock farms are concentrated can be considered. This is expected not only to make using livestock farms more efficient and reduce transportation costs but also to eliminate the cause of civil complaints by placing public recycling facilities among livestock farms. Given the large area of the Yeongcheon, this model is a way to alleviate concerns over excessive manure transport costs. It is more likely that the transportation costs incurred due to frequent manure bring-in and carry-out when collecting, storing, and distributing according to the user's dispersed location are higher than the cost saving level due to the enlargement of the storage capacity.

2.4.2. Nitrogen, phosphorus and potassium flow analysis from livestock manure

Based on equation (2.1), the annual amount of livestock manure by region which is brought to public recycling facilities or treated at each farm is shown in **Table 2.5**. The amount of Nonsan's livestock manure was highest, which resulted from the large number of swine. There was little difference in the production amounts between Nonsan and Namwon, but the amounts of cattle and poultry manure were relatively high in Namwon. The least amounts of livestock manure was shown in Jinju. Yeongcheon had fewer chickens and ducks but the number of pigs and Korean-cattle were larger than other regions, resulting in a large amount of livestock manure. According to the current status of agricultural land use[10] in four regions of this study, rice cultivation was in the range of 38% to 74%. In Nonsan, rice farming occupied the most agricultural area with 74% followed by field farming such as strawberry and sweet potato. In Namwon, rice farming and fruit farming mainly consisted of agricultural land (**Fig 2.2**). Yeongcheon's agricultural land was typically used for rice farming and fruit farming, and garlic is produced more than other regions in this study. In Jinju, agricultural land cultivated with rice and barley was 59%, and the rest was used for field farming and fruit farming (**Fig 2.3**). One dairy cow was defined as one unit of livestock unit (LU). The LU of other livestock was estimated using conversion factors described in **Table 2.6**. The land-application of livestock manure in Jinju seemed to be relatively suitable,

[10] The status of agricultural land use was adapted from the statistical yearbook of 2011 in each region (Nonsan, Namwon, Yeongcheon and Jinju)

as the area of cropland per LU (ha / LU) was the highest (0.31 ha / LU). On the other hand, Yeongcheon showed the lowest value at 0.12 ha / LU. For improving the ICAF system, it was necessary to reduce the stocking density of livestock or to secure enough cropland area.

Table 2.5. Livestock manure production by sampling sites

Species	Namwon		Nonsan		Yeongcheon		Jinju	
	number of head	amounts (tons yr^{-1})	number of head	amounts (tons yr^{-1})	number of head	amounts (tons yr^{-1})	number of head	amounts (tons yr^{-1})
Korean-cattle	37,309	186,564	22,029	110,156	43,350	216,772	11,372	56,866
Dairy Cow	2,711	37,305	4,283	58,936	2,839	39,066	2,251	30,975
Pig	110,304	205,331	188,357	350,627	199,269	370,939	61,107	113,751
Poultry	6,599,495	289,058	4,610,270	201,930	1,698,411	74,390	1,340,014	58,693
total	6,749,819	718,257	4,824,939	721,649	1,943,869	701,167	1,414,744	260,284

Table 2.6. Relationship between number of livestock (LU basis) and cropland area

Species	Namwon		Nonsan		Yeongcheon		Jinju	
	number of head	LU [1]	number of head	LU	number of head	LU	number of head	LU
Korean-cattle	37,309	27,982	22,029	16,522	43,350	32,513	11,372	8,529
Dairy Cow	2,711	2,711	4,283	4,283	2,839	2,839	2,251	2,251
Pig	110,304	18,752	188,357	32,020	199,269	33,876	61,107	10,388
Poultry	6,599,495	65,995	4,610,270	46,102	1,698,411	16,984	1,340,014	13,400
total	6,749,819	115,439	4,824,939	98,927	1,943,869	86,211	1,414,744	34,568
ha/LU [2]	0.20		0.17		0.12		0.31	

[1] Livestock Unit (LU): Cows = 1LU, Korean-cattle = 0.75LU, Pigs (finishing pigs) = 0.17LU, Poultry = 0.01LU (adapted from http://adlib.everysite.co.uk/adlib/defra/content.aspx?id=000IL3890W.198AWLDOHJ69F3)

[2] Cropland (ha): Namwon (23,569ha); Nonsan (16,404ha); Yeongcheon (10,393ha); Jinju (10,679ha)

In Namwon, public recycling facilities treated 41% and individual recycling facilities treated 57% of all livestock manure. Based on equations (2.8) and (2.9), the annual amounts of N, P_2O_5[11], and K_2O in solid and liquid fertilizers are shown in **Table 2.7**. These are the amounts which were returned to Namwon's cropland in a year after going through recycling facilities. The amounts of N, P_2O_5, and K_2O in solid fertilizers were 379.9 kg ha^{-1} yr^{-1}, 361.4 kg ha^{-1} yr^{-1} and 270.4 kg ha^{-1} yr^{-1}, respectively. The amounts of N, P_2O_5, and K_2O in liquid fertilizers were lower than in solid fertilizers. In Namwon, where relatively more P_2O_5 was generated from livestock manure than N, it would be better for the nutrient cycle to expand cultivation of crops that require a lot of P, such as sweet potato, tomato, and cucumber[12]. As of 2011, 42% of the cultivated areas of Namwon were used for rice cultivation and 45% were used for fruit such as pear, grape and persimmon (**Fig 2.2**). The nutrient requirements used here were based on data from Fertilizer Prescription Standards by Crop[13]. The amounts of N, P_2O_5, and K_2O in solid and liquid fertilizers made of livestock manure in Nonsan were quantified, considering 35% at public recycling facilities, 51% at individual solid and liquid fertilization facilities, and the rest at purification and release systems. In Nonsan, solid fertilizers had more N and P_2O_5 than liquid fertilizers, while there was relatively little difference in K_2O between them. In general, when deciding the amount of

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⑪ P and K are traditionally used as oxides in fertilizer applications. That is, P is used as P_2O_5 (Phosphate) and K is used as K_2O (Potash). To convert P to P_2O_5, multiply by 2.29. To convert K to K_2O, multiply by 1.20 (Rural Development Administration Manual for Livestock Manure Composting / liquid fertilizer, 2010).

⑫ Refer to 'Fertilizer Prescription Standards by Crop' provided by the National Academy of Agricultural Science, RDA, 2010.

⑬ Fertilizer Prescription Standards by Crop. National Academy of Agricultural Science, RDA, 2010.

fertilizer to be applied, considering N and P as standards, the nutrient flow in solid fertilizers has to be taken into account more than in liquid fertilizers. As indicated in the total production amount of nutrients, the amounts of N and K_2O from livestock manure are relatively higher than P_2O_5. Thus, it is necessary to consider expanding cultivation of crops that require a lot of N and K, such as tomato, cucumber, pumpkin, pepper, scallion, and persimmon. As of 2011, 74% of the cultivated areas of Nonsan were used as rice crops. The main crops were strawberries, persimmons, pears, watermelons, sweet potatoes, and barley (**Fig 2.2**).

Table 2.7. Three primary nutrients (N, P_2O_5, K_2O) production in sampling sites

Site	Type of fertilizer	N	P_2O_5	K_2O
		---------- kg ha^{-1} yr^{-1} ----------		
Namwon	Compost	349.8 (92.1)[1]	361.4 (95.7)	270.4 (73.5)
	Liquid fertilizer	30.1 (7.9)	16.4 (4.3)	97.7 (26.5)
	Total	379.9 (100)	377.8 (100)	368.1 (100)
Nonsan	Compost	376.4 (67.3)	414.0 (91.1)	331.2 (58.0)
	Liquid fertilizer	183.2 (35.5)	40.2 (8.9)	239.7 (42.0)
	Total	559.6 (100)	454.2 (100)	570.9 (100)
Yeongcheon (before model applied)	Compost	459.3 (60.6)	692.7 (91.4)	368.6 (48.5)
	Liquid fertilizer	298.7 (39.4)	65.6 (8.6)	391.0 (51.5)
	Total	758.0 (100)	758.3 (100)	759.6 (100)
Jinju (before model applied)	Compost	213.5 (67.2)	276.7 (92.4)	202.2 (59.8)
	Liquid fertilizer	104.1 (32.8)	22.8 (7.6)	136.1 (40.2)
	Total	317.6 (100)	299.5 (100)	338.3 (100)

Yeongcheon[2] (after model applied)	Compost	462.3 (59.1)	696.7 (90.8)	370.6 (46.9)
	Liquid fertilizer	320.1 (40.9)	70.2 (9.2)	418.9 (53.1)
	Total	782.4 (100)	766.9 (100)	789.5 (100)
Jinju[2] (after model applied)	Compost	213.6 (67.0)	276.8 (92.3)	202.3 (59.5)
	Liquid fertilizer	105.1 (33.0)	23.0 (7.7)	137.5 (40.5)
	Total	318.7 (100)	299.8 (100)	339.8 (100)

[1] the value in the parenthesis indicates percentage of the total N, P_2O_5, K_2O, respectively.

[2] nutrients mass flow after models are applied in each sites respectively.

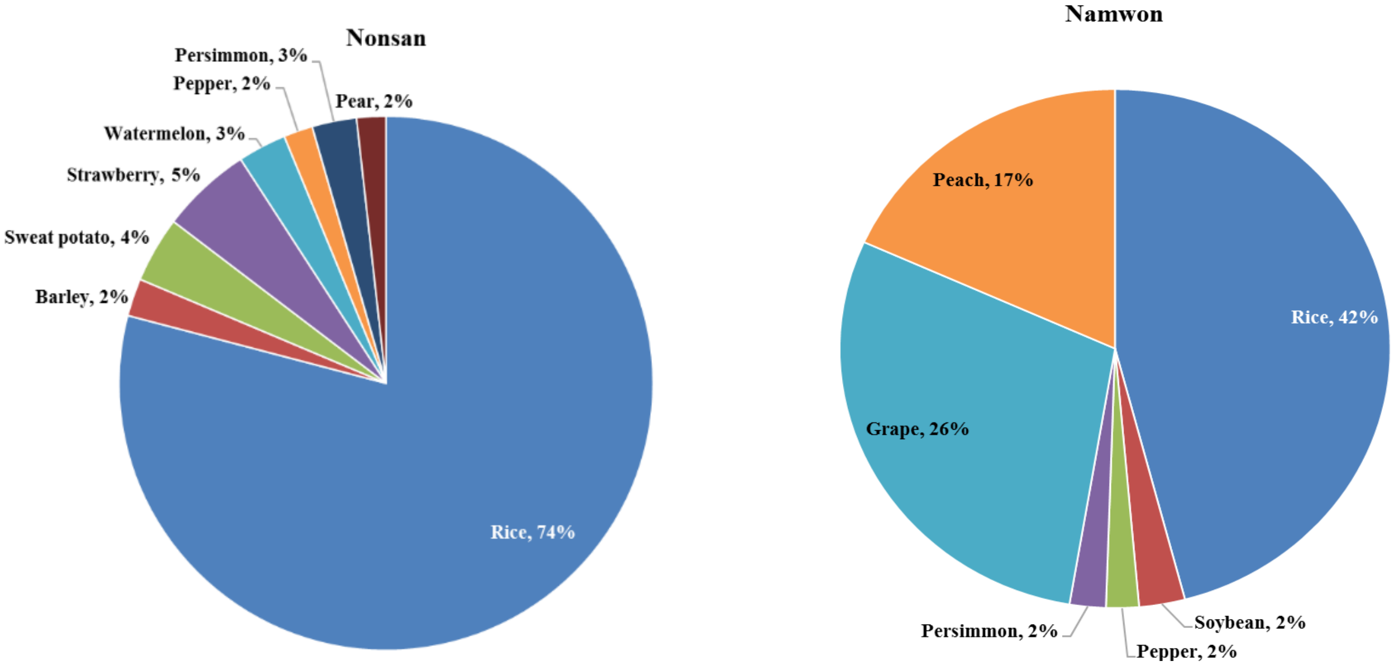

Fig 2.2. Crop cultivation status in Nonsan and Namwon (adapted from statistical yearbook of 2011). These figures exclude crops with less than 2% cultivation area.

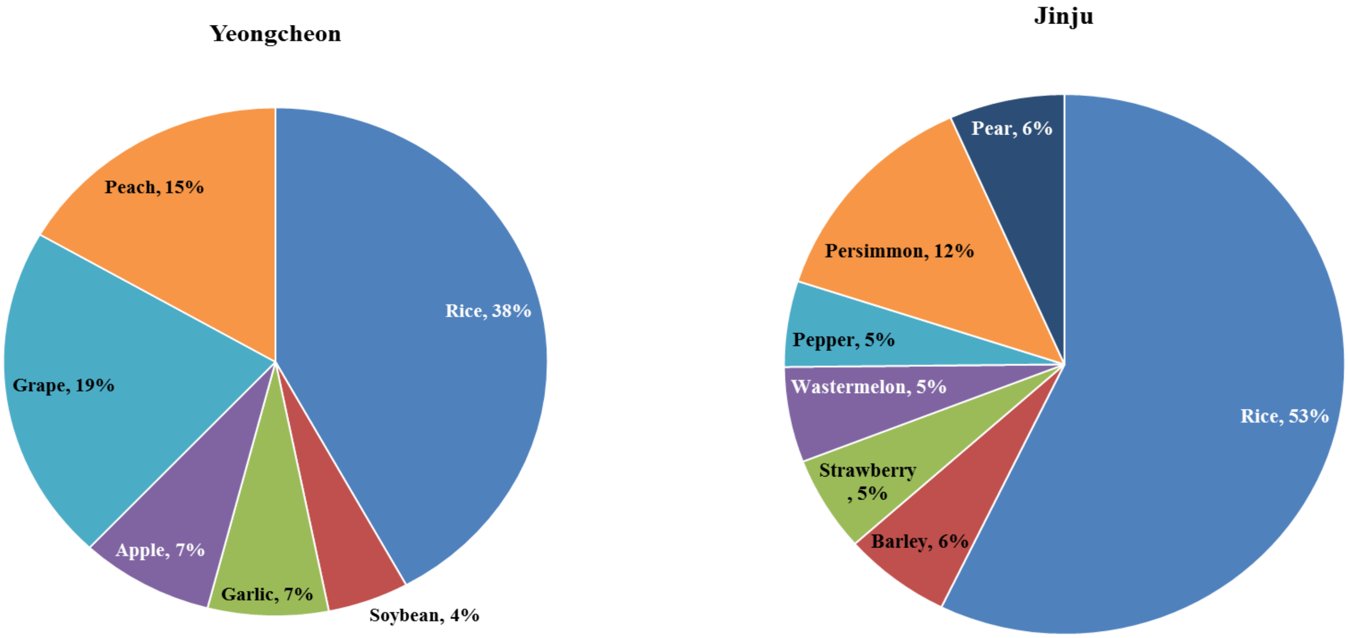

Fig 2.3. Crop cultivation status in Yeongcheon and Jinju (adapted from statistical yearbook of 2011). These figures exclude crops with less than 2% cultivation area.

In Yeongcheon, livestock manure was being treated only at individual public recycling facilities without a public facility, which accounts for 84% overall. Considering this, the total amount of N, P_2O_5, and K_2O added to the cropland of Yeongcheon derived from the processed livestock manure (compost and liquid fertilizer) were 758 kg ha^{-1} yr^{-1}, 758 kg ha^{-1} yr^{-1} and 760 kg ha^{-1} yr^{-1}, respectively. A similar amount of K_2O was generated between solid and liquid fertilizers, and most P_2O_5 was generated in solid fertilizers. Likewise, liquid fertilizers contained a small amount of P_2O_5 in other regions. The phosphorus ratio of feces to urine in swine manure was about 9:1 because liquid fertilizer consists mostly urine (RDA, 2008). Lastly, in Jinju, it was found that there was no public recycling facility, and only individual solid and liquid fertilization facilities were working on recycling. However, 98% of livestock manure was recycled and the remaining 2% was purified and discharged to rivers, and relatively more N and K_2O were generated from livestock manure than P_2O_5. In order to propose the ICAF system of Yeongcheon and Jinju, the proportion of the recycling facilities to the total processing was about 38% (average value of Namwon and Nonsan). Yeongcheon and Jinju's existing livestock manure treatment facilities were maintained. After reviewing the nutrient flow in the scenario that applied the rate of the existing treatment facilities to public recycling facilities, it was found that N, P_2O_5 and K_2O did not differ greatly before and after applying the model in Jinju. This is the result of the high recycling rate of livestock manure (98%) in Jinju. In Yeongcheon where the ICAF model was applied, N, P_2O_5, and K_2O were generated from livestock manure generally in a similar amount as well. The N, P_2O_5 and K_2O values of

Yeongcheon after applying the model increased by 3.2%, 1.1% and 3.9%, respectively **(Table 2.7)**. However, comparing the nutrient requirement of the crop with the amount of nutrient input to the cropland, it can be seen that 113 kg ha^{-1} yr^{-1} of N and 146 kg ha^{-1} yr^{-1} of P_2O_5 were over-supplied annually **(Table 2.8)**. Rice, grape, peach, apple, garlic and soybean were major crops of Yeongcheon (**Fig 2.3**). It is necessary to consider focusing on cultivation of crops which require relatively more N and P, such as tomato, cucumber, pumpkin, water parsley, and garlic. In Jinju, rice accounted for 53% of total agricultural land, and the main crops were persimmon, pear, watermelon, strawberry, barley and pepper. Using the eq. 2.11 and 2.12, 12 kg ha^{-1} yr^{-1} of P_2O_5 was expected to have an oversupply in comparison with the amount of nutrients required for crops described in **Table 2.7**. Since Jinju and Yeongcheon may cause eutrophication problems, P_2O_5 supply should be considered as an essential factor in building ICAF system.

Table 2.8. Additional chemical fertilizer requirement (A_X) and excessive N and P_2O_5 (B_X) in Namwon, Nonsan, Yeongcheon and Jinju

Region	**Additional chemical fertilizer requirement (A_X)**		**Excessive N and P_2O_5 (B_X)**	
	N	**P_2O_5**	**N**	**P_2O_5**
	-------------------------- **kg ha^{-1} yr^{-1}**	--------------------------		
Namwon	0.0	0.0	26.0	53.8
Nonsan	0.0	0.0	66.5	78.9
Yeongcheon	0.0	0.0	108.7	145.3
Jinju	46.5	0.0	0.0	12.2
Yeongcheon (after model applied)	0.0	0.0	113.3	146.2
Jinju (after model applied)	46.1	0.0	0	12.4

2.5. Conclusion

This study was designed to understand the status and quality of domestic ICAF system, propose its models considering regions where the systems are relatively poor, and to obtain baseline data for ICAF models through analysis of the manure nutrient flow. This analysis was conducted by a field investigation and questionnaire survey of public recycling facilities, public treatment facilities, and individual farms. To propose ICAF models that reflect regional characteristics, a preceding investigation of the number of livestock, species, the amount of livestock manure production, the status of livestock manure treatment, urbanization rate and crop species was conducted. For Namwon, relatively more P_2O_5 and K_2O were generated from livestock manure than N. For regions of Nonsan and Jinju, relatively more N and K_2O were generated from livestock manure than P_2O_5. For Yeongcheon, N, P_2O_5, and K_2O were generated from livestock manure generally in similar amounts. Jinju and Yeongcheon, where livestock manure has been discharged into the sea after treatment, relatively lacked experience in ICAF model compared to Nonsan and Namwon. As a result, both of the two regions had trouble in recycling livestock manure without treatment facilities like public recycling centers. For Jinju, where the urbanization rate is relatively high, it was considered that a two-track ICAF model would be suitable. This model promotes the use of solid and liquid fertilization facility and waste-to-energy facility together. For Yeongcheon, a decentralized public recycling facility was proposed because livestock industries were concentrated in some *myeon* and large-scale farms with more than 3,000 livestock were equipped with their own purification facilities. This system is a model that involves constructing 3–4 medium-sized (about 30 tons) decentralized public recycling facilities in a few *myeon*. In reviewing the nutrient flow in this case study, it is considered that both Jinju and Yeongcheon, where the level of P_2O_5 from livestock manure tends to increase, need to establish ICAF models which can reduce environmental impacts, such as eutrophication. In particular, it is necessary to provide a nutrient prediction tool that includes livestock manure production, treatment of livestock manure, land-application, and crop uptake through modeling of nutrient flow mathematics of ICAF system in case area. This will help to utilize and predict livestock manure and chemical fertilizers at appropriate levels.

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CHAPTER 3. EFFECT OF FLOOR SPACE ALLOWANCE ON PIG PRODUCTIVITY AND MANURE NUTRIENTS FLOW

3.1. Abstract

A total of 152 pig farms were randomly selected from the five provinces in South Korea. During the experiment, the average temperature and relative humidity was 24.7°C and 74% in summer and 2.4°C and 53% in winter, respectively. The correlation between floor space allowance (FSA) and productivity index was analyzed, including non-productive sow days (NPD), number of weaners (NOW), survival rate (SR), appearance rate of A-grade pork (ARA), and days at a slaughter weight of 110 kg (d-SW) at different growth stages. The objectives of this study were (1) to determine the effect of FSA on the pig productivity index, (2) to suggest the minimum FSA for pigs and (3) to estimate the nutrient flow of livestock manure in soil-crop systems based on the proposed FSA. The average SR of growing pigs tended to increase with increasing FSA. It was found that if the FSA of "0.8 ~ 1.0 m^2 $head^{-1}$" is increased to "1.1 ~ 1.27 m^2 $head^{-1}$", it contributed to raise the average SR. The d-SW of fattening pigs also showed a tendency to decrease with increasing FSA. It is considered that the fattening pigs raised in moderately wide space (1.27 to 1.54 m^2 $head^{-1}$) were helpful for the increase of the growth rate due to stress reduction. For the pregnant sow, NPD could be decreased if pregnant sows were raised with a medium level (M) of FSA (3.10 to 3.67 m^2 $head^{-1}$) while also keeping the pig house clean which improves hygiene, and operating the

ventilation system properly. For the farrowing sows, the NOW tended to decrease as the FSA increased. Similarly, a high level of FSA (H) is significantly negative with weaner SR of farrowing sows (p-value = 0.017), indicating this FSA tends to depress SR. Therefore, a FSA of 2.30 to 6.40 m^2 $head^{-1}$ could be appropriate for weaners because a limited space can provide a sense of security and protection from external interruptions. ARA of male fattening pigs showed opposite results. H level of FSA (1.27 to 1.47 m^2 $head^{-1}$) was suggested to increase productivity because ARA was most affected by H level of space allowance with positive correlation (R^2 = 0.523). As FSA increased, the amount of nutrients (N, P_2O_5 and K_2O) from livestock manure was reduced. In the case of N, 20%, 27%, 37% and 48% of N were reduced in 1.0 m^2 $head^{-1}$, 1.1 m^2 $head^{-1}$, 1.27 m^2 $head^{-1}$ and 1.54 m^2 $head^{-1}$, respectively, compared to the N value of 0.8 m^2 $head^{-1}$. Other nutrients (P_2O_5 and K_2O) were also reduced at a similar rate (ranged from 20% to 48%). According to the nutrient flow calculation method of the four regions (Namwon, Nonsan, Yeongcheon and Jinju), increasing the FSA from 0.8 to 1.54 m^2 $head^{-1}$ resulted in a reduction of surplus N up to 60%. In the case of P_2O_5, 5% ~ 16% was reduced as the FSA increased, and the deviation by region excluding Jinju was not large. Jinju showed the highest surplus P_2O_5 reduction (61%) compared to other regions probably due to the large cropland area per LU. A slight increase in the FSA can have a positive impact on productivity, while also solving environmental problems.

Keywords: Floor space allowance, pig productivity, field-scale analysis,

manure nutrient flow

3.2. Introduction

Recent livestock industries tend to operate with intensive livestock farming (ILF) in European and Asia countries (Tamminga, 2003; Gerber et al., 2005). The ILF can maximize livestock productivity through its high animal density in a limited space. However, disadvantages such as nutrient imbalance (Otten and Van den Weghe, 2013) and reduction of N use efficiency (Powell et al., 2010) have been reported in ILF. There have been many studies on the stocking density and environmental aspects (N use efficiency, nutrient balance and nutrient recycling ability, etc.) of dairy farming systems (Saam et al., 2005; Powell et al., 2010; McCarthy et al., 2015; Buckley et al., 2016; Cotching et al., 2017). Studies on the nutrient mass balance in intensive pig farming systems have also been carried out (Aarnink and Verstegen, 2007; Otten and Van den Weghe, 2013).

However, there is a lack of research on proper FSA that satisfies both productivity and environmental aspect in pig farming system. A correlation between the floor space requirement and production efficiency (livestock productivity, welfare, disease incidence, etc.) is necessary to explore the optimal floor space allowance (FSA). The Council of the European Union (2001) proposed the floor space requirement of pigs which was generally categorized by weight. For a pig weighing up to 10 kg, for example, a floor space requirement of 0.15 m^2 $head^{-1}$ was suggested. The recommended floor space requirement that was suggested for pigs weighing more than 10 kg and up to 50 kg ranged from 0.2 to 0.4 m^2 $head^{-1}$. The pig weight ranged from 50 to 85 kg and more than 85 to 110 kg, requiring 0.55 m^2 and 0.65 m^2, respectively. In addition to the floor space requirement suggested, farmers and policy makers became interested in the relationship between FSA and animal productivity. The FSA has been extensively studied in terms of productivity, including growth performance and animal behavior (Weng et al., 1997; Hyun et al., 1998; Gonyou and Stricklin, 1998; Turner et al., 2000; Jensen et al., 2012). However, the results of the FSA effect on productivity varied. According to the studies regarding pig productivity and performance, the impact of different space allowances ranging from 1.4 m^2 to 3.3 m^2 on the pregnant sow's performance was evaluated, resulting in a growth of body weight and depth of backfat as the floor space increased (Salak-Johnson et al., 2007). Other studies reported that the average daily gain (ADG) decreased with decreasing FSA from 0.78 m^2 $head^{-1}$ to 0.52 m^2 $head^{-1}$ (Street and Gonyou, 2008). In the early growing pig period, the ADG was improved at the intermediate level of FSA rather than the low or high level (Kim et al., 2006).

The relationship of FSA and productivity cannot be clearly concluded yet because pig welfare and economic conflict (Powell and Brumm, 1992; Gonyou et al., 2006). From the perspective of the pigs' welfare, a relatively large FSA can produce healthier pigs with high immunity because ease of movement and comfort are improved. To reflect this trend, the Ministry of Agriculture, Food and Rural Affairs (MIFAFF) in South Korea organized a subcommittee, which was composed of experts and producers, to enforce the livestock industry's registration system. The recommended stocking density or

FSA (area per animal) for sows and sows in farrow was 1.43 m^2 head^{-1} and 3.96 m^2 head^{-1}, respectively (MIFAFF, 2005). The growing pig's FSA recommendation by MAFRA is as follows. For a pig weighing up to 20 kg, 0.2 m^2 head^{-1} was suggested. The recommended FSA that was suggested for pigs weighing more than 20 kg and up to 60 kg ranged from 0.3 to 0.45 m^2 head^{-1}. A pig weighing more than 60 kg recommended an FSA of 1.0 m^2 head^{-1}. The FSA recommendation that includes animal welfare concepts was also presented. In growing and finishing stage, the FSA of welfare pig house was recommended to be increased by 22 ~ 25% compared to existing FSA (**Table 3.1**). Although the interplay between FSA and pig productivity is important for pig producers and policy makers, it has not been widely studied at the field scale.

Table 3.1. Floor space allowance standard according to the growth stage of pigs in South Korea

Weight	Normal pig house[14]	Welfare pig house[15]
----- kg -----	--------------------- m^2 head^{-1}	----------------------
< 10	0.2	0.15
10 – 20	0.2	0.2
20 – 30	0.3	0.3
30 – 60	0.45	0.55
> 60	0.8	1.0

[14] MAFRA, 2015. Proper floor space allowance of livestock housing facility

[15] Animal protection management system.
http://www.animal.go.kr/portal_rnl/farm_ani/certify_info.jsp

The National Institute of Animal Science (2016) conducted experiments with five different weights (11 to 25kg, 25 to 45kg, 45 to 65kg, 65 to 85kg, and 85 to 115kg). The FSA was distributed at a low density and a high density in the range of 0.27m^2 to 0.91m^2 depending on the body weight. Low FSA was found to increase ADG in pigs. Fattening pig's feed intake was not significantly affected by FSA differences, except at the late stage (85 to 115kg). It was also confirmed that the higher the FSA, the more stress the pig receives.

Studies on the optimal FSA of pigs in South Korea have been carried out in a fragmentary way. It is necessary to provide appropriate FSA through analysis of the relationship between FSA and productivity through field survey of pig farmers. The evaluation of the appropriate FSA effect on manure nutrient flow in soil-crop system is also necessary. The objectives of this study were (1) to determine the effect of FSA on pig production efficiency, including productivity and performance based on the field analysis, (2) to suggest the minimum FSA for pigs and (3) to estimate the nutrient flow of livestock manure in soil-crop systems based on the proposed FSA.

3.3. Materials and methods

3.3.1. The farm survey

The National Agricultural Cooperative Federation (NH) and Seoul National University (SNU) collaborated in designing the survey. The content and questions of the survey were determined based on a pre-survey reflecting practical field conditions. In 2005, a door-to-door survey was conducted to collect information from farmers of pig farms belonging to the regional livestock cooperative federation, and actual measurements were carried out when necessary. A total of 152 pig farms were selected randomly from the five provinces in South Korea: 32 farms in Chungnam, 28 farms in Jeonbuk, 4 farms in Gyongbuk, 36 farms in Gyungnam, and 52 farms in Jeonnam were surveyed during the summer (Jun. – Aug.) and winter seasons (Dec. – Mar.). The average maximum and minimum temperature of the summer season was 29.0℃ and 21.5℃, respectively. The average humidity was 74.2%. The average maximum temperature and minimum temperature in the winter season was 7.2℃ and -1.8℃, respectively and the mean humidity was 53.2%.

3.3.2. Pig productivity index, floor space allowance, and estimation of manure nutrient flow

The pig productivity index was determined by reflecting the opinions of pig producers and experts from the National Agricultural Cooperative Federation (**Table 3.2**). The correlation between FSA and the productivity index was analyzed, including non-productive sow days (NPD), number of weaners (NOW), survival rate (SR), appearance rate of A-grade pork (ARA), and days at a slaughter weight of 110 kg (d-SW). The appropriate FSA was proposed considering the above productivity factors. The effects of those FSAs on surplus N and P_2O_5 were analyzed based on the nutrient flow calculation method of the four regions (Namwon, Nonsan, Yeongcheon and Jinju) discussed in Chapter 2.

3.3.3. Statistical analysis

The correlation between four different levels of FSA (very low, VL;

low, L; medium, M; high, H) and pig productivity index (the dependent variable) was analyzed using the multiple regression analysis model within IBM SPSS STATISTICS 22. ANOVA was conducted at the significance level of 0.05.

Table 3.2. Productivity index of pig with the different growth stages

	Growth stages				
	Pregnant sow	**Farrowing sow**	**Weaning pig**	**Growing pig**	**Fattening pig**
Productivity Index	-Non-productive sow days [1]	-Number of weaners -Survival rate [2]	-Survival rate	-Survival rate	-Appearance rate of A grade pork -Days of slaughter weight at 110kg -Survival rate

[1] Non- productive sow days (NPD) = 365 – [(litter/sow/year) x (gestation days + lactation days)]; adapted from Shaw, (2005)

[2] Survival rate (%) = [1-(number of pigs that died / total number of pigs)] x 100

3.4. Results and discussion

3.4.1. Non-productive sow days

The survey found that the range of FSA for pregnant sows during summer were from 0.90 m^2 to 9.00 m^2. The average non-productive sow days (NPD) was 41.8 d. The highest coefficient of determination ($R^2 = 0.648$) was obtained with L level of FSA ranged from 2.53 to 3.00 m^2 $head^{-1}$. Approximately 65% of dependent variable (NPD) could be explained by L level of FSA during the summer season (**Table 3.3**). L level of FSA is positively correlated with NPD at high significance. The H level of FSA ranged from 3.70~9.00 m^2 $head^{-1}$ was also expected to have higher NPD. Other variables such as VL and M level of FSA were negatively correlated with NPD. Consequently, NPD tended to decrease with M and VL level of FSA. The FSA variables had no significant effect on NPD in winter season. However, the results also showed that L variable tend to have relatively higher NPD than other variables

Table 3.3. The correlation between four different FSAs (VL, L, M, H) and pig productivity index

Dependent variables	Season	Independent variables (m^2 $head^{-1}$)	R^2	B	B	t	p[1]
NPD (Pregnant sow)	Summer	VL (0.90 ~ 2.50)	0.142	-9.653	-0.377	-0.999	0.357
		L (2.53 ~ 3.00)	0.648	63.893	0.805	3.324	**0.016**
		M (3.10 ~ 3.67)	0.163	-11.418	-0.404	-1.081	0.321
		H (3.70 ~ 9.00)	0.421	3.818	0.649	2.088	0.082
	Winter	VL (0.90 ~ 2.50)	0.165	-11.320	-0.407	-1.091	0.318
		L (2.53 ~ 3.00)	0.428	45.689	0.654	2.120	0.078
		M (3.10 ~ 3.67)	0.218	-23.306	-0.467	-1.293	0.244
		H (3.70 ~ 9.00)	0.058	1.250	0.241	0.609	0.565
NOW (Farrowing pig)	Summer	VL (2.30 ~ 6.40)	0.255	0.813	0.505	1.548	0.166
		L (6.60 ~ 7.61)	0.075	-1.191	-0.274	-0.753	0.476
		M (7.92 ~ 8.82)	0.002	0.177	0.045	0.119	0.908
		H (9.13 ~ 12.50)	0.103	-0.163	-0.321	-0.895	0.400
	Winter	VL (2.30 ~ 6.40)	0.300	0.850	0.548	1.732	0.127
		L (6.60 ~ 7.61)	0.189	-2.192	-0.435	-1.277	0.242
		M (7.92 ~ 8.82)	0.001	-0.125	-0.023	-0.060	0.954
		H (9.13 ~ 12.50)	0.086	0.010	0.294	0.813	0.443
SR (Farrowing pig)	Summer	VL (2.30 ~ 6.40)	0.340	1.436	0.583	1.898	0.100
		L (6.60 ~ 7.92)	0.121	-1.671	-0.348	-0.981	0.359
		M (8.00 ~ 9.13)	0.002	0.452	0.048	0.127	0.902

		H (10.30 ~ 14.40)	0.578	-3.444	-0.760	-3.094	**0.017**
	Winter	VL (2.30 ~ 6.40)	0.240	1.667	0.490	1.487	0.181
		L (6.60 ~ 7.92)	0.046	-1.506	-0.215	-0.583	0.578
		M (8.00 ~ 9.13)	0.077	-1.628	-0.277	-0.764	0.470
		H (10.30 ~ 14.40)	0.335	-2.504	-0.579	-1.879	0.102
SR (Growing pig)	Summer	VL (0.40 ~ 0.80)	0.102	8.576	0.319	0.891	0.402
		L (0.80 ~ 0.95)	0.240	-45.542	-0.490	-1.488	0.180
		M (0.97 ~ 1.10)	0.000	0.891	0.021	0.055	0.957
		H (1.12 ~ 1.90)	0.020	0.754	0.143	0.354	0.736
	Winter	VL (0.40 ~ 0.80)	0.156	9.776	0.395	1.137	0.293
		L (0.80 ~ 0.95)	0.264	-117.799	-0.514	-1.584	0.157
		M (0.97 ~ 1.10)	0.157	-19.211	-0.396	-1.142	0.291
		H (1.12 ~ 1.90)	0.032	-0.923	-0.180	-0.448	0.670
SR (Fattening pig)	Summer	VL (0.90 ~ 1.05)	0.090	-20.492	-0.299	-0.543	0.625
		L (1.07 ~ 1.10)	0.095	44.444	0.309	0.459	0.691
		M (1.10 ~ 1.27)	0.651	29.115	0.807	2.365	0.099
		H (1.30 ~ 2.80)	0.676	-4.338	-0.822	-2.042	0.178
	Winter	VL (0.90 ~ 1.05)	0.057	-16.393	-0.239	-0.427	0.698
		L (1.07 ~ 1.10)	0.605	-77.778	-0.778	-1.750	0.222
		M (1.10 ~ 1.27)	0.860	48.649	0.927	4.294	**0.023**
		H (1.30 ~ 2.80)	0.072	-1.323	-0.269	-0.395	0.731
ARA	Summer	VL (0.90 ~ 1.00)	0.120	86.111	0.346	0.521	0.654

(Fattening pig)		L (1.00 ~ 1.05)	0.026	-110.448	-0.163	-0.233	0.837
		M (1.10 ~ 1.18)	0.429	-181.930	-0.655	-1.227	0.345
		H (1.27 ~ 1.47)	0.523	56.459	0.723	1.480	0.277
	Winter	VL (0.90 ~ 1.00)	0.118	105.556	0.344	0.519	0.656
		L (1.00 ~ 1.05)	0.019	-97.015	-0.138	-0.196	0.862
		M (1.10 ~ 1.18)	0.974	-124.893	-0.987	-6.141	0.103
		H (1.27 ~ 1.47)	0.440	82.204	0.663	1.254	0.337
d-SW (Fattening pig)	Summer	VL (0.90 ~ 1.00)	0.179	-77.379	-0.423	-0.933	0.403
		L (1.00 ~ 1.07)	0.161	-92.742	-0.401	-0.876	0.430
		M (1.09 ~ 1.20)	0.148	-47.552	-0.384	-0.832	0.452
		H (1.27 ~ 1.54)	0.010	7.549	0.098	0.197	0.854
	Winter	VL (0.90 ~ 1.00)	0.019	-36.111	-0.138	-0.241	0.825
		L (1.00 ~ 1.07)	0.441	-270.161	-0.664	-1.778	0.150
		M (1.09 ~ 1.20)	0.026	-24.918	-0.161	-0.326	0.761
		H (1.27 ~ 1.54)	0.760	-58.168	-0.872	-3.562	**0.024**

VL, very low FSA; L, low FSA; M, medium FSA; H, high FSA

[1] The P value for the independent variable ($p < 0.05$)

A wide variation was observed in the entire NPD dataset such as the lowest number of NPD (14 d) allowed in VL range, and the highest number of NPD (60 d) was also observed with the same FSA group. This result probably indicates that other factors, such as feeding, management, and environmental control, could affect the NPD. Therefore, productivity could be increased if pregnant sows were raised with a floor space level of M while also keeping the pig house clean which improves hygiene and operating the ventilation system properly. Because pregnant sows require absolute emotional stability, it is necessary to provide the proper amount of space so that the pregnant sow can feel this sense of stability. This result agrees with those of previous studies on the effect of space allowance on NPD of gilts in a commercial swine production system (Young et al., 2008). The appropriate level of FSA may play a key role in providing improved performance of pregnant sows in terms of the sow's emotional stability, sense of comfort, and reproductive efficiency. Subsequently it results in more profit and higher income for pig producers (Suwanasopee et al., 2005). In contrast, pregnant sows kept in a large space may have a sense of fear or insecurity, resulting in low productivity. Other than FSA, feeding and management are other important factors that could potentially affect the productivity of pregnant sows. Therefore, it is necessary to quantify the correlation among these factors in further studies.

3.4.2. Number of weaners

Although the value of the coefficient of determination was low, the NOW tended to decrease as the FSA increased. The tendency in the present study agreed with the results found by Salak-Johnson et al. (2007). This trend can be understood by observing the characteristics of the pig. When the pig gives birth, the space to raise piglets should be limited to provide a sense of security and protection from external interruptions. A large space can create anxiety in farrowing sows. The FSA that is currently used in South Korea seems excessively large. Therefore, a FSA of 2.30~6.40 m^2 $head^{-1}$ (VL) would be appropriate to have high weaner production. The average NOW was 20.6 weaners per year during the winter season, which was 0.3 higher than that during the summer. A pregnancy disorder caused by the intense heat of sun during the summer season could play a key role in the decrease of weaner production. More fundamental causes should be studied using an in-depth analysis with accumulated data.

3.4.3. Survival rate

During the summer season, the regression analysis showed that the highest coefficient of determination was approximately 58% (R^2 = 0.578) with H level of FSA ranged from 10.30 to 14.40 m^2 $head^{-1}$ (**Table 3.3**). H level of FSA was negatively correlated with SR at significant level, indicated that those FSAs tend to depress SR. Although the value of R^2 was low, the SR tended to increase as the FSA decreased. Again, limited space can give the pig a sense of stability during the initial weaning period. A larger space, however, will be required as the weaners gain weight and become active. The impact of seasonal differences on the weaner SR of farrowing sows was not statistically significant. Therefore, a FSA of 2.30~6.40 m^2 $head^{-1}$ (VL) could be suggested to maintain an appropriate environmental condition for weaners of farrowing pig.

According to the overall data from the summer season, the SR of growing pigs tended to increase. It indicates that an increase in floor space led to increased pig productivity. The SR of growing pigs with the VL, L and M level of FSA (<1.12 m^2 $head^{-1}$) showed a large deviation, ranging from 86 to 99%. The influence of farmers' meticulous feed management on SR may be large, such that the drawbacks of high stocking density can be compensated for, resulting in a high SR with smaller FSA. For the farms that provided a relatively large floor space (1.12 ~ 1.90 m^2 $head^{-1}$), the SR was stable (greater than 95%). The SR depends somewhat on the FSA. A regression analysis, however, showed that the SR was not significantly affected by the FSA during the summer period. During the winter season, as was observed in the summer, a high level of variation in SR with change in FSA. The average SR of growing pigs during the winter season was 94.5%, which was 0.9% lower than the summer season result. A severe daily temperature difference in winter may have a vital influence on lowering the SR due to respiratory disease.

The highest coefficient of determination (R^2 = 0.676) was obtained with H level of FSA (1.30 ~ 2.80 m^2 $head^{-1}$). The negative correlation with SR was observed so those FSAs tend to have lower SR of fattening pigs (**Table 3.3**). M level of FSA, however, was positively correlated with SR, indicated SR tended to increase with the FSA of 1.10 ~ 1.27 m^2 $head^{-1}$. The SR was also significantly and positively affected by the M level of FSA (R^2 = 0.651) during the winter period. The lowest SR (90%) was obtained in the range of 0.90 to 1.10 m^2 $head^{-1}$, and the highest SR (99%) was also observed in the same FSA level (**Fig 3.1**).

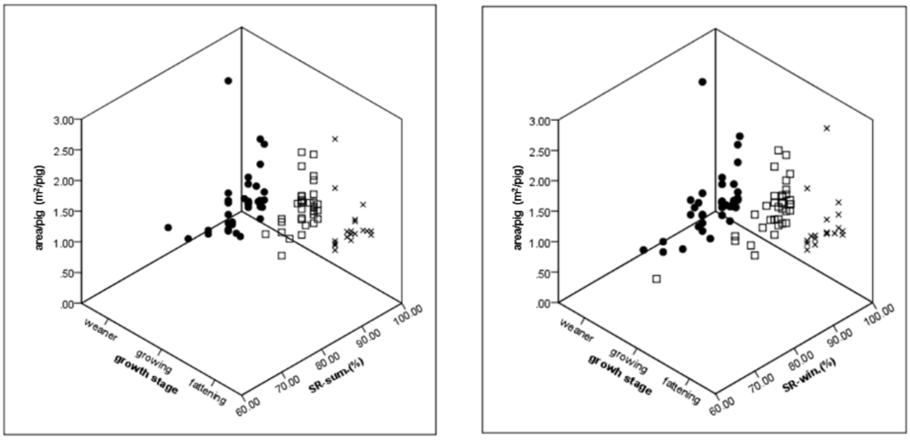

Fig 3.1 The distribution of weaner, growing, and fattening pig's survival rate (SR) over floor space allowance (FSA) by season: summer and winter (●: weaner, □: growing pigs, ×: fattening pigs)

Similar results were also obtained in the winter season especially with VL level. It is likely that variable feed management caused the high variation in the SR of fattening pigs. The average SR during the winter season was 92.7%, which is 1.9% lower than during the summer season. It is natural to expect decrease in SR during the winter period compared with that during the summer, due to the large daily temperature difference. A tendency for the weaner SR to increase was observed. A regression analysis, however, showed that the weaner SR was not significantly affected by the FSA during the both summer and winter period. A very low value of R^2 was obtained which represented a high level of variation in SR with change in the FSA (data not shown). The weaner SR with smaller floor spaces ($0.10 \sim 0.56$ m^2 $head^{-1}$) showed a large deviation, ranging from 80 to 99%. This deviation can be explained by examining other management factors, such as the meticulous weaner management of farmers, as a high-quality facility (i.e., ventilation) and cleanliness may play key roles in producing the large variance. For the farms that provided a relatively large floor space (0.57 ~ 2.75 m^2 $head^{-1}$), the SR was stable (greater than 90%). The results in winter season were similar to summer. It seems that the impact of FSA on weaner SR was somewhat little, and larger spaces are difficult to accommodate economically. Therefore, a FSA of 0.57 m^2 $head^{-1}$ with high-intensity feed management could satisfy such an economic situation for weaner pigs.

3.4.4. Average appearance rate of A-grade pork

The yield grade of pork was investigated. The average appearance rate of A-grade pork (ARA) for the male fattening pig was 53.7% during the summer season. H level of FSA (1.27 ~ 1.47 m^2 $head^{-1}$) was suggested to increase productivity because ARA was most affected by H space allowance with positive correlation (R^2 = 0.523). Previous studies, however, showed that there was no correlation between FSA and meat quality. According to Gentry et al. (2002), an uncrowded FSA (9.45 m^2 $head^{-1}$) with increased exercise had no effect on meat quality improvement. Morrison et al. (2007) also reported that the large group housing system (1.7 m^2 $head^{-1}$) was not evident for pork quality compare to conventional confinement pig system. The average ARA for male fattening pigs was 53.5% during the winter season, but the impact of the seasonal difference on the ARA was not statistically significant. Interestingly, the highest coefficient of determination (R^2 = 0.974) was observed with M level of FSA (1.10 ~ 1.18 m^2 $head^{-1}$) in winter season and it had negative effect on ARA. The M level of FSA could be the critical factor at which decrease of ARA begins.

3.4.5. Days at a slaughter weight of 110 kg

The regression analysis showed that the values of R^2 during the summer season were low. It is difficult to identify a clear relationship between the FSA and d-SW of fattening pigs. However, the farms that provided a relatively large floor space (1.27 ~ 1.54 m^2 $head^{-1}$) during the winter season showed d-SW was significantly and negatively affected by FSA. A relatively large floor space can provide healthier pigs with high immunity because they are easier to move and more comforted when resting are improved. Hyun et al. (1998) reported that a lower ADG with lower floor space was obtained due to an increase in the abnormal behavior and aggression level. Because pigs do not have sweat glands, the higher heat load for pigs, especially during the summer, could be the main factor that decreases the ADG compared with the large FSA. Another possible factor affecting ADG may be feeder space (Jensen et al., 2012). Consequently, the market day of pigs at the slaughter weight of 110 kg should be shortened with the large FSA.

3.4.6. Effect of floor space allowance on manure nutrients flow in soil-crop system

If the floor space allowance is increased by just a little bit, the productivity will increase and the aforementioned problems will be solved at the same time. As FSA increased, the amount of nutrients (N, P_2O_5 and K_2O) from livestock manure was reduced (**Table 3.4**). To estimate the nutrient production, a farm of 3000 m^2 size was applied. Related calculations are discussed in detail in Chapter 2. The amount of N, P_2O_5 and K_2O in pig manure (feces and urine) was adapted from 'The study to re-establish the amount and major compositions of manure from livestock' (RDA, 2008). In the case of N, 20%, 27%, 37% and 48% of N were reduced in 1.0 m^2 $head^{-1}$, 1.1 m^2 $head^{-1}$, 1.27 m^2 $head^{-1}$ and 1.54 m^2 $head^{-1}$, respectively, compared to the N value of 0.8 m^2 $head^{-1}$. Other nutrients (P_2O_5 and K_2O) were also reduced at a similar rate.

Table 3.4. Estimation of the amount of nutrients generated by FSA change (based on area of 3,000 m^2)

Floor space allowance	**Number of pigs**	**Nutrients**		
		N	P_2O_5	K_2O
---- m^2 $head^{-1}$ ----	--- head ---	-------------- tons yr^{-1} ---------------		
0.8	3,750	23.0	8.9	28.0
1.0	3,000	18.4	7.1	22.4
1.1	2,727	16.7	6.4	20.4
1.27	2,362	14.5	5.6	17.7
1.54	1,948	11.9	4.6	14.6

Table 3.5 shows the effect of FSA on manure nutrient flow in the four regions covered in Chapter 2. Increasing the FSA from 0.8 to 1.54 m^2 $head^{-1}$ resulted in

a reduction of surplus N up to 60%. A slight FSA increase from 0.8 m^2 $head^{-1}$ (current FSA standard) to 1.1 m^2 $head^{-1}$ showed 34% to 39% N reduction effect. This has shown that the simple way of reducing the number of pigs can also effectively reduce the excess N supply to cropland. Jinju showed the highest surplus P_2O_5 reduction (61%) among the four investigated regions because the cropland per LU was 1.6 to 2.6 times larger than other regions. Consequently, the decrease in the number of pigs have a significant effect on P_2O_5 reduction in Jinju (**Fig 3.2-Fig 3.5**).

Table 3.5. Effect of floor space allowance on manure nutrient surplus (N and P_2O_5) in Namwon, Nonsan, Yeongcheon and Jinju

Region	Floor space allowance	Nutrients surplus	
		N	P_2O_5
	-- m^2 $head^{-1}$ --	-------------- kg ha^{-1} yr^{-1} --------------	
Namwon	0.8	26.0	53.8
	1.0	19.6	51.3
	1.1	17.2	50.4
	1.27	14.1	49.1
	1.54	10.5	47.7
Nonsan	0.8	66.5	78.9
	1.0	52.5	73.5
	1.1	47.4	71.5
	1.27	40.5	68.9
	1.54	32.7	65.9
Yeongcheon	0.8	108.7	145.3
	1.0	85.7	136.4
	1.1	77.4	133.2
	1.27	66.2	128.9
	1.54	53.5	124.0
Jinju	0.8	0.0	12.2
	1.0	0.0	9.1
	1.1	0.0	8.0
	1.27	0.0	6.5
	1.54	0.0	4.8

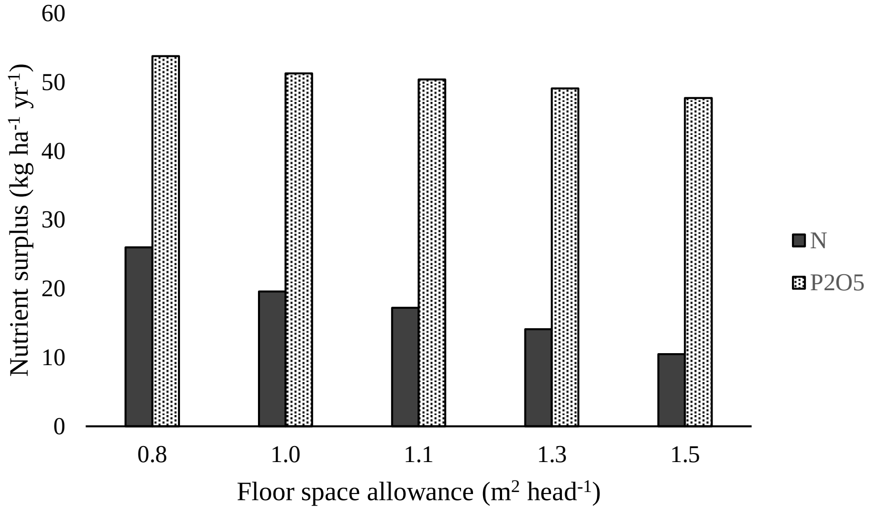

Fig 3.2. Effect of floor space allowance on nutrient (N and P_2O_5) surplus in Namwon

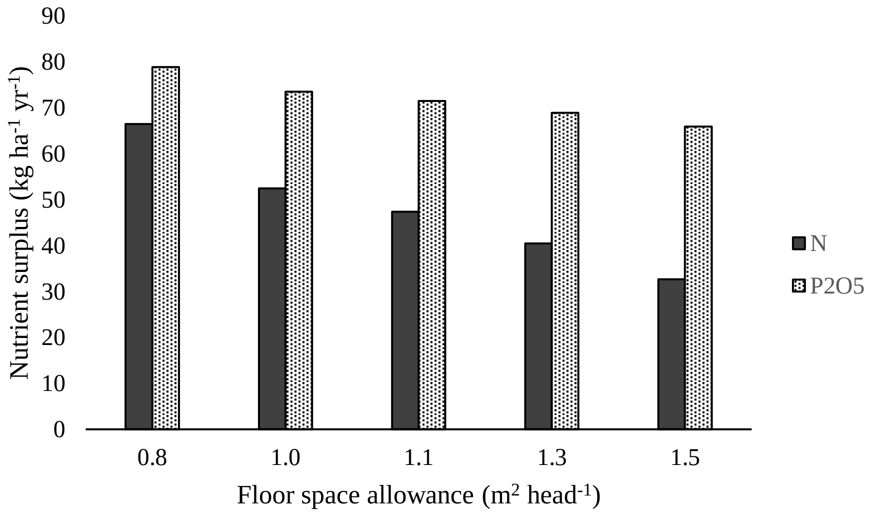

Fig 3.3. Effect of floor space allowance on nutrient (N and P_2O_5) surplus in Nonsan

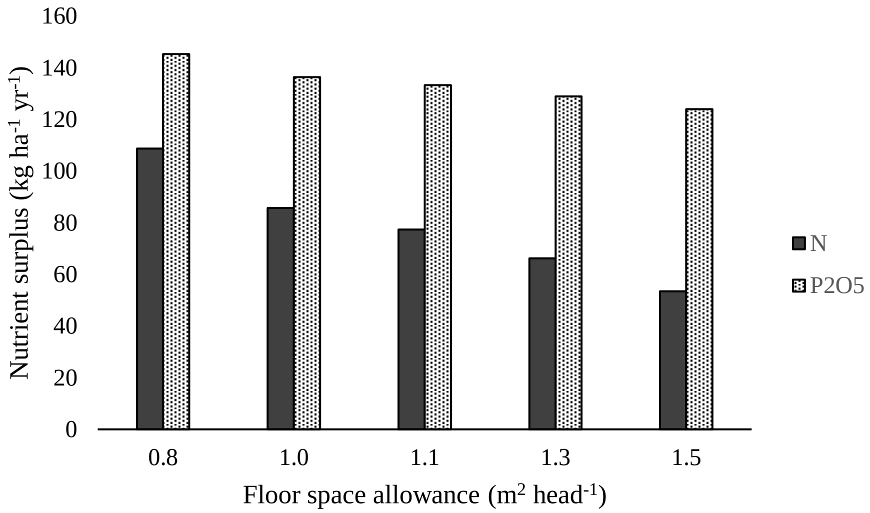

Fig 3.4. Effect of floor space allowance on nutrient (N and P_2O_5) surplus in Yeongcheon

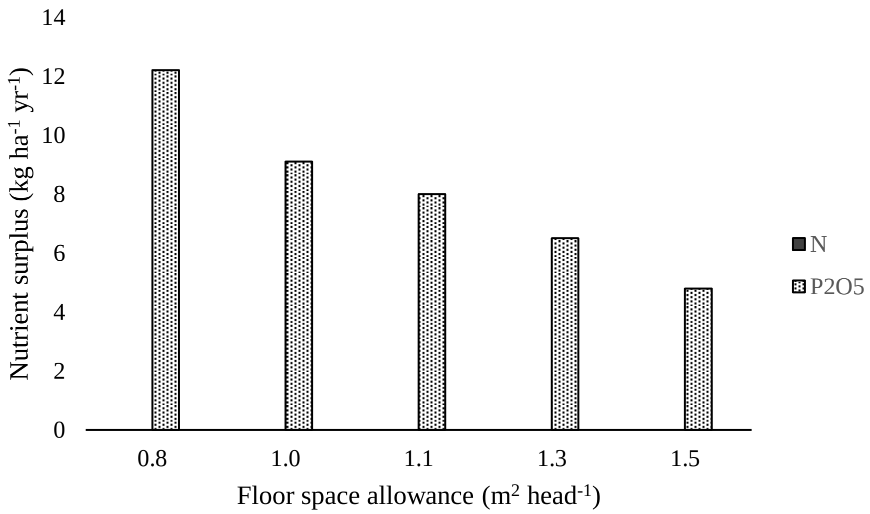

Fig 3.5. Effect of floor space allowance on nutrient (N and P_2O_5) surplus in Jinju

It is expected that the FSA of the livestock will naturally decrease if the intuitive and simple meat consumption method of the consumer is converted to consumption that takes into account livestock welfare, management methods and housing environment. These consumer movements will affect the policy changes of the government, and policy proposals will be possible considering both the interests of producers and consumers.

3.5. Conclusion

A total of 152 pig farms were randomly selected from the five provinces in South Korea. The correlation between floor space allowance (FSA) and productivity index was analyzed, including non-productive sow days (NPD), number of weaners (NOW), survival rate (SR), appearance rate of A-grade pork (ARA), and days at a slaughter weight of 110 kg (d-SW) at different growth stages. The average survival rate (SR) of growing pigs tended to increase with increasing FSA. Generally, fattening pigs in South Korea were being raised in a small space. Therefore, it was found that if the FSA of "0.8 ~ 1.0 m^2 $head^{-1}$" is increased to "1.1 ~ 1.27 m^2 $head^{-1}$", it contributed to raise the average SR. The days at a slaughter weight of 110 kg (d-SW) of fattening pigs also showed a tendency to decrease with increasing FSA. It is considered that the fattening pigs raised in moderately wide space (1.27 ~ 1.54 m^2 $head^{-1}$) were helpful for the increase of the growth rate due to stress reduction. A slight increase in the FSA can have a positive impact on productivity, while also solving environmental problems. As FSA increased, the amount of nutrients (N, P_2O_5 and K_2O) from livestock manure was reduced.). In the case of N, 20%, 27%, 37% and 48% of N were reduced in 1.0 m^2 $head^{-1}$, 1.1 m^2 $head^{-1}$, 1.27 m^2 $head^{-1}$ and 1.54 m^2 $head^{-1}$, respectively, compared to the N value of 0.8 m^2 $head^{-1}$. Other nutrients (P_2O_5 and K_2O) were also reduced at a similar rate. According to the nutrient flow calculation method of the four regions (Namwon, Nonsan, Yeongcheon and Jinju), increasing the FSA from 0.8 to 1.54 m^2 $head^{-1}$ resulted in a reduction of surplus N up to 60%. About 5% to 16% of surplus P_2O_5 was reduced as the FSA increased, and the deviation by region excluding Jinju was not large. Jinju showed the highest surplus P_2O_5 reduction (61%) compared to other regions probably due to the large cropland area per LU. It is expected that the FSA of the livestock will naturally decrease if the intuitive and simple meat consumption method of the consumer is converted to consumption that takes into account livestock welfare, management methods and housing environment. These consumer movements will affect the policy changes of the government, and policy proposals will be possible considering both the interests of producers and consumers.

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CHAPTER 4. THE DYNAMICS OF NITROGEN DERIVED FROM A CHEMICAL NITROGEN FERTILIZER WITH ANAEROBICALLY-AEROBICALLY TREATED SWINE SLURRY IN PADDY SOIL-PLANT SYSTEMS

4.1. Abstract

A well-managed chemical N fertilization practice combined with treated swine slurry (TSS) is necessary to improve sustainability and N use efficiency in rice farming. However, little is known about the fate of N derived from chemical N fertilizer with and without TSS in paddy soil-plant systems. The objectives of this study were (1) to estimate the contribution of applied N fertilizer to N turnover in rice paddy soil with different N fertilization practices that were manipulated by the quantity of treated swine slurry and chemical N fertilizer (i.e., HTSS+LAS, a high amount of TSS with a low amount of ammonium sulfate; LTSS+HAS, a low amount of TSS with a high amount of ammonium sulfate; AS, ammonium sulfate with phosphorus and potassium; C, the control) and (2) to compare the rice response to applied N derived from each N fertilization practice. Rice biomass yield, ^{15}N recovery in both rice grain and stems, soil total N (TN), soil inorganic N, and soil ^{15}N recovery were analyzed. Similar amounts of ^{15}N uptake by rice in the TSS+AS plots were obtained, indicating that the effects of the different quantities of TSS on chemical fertilizer N recovery in rice during the experimental period were not significant. The soil ^{15}N recoveries of HTSS+LAS, LTSS+HAS, and AS in each soil layer were not significantly different. For the HTSS+LAS, LTSS+HAS and AS

applications, total ^{15}N recoveries were 42%, 43% and 54%, respectively. Because the effects of reducing the use of chemical N fertilizer were attributed to enhancing soil quality and cost-effectiveness, HTSS+LAS could be an appropriate N fertilization practice for improving the long-term sustainability of paddy soil-plant systems. However, N losses, especially through the coupled nitrification-denitrification process, can diminish the benefits that HTSS+LAS offers.

Keywords: Treated swine slurry, nitrogen balance, paddy soil, nitrogen-15 analysis, ammonium sulfate

4.2. Introduction

Rice grain yield has increased with the rapid increase in the use of inorganic N fertilizers, especially the ammonium forms of N fertilizers. The application of ammonium-based N fertilizer to irrigated rice paddy soil is the generally accepted method for avoiding denitrification losses. However, the indiscriminate use of chemical N fertilizers causes the long-term depletion of soil organic matter (Khan et al., 2007). Thus, the application of organic amendments (such as livestock manure) with chemical N fertilizer has been used as an alternative for chemical N fertilization and related long-term based studies have also been conducted (Liu et al., 2009; Pan et al., 2009; Liu et al., 2011; Tong et al., 2009; Li et al., 2010; Su et al., 2006, Manda et al., 2007). Livestock manure generated from swine houses is a good source of organic amendment in South Korea because of its local abundance and high productivity.

According to the Korean Statistical Information Service in 2016 (KOSIS), approximately 10 million pigs were raised through concentrated animal feeding operations (CAFOs). The number of CAFOs have been increasing throughout the country, particularly in local areas in South Korea. The high amount of swine slurry production has always been an inevitable by-product of CAFOs. Most local governments in South Korea are not allowed to build or expand pig farms due to the farm odor. These circumstances are favorable for large-scale pig farms that can operate expensive odor reduction facilities and swine slurry treatment systems. Thus, small-scale farms with less than 1,000 pigs are typically unable to control odor complaints and treat pig manure and tend to abandon their farm operations.

The biological treatment of swine slurry is essential before it flows into soil-water systems because of its high organic matter (OM) and nutrient contents, which could cause serious environmental problems. Air and water pollution have been caused by excessive livestock manure nutrients (Beegle and Lanyou, 1994; Wagner, 1999). The high amount of manure produced by confined livestock in restricted areas has become a serious environmental concern because excess nutrients can adversely affect both the ground water and surface water via leaching and runoff, respectively (Matson et al., 1997). These environmental issues have been highlighted, and a movement towards an environmentally friendly treatment system for swine slurry has been initiated. Currently, anaerobic digestion coupled with an aerobic/anoxic reactor is considered a more sustainable swine slurry treatment system to produce treated swine slurry (TSS). Although anaerobic digestion has been suggested as an effective solution to treat swine slurry, the anaerobically digested slurry or sludge remaining in the reactor remains as another negative environmental influence.

Previous studies have shown that anaerobically digested slurry applied as an N source in paddy fields and grasslands had a negative impact on the environment, occurring primarily through ammonia (NH_3) and nitrous oxide (N_2O) volatilization (Amon et al., 2006; Chen et al., 2013). Additionally, Bernal and Kirchmann (1992) reported in their incubation experiments that NH_3 volatilization after 9 days of application of anaerobically treated pig manure was higher than that of aerobically treated pig manure. Thus, the combined anaerobic-aerobic approach is being implemented as an alternative to the conventional anaerobic digestion processes because it can effectively remove OM and N that are present in anaerobically digested slurry (Akunna et al., 1994; Bernet et al., 2000). However, little is known about the mechanisms of a land-application of chemical N fertilizer with TSS, especially the fate of N derived from chemical N fertilizer in a paddy soil-plant system when TSS is also used. Accordingly, the objectives of this study were (1) to estimate the contribution of applied N fertilizer to N turnover in a rice paddy soil with different N fertilization practices that are manipulated by the quantity of TSS and chemical N fertilizer and (2) to compare the rice response to applied N derived from each N fertilization practice.

4.3. Materials and methods

4.3.1. Lysimeter description

Twelve lysimeters (250 mm in diameter and 500 mm in depth) were prepared using a PVC pipe and installed in a greenhouse (15.0 m × 9.8 m) that was located at a livestock experimental farm in Suwon, South Korea. Each lysimeter contained an undisturbed soil monolith, which was extracted from an agricultural field located near Suwon (37°15’51”N, 126°58’48”W) with the permission of University Animal Farm, College of Agriculture & Life Science, Seoul National University **(Fig 4.1)**. The soil used in this study was a coarse loamy, mixed, mesic family of Typic Dystrudepts. The amount of OM in the soil sample was 9.0 g kg^{-1}. The baseline soil sample had a mean pH of 5.8 (1:5 water). The available inorganic elements in the baseline soil sample include 299 mg kg^{-1} of phosphorous (Cox, 2001), 0.59 $cmol^{+}kg^{-1}$ of potassium ion (K^{+}), 4.7 $cmol^{+}kg^{-1}$ of calcium ion (Ca^{2+}), and 1.5 $cmol^{+}kg^{-1}$ of magnesium ion (Mg^{2+}) (ICP-MS analysis). The electrical conductivity (EC) was 0.4 dS/m. The TN, NO_3^-, and NH_4^+ levels of the initial soil were 0.14%, 9.48 mg kg^{-1}, and 9.67 mg kg^{-1}, respectively. The leachate drained through the perforated bottom plate of the lysimeter to mimic natural leaching conditions **(Fig 4.2)**. Rice (*Oryza sativa* L.) seedlings were grown in a seedling box (30 cm × 60 cm) and transplanted to the lysimeters on July 5, 2014. The rice was harvested on 24 December 2014. Rice biomass at 5 cm above the soil surface was harvested and placed into a paper bag. The paper bags containing the rice biomass were oven dried (35 °C for 10 days), and the weight was measured. The dried rice was separated into the grain and stem portions, ground in a stainless-steel mill and sieved through a 1.0-mm screen.

Fig 4.1. Undisturbed soil monolith collection from the field at Suwon SNU farm, South Korea (37°15’51”N, 126°58’48”W)

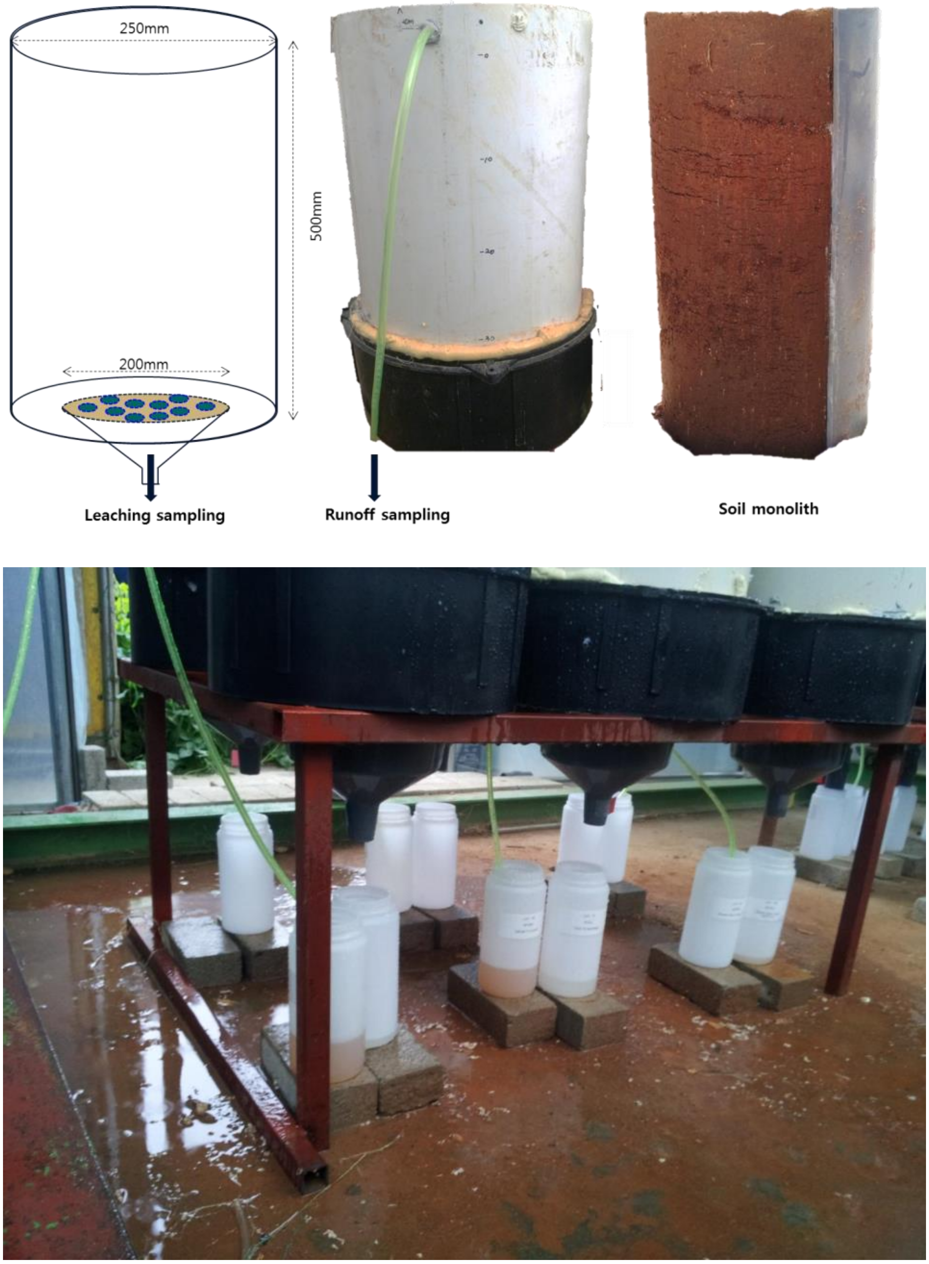


Fig 4.2. Lysimeter design: The leachate drained through the perforated bottom plate of the lysimeter to mimic natural leaching conditions

4.3.2. Experimental design

A randomized complete block design was used in the study in which the main plots consisted of three replicates **(Fig 4.3)**. The main plots were divided into four subplots corresponding to the four treatments: a high amount of treated swine slurry with a low amount of ^{15}N-labeled ammonium sulfate (HTSS+LAS), a low amount of treated swine slurry with a high amount of ^{15}N-labeled ammonium sulfate (LTSS+HAS), ^{15}N-labeled ammonium sulfate with phosphorus and potassium (AS), and a control (C, no soil amendments). Each treatment was evenly distributed on the soil surface in the lysimeter (0.073 m^2) using different colored stickers to distinguish each subplot. The temperature and humidity data were collected at a weather station (WatchDog 2900ET, Spectrum Technologies, Inc.) at the experimental site **(Fig 4.4)**. The source water for the simulation was tap water, which was stored in a 1.0 m^3 tank for at least two weeks before rainfall to remove hypochlorite. Three rainfall events (June 03, August 10 and September 21) with moderate intensity (9.0 mm hr^{-1}) were applied during the experimental period. The surface water level of each plot was maintained at 2 cm above the soil surface through rainfall and irrigation until September 30 to exemplify a waterlogged paddy plot.

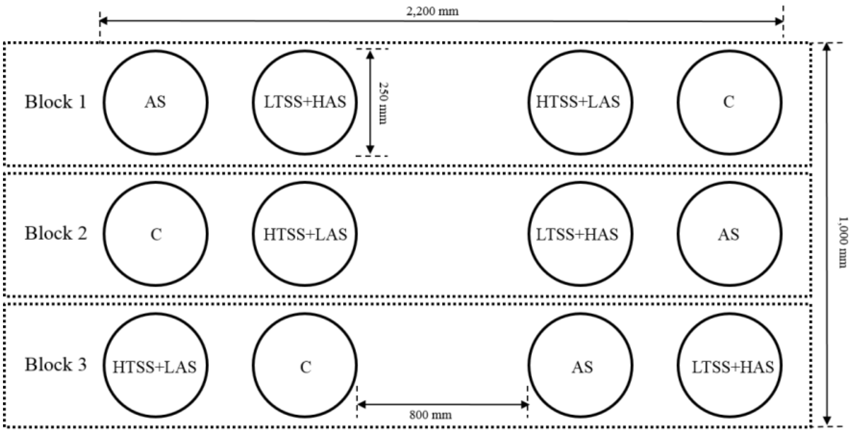


Fig 4.3. Experimental layout: A randomized complete block design; the main plots consisted of three replicates. The main plots were divided into four subplots corresponding to the four treatments (HTSS+LAS, LTSS+HAS, AS, and C).

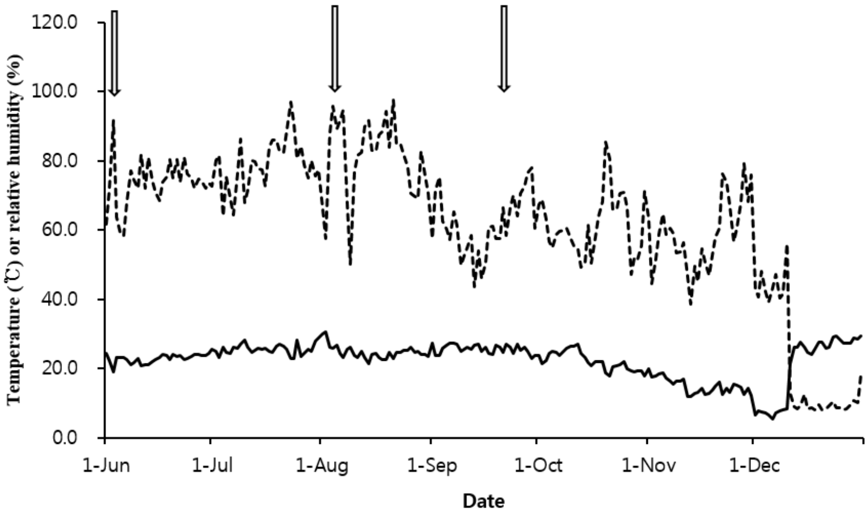
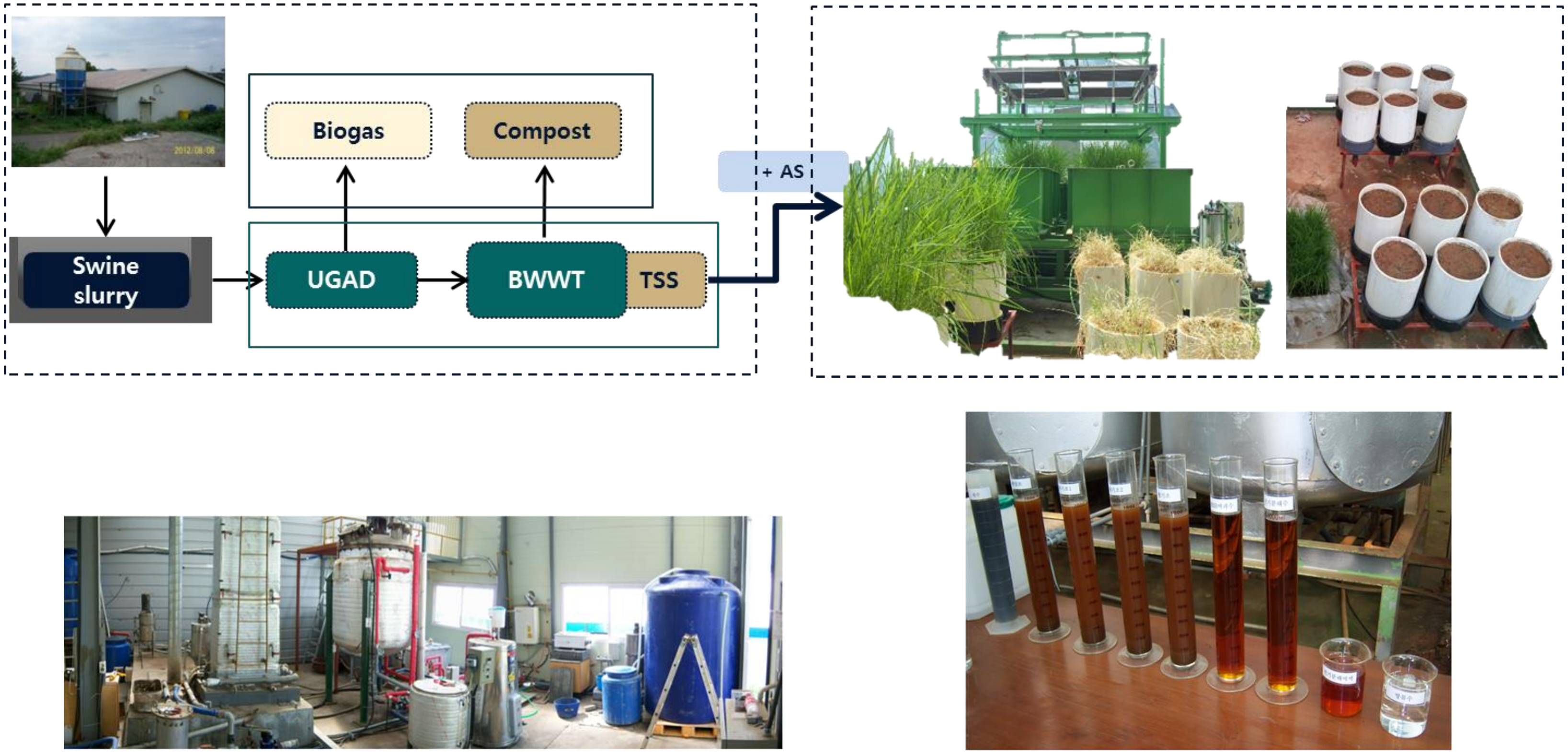


Fig 4.4. Relative humidity (dashed-line) and temperatures (solid-line) at the livestock experimental farm in Suwon, South Korea during the 2014 experimental period. The open arrow indicates the rainfall date using a simulator. To prevent the rainfall simulator from freezing, a heater was used at the experimental site on December 11

4.3.3. Application of chemical N fertilizer (^{15}N-labelled ammonium sulfate) with treated swine slurry

Swine slurry was produced from a livestock experimental farm in Suwon, South Korea and was treated using a biological wastewater treatment (BWWT) system (**Fig4.5**). The system was constructed as a pilot scale (1,000 L of swine slurry/day) and consisted of sequencing the reactors using activated sludge processes. First, the raw swine slurry goes through an underground anaerobic digestion (UGAD, 20 m^3 capacity) process as a pretreatment to produce biogas (methane) and to reduce the high concentration of OM in the swine slurry. Then, the anaerobically digested swine slurry flows into the BWWT reactors that consist of five aerobic-anaerobic tanks (Tank 1 and Tank 4 are anaerobic processes; Tank 2, Tank 3, and Tank 5 are aerobic processes). A 10-kg slurry sample collected from Tank 5, where the OM, N, and phosphorus were reduced, was transferred to a 20-L pail. TSS was well mixed and divided into 1-L plastic sample bags for eventual lysimeter application. The TSS sample bags were frozen as quickly as possible to prevent NH_3 gas losses and stored at -15 °C. The total solids (TS), volatile solids (VS), total chemical oxygen demand (TCOD), TN, and pH of TSS were 15.6 g L^{-1}, 8.6 g L^{-1}, 13.1 g L^{-1}, 0.65 g L^{-1} and 5.16, respectively.



Underground Anaerobic Digestion (UGAD)

Treated Swine Slurry (TSS)

Fig 4.5. Treated swine slurry production process: subsequent treatment process after UGAD and BWWT system

Rice was fertilized with TSS and labelled with ^{15}N AS (5 atom % ^{15}N) at an equivalent rate of 80 kg N ha^{-1} (60 kg N ha^{-1} TSS and 20 kg N ha^{-1} AS for the HTSS+LAS treatment and 26.7 kg N ha^{-1} TSS and 53.3 kg N ha^{-1} AS for the LTSS+HAS treatment). All treatments (HTSS+LAS, LTSS+HAS, and AS) were applied as split applications (three-fourths on August 08 and one-fourth on September 19). The rates of the TN applied in HTSS+LAS, LTSS+HAS, and AS are given in **Table 4.1**.

4.3.4. Chemical analysis

The TS and VS values of TSS were analyzed according to APHA standard methods. The TCOD and TN of TSS was determined via the Hach chemical reagents manual (DR 5000, Hach, Loveland, Colo.). A stainless steel auger (12.6-mm diameter) was used to collect the soil sample. Ten soil cores of each soil depth (0–5, 5–10, 10–20 and 20–30 cm) were collected after rice harvest in December 2014, composited, and placed in plastic bags for TN, NO_3^-, NH_4^+, and ^{15}N analysis. The soil samples were mixed well in the bag, and 5.0 g was weighed and then dried at 105 °C for 24 hours. The atom % ^{15}N and TN values of the dried soil samples were analyzed via the combustion method using an elemental analyzer linked to a stable isotope mass spectrometer (Isoprime-EA, Micromass, UK). The isotopic ratios were reported in standard notations with respect to atmospheric N gas (N_2) as the working standard (Ozteck, USA; $\delta^{15}N$ value of – 0.22‰). The accuracy (<1.0‰) and reproducibility (<0.5‰) of the measurements were verified using a reference material (IAEA-N3, KNO_3) from the International Atomic Energy Agency. Ten grams of soil and 100 mL of 2

M KCl were added to 250-mL plastic bottles and shaken for 30 min. After centrifuging for 5 minutes, the KCl extract was filtered through Whatman no.1 filter paper. Devarda's alloy (0.5 g) and MgO (0.5 g) were added to the 50 mL of subsample and analyzed for NH_4^+_N and NO_3^-_N using a Kjeltec auto 2400/8400 System (Tecator AB, Sweden).

Table 4.1. List of treatments and the application rate of nitrogen (N)

	Treatments	**Rate of total N application (kg ha^{-1})**
HTSS+LAS	Treated swine slurry and ammonium sulfate (3:1 ratio)	80 [a]
LTSS+HAS	Treated swine slurry and ammonium sulfate (1:2 ratio)	80 [a]
AS [b]	Ammonium sulfate only	80 [a]
C	Control	No fertilizer, treated swine slurry applied

[a] Split application is used (applied three-fourths of TN at the tillering stage and one-fourths of TN at panicle initiation).

[b] AS treatment includes phosphorus (45 kg ha^{-1}) and potassium (57 kg ha^{-1}).

4.3.5. Rice ^{15}N uptake, soil ^{15}N recovery and total ^{15}N recovery calculation

The recovery of AS ^{15}N in harvested rice and soil was calculated using the procedures outlined by Powell et al. (2005). Rice ^{15}N uptake was calculated according to equation (3.1).

$$\text{Rice 15N recov \%} = \frac{P\ (c-d)}{f\ (a-b)} \times 100 \qquad (3.1)$$

In this equation, *P* is total rice N uptake (mg), *f* is ammonium sulfate N (mg), *a* is the atom % ^{15}N of the applied ammonium sulfate, *b* is the atom % ^{15}N in non-labeled ammonium sulfate (assuming 0.366 for all three inputs), *c* is the atom % ^{15}N in rice (an average of 3 circles within a treatment), and *d* is the atom % ^{15}N in the control rice (an average of 3 'control' circles). The recovery of applied ^{15}N in total soil N was calculated according to equation (3.2).

$$\text{Soil 15N recov \%} = \frac{Q\ (e-g)}{f\ (a-b)} \times 100 \qquad (3.2)$$

where *Q* is total soil N, *e* is the atom % ^{15}N of total soil N in the treatment plots, *g* is the atom % ^{15}N in the control plots, and the other terms are identical to those described for equation (3.1). The total ^{15}N recovery was calculated as the sum of the recoveries in the rice and soil components using equation (3.3).

$$\text{Total N recovery \%} = \%N\ recov_{harv\ rice} + \%N\ recov_{soil} \qquad (3.3)$$

4.3.6. Statistical analysis

The differences in rice ^{15}N uptake and soil ^{15}N recovery between soil depths and the different N fertilization practices were analyzed using ANOVA with IBM SPSS STATISTICS 22. Tukey's test was used for post-hoc analysis. The correlation between ^{15}N isotope abundance (δ scale, the dependent variable) and inorganic N (independent variable) in soil was analyzed using the linear regression analysis model. The analysis of variance was conducted at a significance level of 0.05.

4.4. Results

4.4.1. Dry matter yield and total N uptake by rice

The effects of HTSS+LAS, LTSS+HAS, and AS on rice biomass production and rice TN uptake are shown in **Fig 4.6.** The highest biomass yield (282.2 g m^{-2}) and the lowest biomass yield (248.7 g m^{-2}) were obtained for the AS application and the LTSS+HAS application, respectively. The total biomass yield increased by 18% and 10% under HTSS+LAS and LTSS+HAS compared with the control plot, respectively. Similarly, the TN uptake by rice for the AS application (4.06 g m^{-2}) was higher than the HTSS+LAS (3.62 g m^{-2}) and LTSS+HAS (3.44 g m^{-2}) applications. The TN uptake by rice decreased by 11% and 15% under HTSS+LAS and LTSS+HAS compared with the AS plot, respectively. However, there was no significant effect on biomass production (whole plant) and rice TN uptake between the treatments. The AS application had a relatively large standard deviation for biomass yield and TN uptake, which was probably due to the inhomogeneous sunlight distribution in the greenhouse.

4.4.2. Soil total nitrogen, soil nitrate N, ammonium N and total soil ^{15}N recovery

Soil TN, soil nitrate N (NO_3^-), ammonium N (NH_4^+), and total soil ^{15}N recovery after application of HTSS+LAS, LTSS+HAS and AS are shown in **Table 4.2.** The different N fertilization practices did not affect the soil TN. A significant decrease in soil TN was observed with an increase in soil depth, regardless of fertilization practice. Regarding soil NO_3^-, there was a significant difference between the treatments, especially for the HTSS+LAS and LTSS+HAS applications in the upper soil layer (0–5 cm). HTSS+LAS and AS had a similar effect on the retention of soil NO_3^- in the same soil layer. A general reduction in soil NO_3^- was observed until the soil depth of 30 cm, indicating that NO_3^- is less available in deeper soil. However, in the AS application, the tendency towards a steady increase was observed after the 20-cm soil depth. The effect of fertilization practice on soil NH_4^+ was not clear at each soil depth, except at the depth of 10–20 cm. The amount of NH_4^+ in the soil decreased with depth regardless of the fertilization practice. The soil ^{15}N recoveries of HTSS+LAS, LTSS+HAS, and AS in each soil layer were not significantly different. Over 70% of the soil ^{15}N recovery was observed in the upper two soil layers (0–5 and 5–10 cm) after the application of each treatment. The predicted influence of the inorganic N form (NO_3^- and NH_4^+) on δ ^{15}N in different soil layers is shown in **Table 4.3.** The N forms NO_3^- and NH_4^+ had positive and negative associations with soil δ ^{15}N in the top 10 cm and 10-20 cm of the soil, respectively.

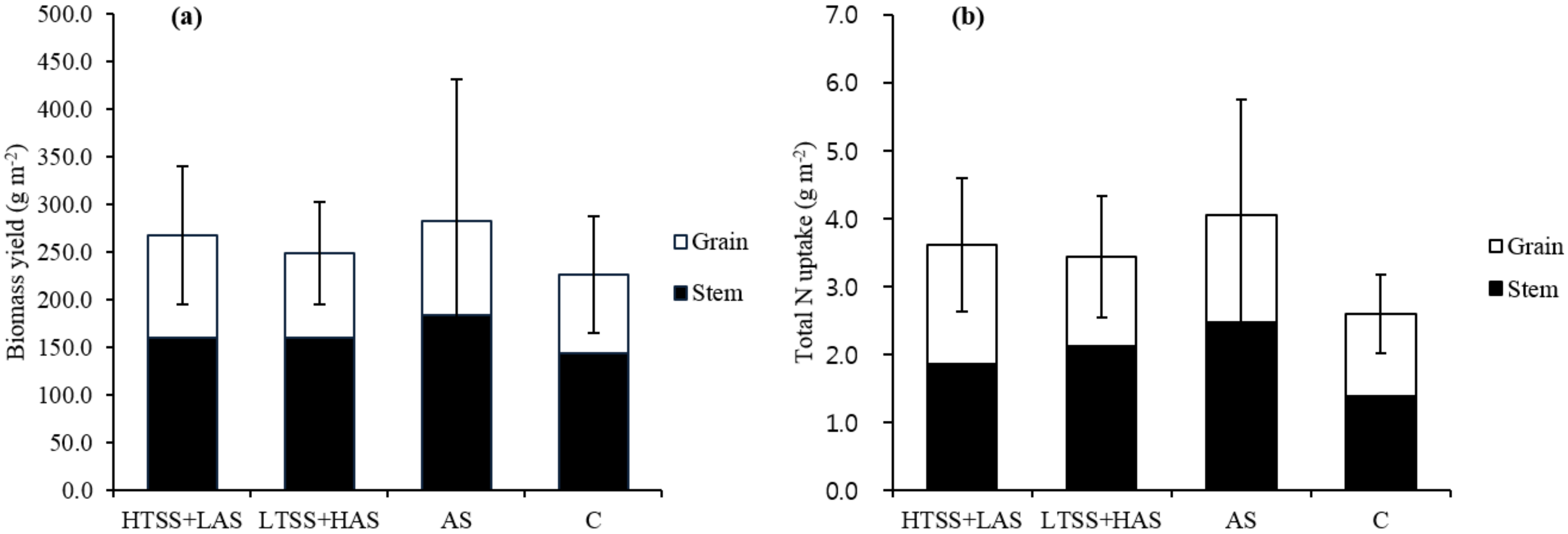


Fig 4.6. Biomass (dry matter) yield (a) and Total N uptake by rice after application of treated swine slurry and chemical fertilizer (b).

Error bars represent standard deviations (n=3) of the means of rice biomass yield (combined value of grain and stem) and total N uptake by rice (combined value of grain and stem)

Table 4.2. Soil total nitrogen (TN), soil nitrate N (NO_3^-), ammonium N (NH_4^+), and total soil ^{15}N recovery following an application of ^{15}N-labeled ammonium sulfate and treated swine slurry

	Treatments			
	Soil depth (cm)	HTSS+LAS	LTSS+HAS	AS
Total N (g kg^{-1})	0 – 5	1.9 ns(a)	1.9 ns(a)	2.0 ns(a)
	5 – 10	1.6 ns(ab)	1.7 ns(ab)	1.6 ns(b)
	10 – 20	1.2 ns(bc)	1.2 ns(bc)	1.3 ns(c)
	20 – 30	0.8 ns(c)	0.9 ns(c)	0.9 ns(d)
Nitrate N (mg kg^{-1})	0 – 5	28.3 A(a)	17.3 B(a)	26.1 A(a)
	5 – 10	13.7 ns(b)	12.8 ns(ab)	16.7 ns(ab)
	10 – 20	9.3 ns(bc)	10.9 ns(b)	11.3 ns(b)
	20 – 30	3.4 B(c)	8.8 AB(b)	15.2 A(ab)
Ammonium N (mg kg^{-1})	0 – 5	16.8 A(a)	14.5 A(a)	14.5 A(a)
	5 – 10	12.4 ns(b)	12.6 ns(a)	11.0 ns(b)
	10 – 20	9.4 A(c)	9.8 A(b)	7.7 B(c)
	20 – 30	5.4 ns(d)	6.0 ns(c)	6.2 ns(c)

Soil ^{15}N recovery (%)	0 – 5	21.1 ns(a)	20.1 ns(a)	22.2 ns(a)
	5 – 10	5.0 ns(b)	8.3 ns(b)	6.7 ns(b)
	10 – 20	4.3 ns(bc)	4.3 ns(b)	7.4 ns(b)
	20 – 30	2.7 ns(c)	3.2 ns(b)	1.8 ns(b)

Data with the different capital letters and small letters in the parentheses indicate significant differences (p-value < 0.05) among the treatments (row) and soil depth (column), respectively.

ns represents not significant (p-value > 0.05).

4.4.3. Nitrogen-15 recoveries in the soil-plant system

Nitrogen-15 recoveries of the labeled N source with the different types of N fertilization practice (HTSS+LAS, LTSS+HAS, and AS) in the soil-plant system are shown in **Table 4.4.** In the case of TN uptake by rice, it is possible that some N from TSS and AS, as well as from soil N, affected TN. However, rice ^{15}N recovery only represents the amount recovered from applied chemical fertilizer. For rice ^{15}N recovery, the HTSS+LAS amended plots showed larger ^{15}N recovery in the rice grain (4.8%) than in the stem (3.8%). In contrast, 4.8% and 8.5% of the total applied ^{15}N, which is larger than the recovery in grain, were recovered from the rice stems following the LTSS+HAS and AS treatments, respectively. In the case of rice ^{15}N recovery (whole plant), there was a significant recovery difference (p-value < 0.05) between the AS and other different N fertilization practices (HTSS+LAS and LTSS+HAS). Rice ^{15}N uptake with LTSS+HAS was 13% and 51% lower than that of HTSS+LAS and AS, respectively. In addition, the AS application resulted in greater soil ^{15}N recovery (38%) compared with the other N sources. The recovery of ^{15}N in the HTSS+LAS amended plots was lower (33%) than that in the recovery of the LTSS+HAS amended plot (36%). For the HTSS+LAS, LTSS+HAS and AS applications, the total ^{15}N recoveries were 42%, 43% and 54%, respectively. A larger amount of unaccounted ^{15}N was observed in the HTSS+LAS treatment (58%) compared to the other fertilizer N sources.

Table 4.3. Linear regression analysis used to describe the predicted influence of inorganic N form on $\delta^{15}N$ in different soil layers.

Soil depth (cm)	Independent variables	B	β	t	P
0 – 10	Nitrate N (NO_3^-)	9.544	0.909	3.537	*
	Ammonium N (NH_4^+)	-11.807	-0.364	-1.417	ns
10 - 20	Nitrate N (NO_3^-)	2.802	0.223	1.741	ns
	Ammonium N (NH_4^+)	-17.098	-0.919	-7.159	**
20 - 30	Nitrate N (NO_3^-)	0.001	0.001	0.001	ns
	Ammonium N (NH_4^+)	4.926	0.354	0.633	ns

Dependent variable is soil $\delta^{15}N$ (‰); B, unstandardized coefficients; β, beta-value; t, t-value; P, p-value for the independent variable (p-value < 0.05).

*p-value < 0.01; **p-value < 0.001; ns represents not significant (p-value > 0.05).

Table 4.4. Nitrogen-15 recoveries of the labeled N source (ammonium sulfate) in the different fertilization practices in a paddy soil-plant system

Treatment	**Rice ^{15}N recovery (%)**			**Soil ^{15}N recovery (%)**	**Total ^{15}N recovery (%)**	**Unaccounted for ^{15}N (%)**
	Grain	Stem	Total			
HTSS+LAS	4.8 ab	3.8 ns	8.6 a	33.1	41.8	58.2
LTSS +HAS	2.7 a	4.8 ns	7.5 a	35.9	43.4	56.6
AS	6.8 b	8.5 ns	15.2 b	38.2	53.4	46.6

Data with different letters in the same column are significantly different (p-value <0.05).

ns represents not significant (p-value > 0.05).

4.5. Discussion

4.5.1. Rice response to the applied N derived from each N fertilization practice

The application of HTSS+LAS, LTSS+HAS and AS resulted in similar rice biomass yield (whole plant) and TN uptake mainly due to the equal TN application rate (80 kg ha^{-1}) of the treatments. However, considering cost-effectiveness, the application of HTSS+LAS on rice fields is recommended as the N fertilization practice. The difference of chemical fertilizer N amount from each treatment is as follows. AS, LTSS + HAS and HTSS + LAS had a chemical fertilizer N content of 80 kg ha^{-1}, 53 kg ha^{-1} and 20 kg ha^{-1}, with the corresponding ratio of 1: 0.67: 0.25, respectively. Chemical fertilizer N is characterized by a fast-release effect that can be absorbed instantaneously by rice after N is applied. Therefore, AS has relatively high rice yield and TN uptake. TSS used as organic amendment also had a partial fast-release effect and showed no significant differences in biomass yield and TN uptake compared to the AS treatment. Although rice yield and TN uptake responses to the different N fertilization practices were not significantly different, rice ^{15}N uptake following AS deposition was significantly higher than that observed for the HTSS+LAS and LTSS+HAS treatments. The chemical fertilizer used with TSS showed similar rice N recoveries of 8.6% and 7.5% for HTSS + LAS and LTSS + HAS, respectively. On the other hand, the N recovery of AS was 15.3%, which was more than 6% higher than that of the mixed treatment. This indicated that the organic amendment and the native soil N showed a potential to contribute to TN recovery by 43% in HTSS and 51% in LTSS, respectively. In the present study, when TSS was three times that of AS, the chemical fertilizer

N uptake increased more than the TSS. On the other hand, when AS was twice that of TSS, chemical fertilizer N was used less than the TSS N. This is most likely explained by the fact that the uptake of chemical fertilizer N seems to be improved in the HTSS+LAS treatment due to increased soil microbial activity (Pan et al., 2009; Mandal et al., 2007; Zhang et al., 2012). The positive effects of the combined HTSS and LAS on the rice N recovery was observed, especially in rice grain N recovery. Similarly, Lee et al. (2014) reported that a dairy slurry application did not affect the whole plant barley N yield, but there was an N response in the barley kernel with the dairy manure application. The high protein level in rice grain associated with the overuse of N fertilizer has a negative impact on the cooking and eating quality of the grain due to low gel consistency, gelatinization or amylose content (Song et al., 2012; Gu et al., 2015). Given this fact, the use of AS fertilizer as a source of N may be avoided in terms of rice grain quality.

4.5.2. The contribution of applied N fertilizer to N turnover in the rice paddy soil with different N fertilization practices

Most of the applied ^{15}N was recovered from the top 10 cm of all N amended soil, which was in agreement with a previous study that suggested that very little applied ^{15}N was recovered in the soil, except that from the surface organic layer (Curis et al., 2005). According to the correlation between soil inorganic N (NO_3^- and NH_4^+) and $\delta^{15}N$ values after fertilizer applications, the NO_3^- N form in the soil had a larger positive beta value ($\beta = 0.909$) than that of the NH_4^+ N form in the upper two soil layers (**Table 4.3**). This can be understood in terms of the nitrification processes that occur in the surface paddy soil regardless of the different N treatments. As the NH_4^+ is converted to NO_3^- through nitrification in the oxidized paddy soil surface, an increase of soil $\delta^{15}N$ is obtained because $^{14}NH_4^+$ is decreased (Choi and Ro, 2003). The N fertilizer (HTSS+LAS, LTSS+HAS and AS) deposited in each plot under waterlogged conditions may have resulted in a limited nitrification process immediately after the application, except for the paddy soil surface, causing certain soil bacteria to obtain oxygen (O_2) from NO_3^-. With the reduction of produced NO_3^- progresses in the lower anaerobic soil layers, NO_3^- is serially converted to nitrite (NO_2^-), nitric oxide (NO), N_2O, and N_2 gas (Jensen et al., 1993; Aulakh et al., 2000). Consequently, relatively lower $\delta^{15}N$ soil NH_4^+ and higher $\delta^{15}N$ soil NO_3^- were observed in waterlogged paddy soil due to restricted nitrification in saturated soil conditions (Lim et al., 2015). The N form of NH_4^+ has a negative correlation with soil $\delta^{15}N$ in the 10 – 20 cm soil layer. In other words, a decrease of soil $\delta^{15}N$ would be observed as NH_4^+ is converted to NO_3^- through nitrification in the rhizosphere of the paddy soil. This may be explained by the results of Arth and Frenzel (2000), who observed that a substantial amount of O_2 is measured around the rice roots, which provides aerobic conditions within the anoxic soil layer, especially during the rice growing period (Revsbech et al., 1999). A laboratory incubation study conducted by Mohanty et al. (2013) reported that fertilization practice (a mixture of farmyard manure and chemical fertilizer) and aerobic soil conditions resulted in relatively high N mineralization kinetics in the soil compared with that of a single fertilizer and anaerobic conditions**.** The correlation of soil NO_3^-, NH_4^+, and soil $\delta^{15}N$ values in different soil layers after application of HTSS+LAS, LTSS+HAS and AS are shown in **Fig 4.7 – Fig 4.10**. As a result of analyzing the topsoil layer of paddy soils by 0-5cm and 5-10cm, the results of each soil layer were not significant. In the 0-5 cm soil layer, the N form that was relatively more involved in the soil $\delta^{15}N$ value was NO_3^-. Conversely, the NH_4^+ was slightly more correlated in the 5-10 cm soil layer.

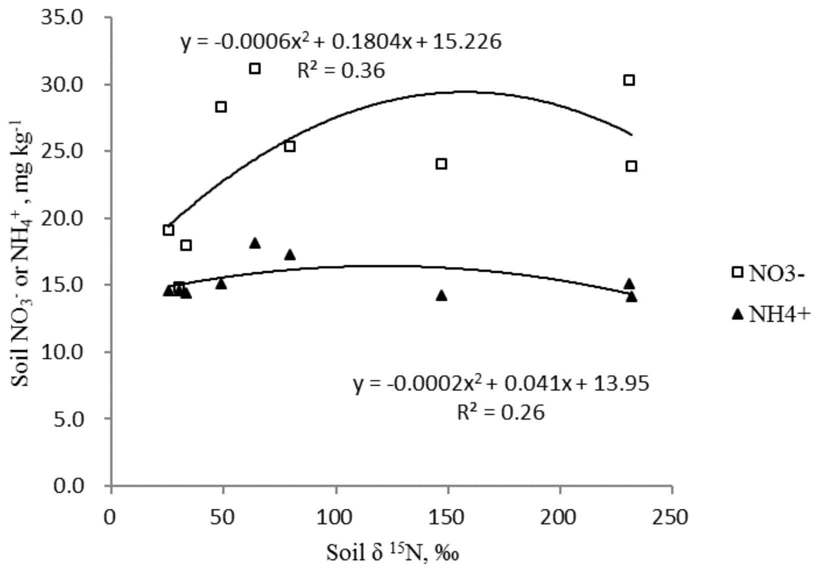


Fig 4.7. Correlation analysis of soil NO_3^-, NH_4^+ and $\delta^{15}N$ values in 0-5 cm soil layer

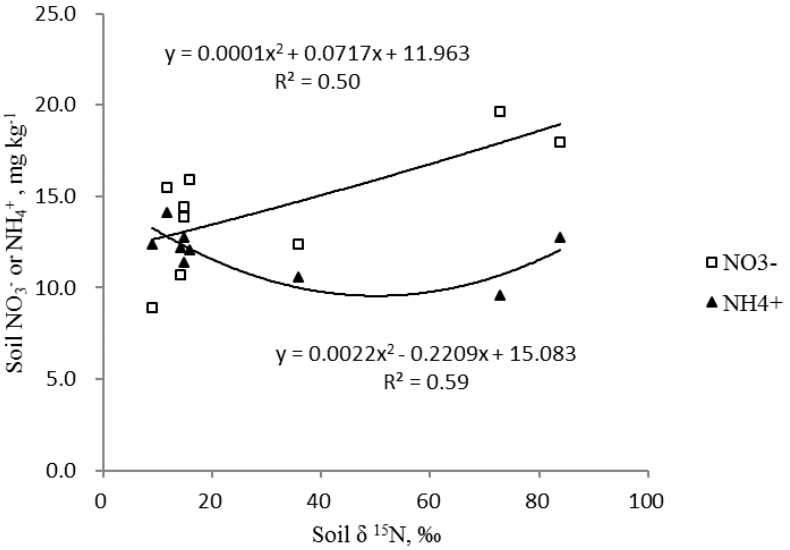


Fig 4.8. Correlation analysis of soil NO_3^-, NH_4^+ and $\delta^{15}N$ values in 5-10 cm soil layer

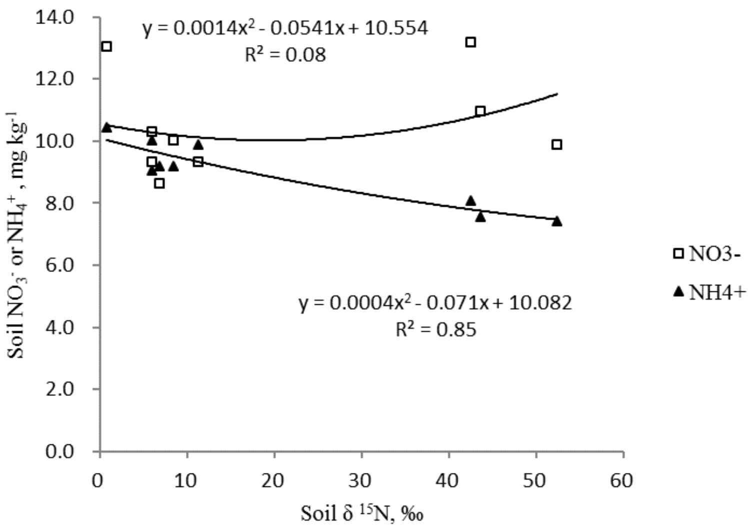


Fig 4.9. Correlation analysis of soil NO_3^-, NH_4^+ and $\delta^{15}N$ values in 10-20 cm soil layer

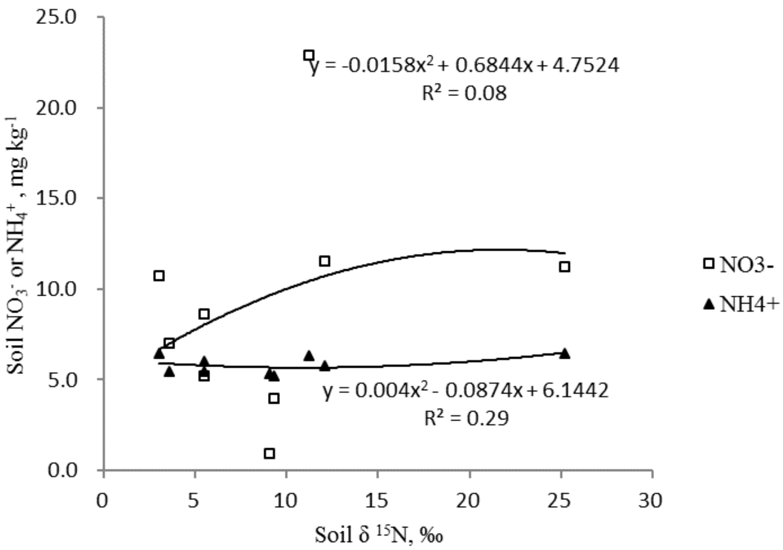


Fig 4.10. Correlation analysis of soil NO_3^-, NH_4^+ and $\delta^{15}N$ values in 20-30 cm soil layer

Fig 4.11 showed that HTSS+LAS had higher correlation with NO_3^- than NH_4^+, which was in agreement with a previous study (Mohanty et al., 2013). The presence of more NO_3^- means that nitrification was activated by the addition of TSS. In addition, the undigested N that is passed through the biological treatment system without being used is decomposed slower in the soil compared with inorganic N. Thus, the mineralization rate of AS is the largest, followed by the less rapid mineralization of TSS undigested N. In the case of high proportion of AS, the possibility of remaining in the form of NH_4^+ was shown (**Fig 4.12 and Fig 4.13**). After the waterlogged period, some of the NH_4^+ transformed by the microbes in TSS amended soil is adsorbed onto negatively charged clay particles, and the plant roots absorb some as well. The NH_4^+ adsorbed onto clay particles is converted to NO_3^- via nitrification.

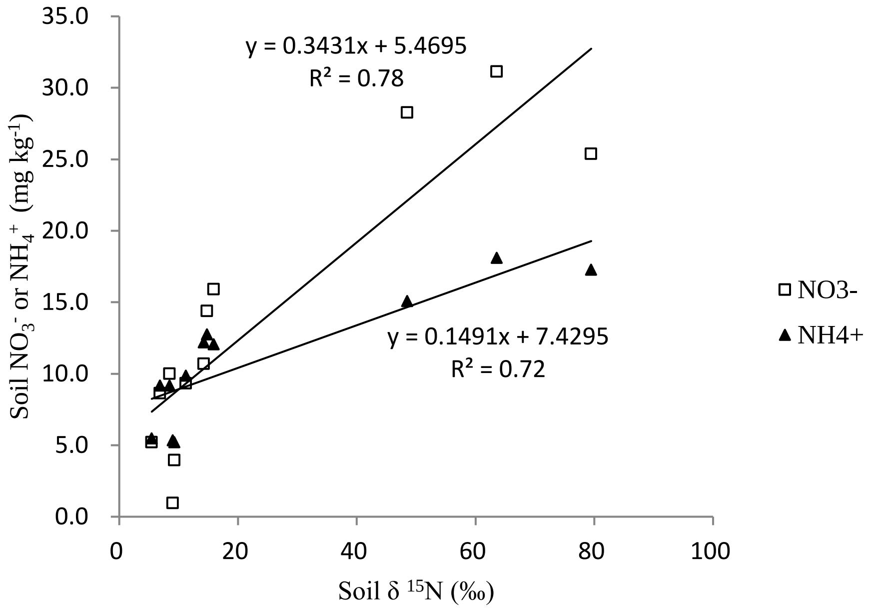


Fig 4.11. Correlation analysis of soil NO_3^-, NH_4^+ and $\delta^{15}N$ values in HTSS + LAS treatment

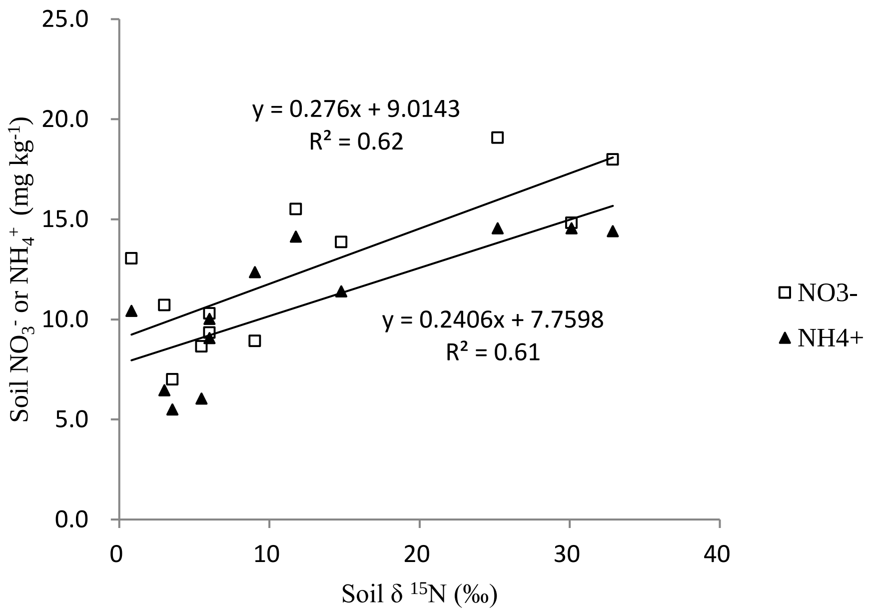


Fig 4.12. Correlation analysis of soil NO_3^-, NH_4^+ and $\delta^{15}N$ values in LTSS + HAS treatment

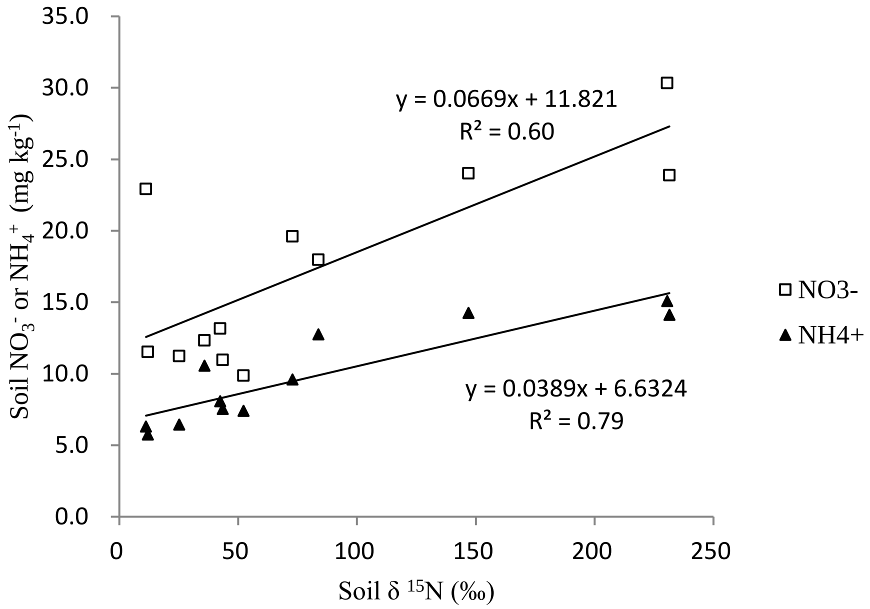


Fig 4.13. Correlation analysis of soil NO_3^-, NH_4^+ and $\delta^{15}N$ values in AS treatment

4.5.3. The fate of ^{15}N derived from a chemical N fertilizer with TSS in paddy soil-plant systems

The result of the total ^{15}N recovery was somewhat smaller (approximately from 42% to 54%) than the value reported by Zhao et al. (2009). The study investigating the fate of fertilizer ^{15}N in paddy soil using an undisturbed monolith lysimeter showed that the ^{15}N recovery in rice and soil were 41% and 22%, respectively. The amount of ^{15}N recovery using the ^{15}N direct methods may be low because the amount of available ^{15}N caused by pool substitution would not be used in the recovery calculations (Rao et al., 1991). The interaction between the added N and native soil N has been described in previous studies (Rao et al., 1991; Jenkinson et al., 1985). Jenkinson et al. (1985)

introduced the term added N interaction (ANI), which is used to indicate that the added N fertilizer can increase the mineralization of the unlabeled soil N. Additionally, the low ^{15}N recovery of applied ^{15}N may occur due to uneven fertilizer application and high variability in bulk density. We assumed that the bulk density of the soil ranged from 1.1 to 1.3 g cm^{-3}, depending on soil depth. In the present study, the calculated unaccounted ^{15}N ranged from 46% to 58%, which is higher than in previous studies. Schnier et al. (1987) reported that the total soil and plant ^{15}N recoveries ranged from 67 % to 78 % at the mature stages, and approximately 22% to 33% of applied ^{15}N fertilizer could not be accounted for in either N remaining in the soil or via plant N uptake. The N losses through NH_3 volatilization, leaching and runoff, and direct N_2O emissions were 12%, 0.3% and 0.12%, respectively (Zhao et al., 2009). NH_3 volatilization in this study could be limited because the pH of the AS and TSS amended soils were less than 9.0 (**Fig 4.14**), which is the pH level where the predominant form of N is NH_4^+. Our results showed the potential for the occurrence of a coupled nitrification-denitrification process due to an oxidized soil surface and aerobic soil conditions around the rice roots in the rhizosphere. Therefore, when considering aerobic and anaerobic soil conditions in the rice paddy soil, the coupled nitrification-denitrification process could play a key role in determining N losses in this study (Reddy et al., 1989; Penton et al., 2013).

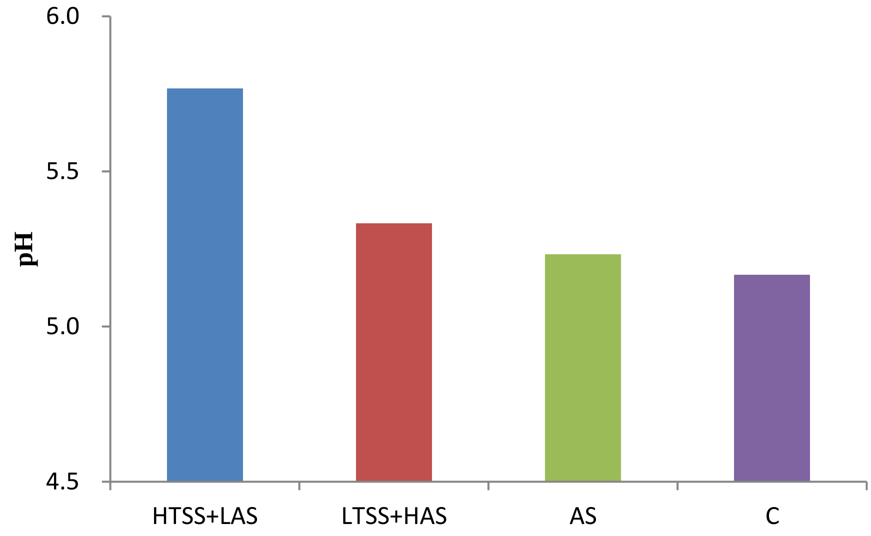


Fig 4.14. The soil pH of each N fertilization practice after harvest

When TSS and AS are used together, a certain amount of AS N tends to be lost, irrespective of the amount of AS used. Therefore, it is a good strategy to use less chemical fertilizer N in terms of soil quality and cost-effectiveness. TSS can be used as a major N source in rice fields, and chemical fertilizer N might be a complement to TSS. The pig manure production in South Korea is about 20 million tons yr^{-1} (as of 2016[16]). The general N content (2.43%) in pig manure is estimated to be 528.3 billion KRW yr^{-1} when converted to 1,087 KRW kg_N^{-1} (**Table 4.5**). Based on the assumption that 0.96% of the total pig manure production is converted to liquid fertilizer, applying the amount of TSS N (0.65 g L^{-1}) used in this study to the corresponding value can reduce the chemical fertilizer cost of 13.5 billion KRW yr^{-1}. Therefore, it is expected that the use of more TSS and less chemical N fertilizer, such as HTSS + LAS fertilization

[16] Refer to the data from Institute of Livestock Environmental Management (ILEM). 2016. http://goit.iptime.org/ILEM/map/map_2.jsp

practice, will bring economic benefits in long-term basis. However, one thing to consider before TSS use as a fertilizer is that the N content of TSS varies with the content of raw pig slurry. This inhomogeneity of N content is an obstacle to the use of TSS as fertilizer. Hashemi et al. (2016) reported that the addition of the bio-seed (*Nitosomonas europaea*) at a concentration of 6 x 10^5 cells mL^{-1} to human urine reduced the stabilization time of N profile in urine and decreased N loss. A method for stabilizing the N component in the unstable TSS by using nitrifying microorganisms should be performed in a subsequent study.

Table 4.5. Replacement value of chemical fertilizer in livestock manure nutrients (as of 2016; adapted from NIAS)

Factor	N	P_2O_5	K_2O
Chemical fertilizer price [17] (KRW / 20kg)	10,000	9,450	10,850
Converted fertilizer ingredient price (KRW / kg) [a]	1,087	2,779	904

[a] 46% of N in urea fertilizer, 17% of P_2O_5 in soluble phosphate and 60% of K_2O in potassium chloride

[17] Refer to the data provided by NH (Nonghyup) 2016, March. http://bukchangwon.nonghyup.com/user/indexSub.do?codyMenuSeq=6757865&siteId=bukchangwon&menuUIType=sub

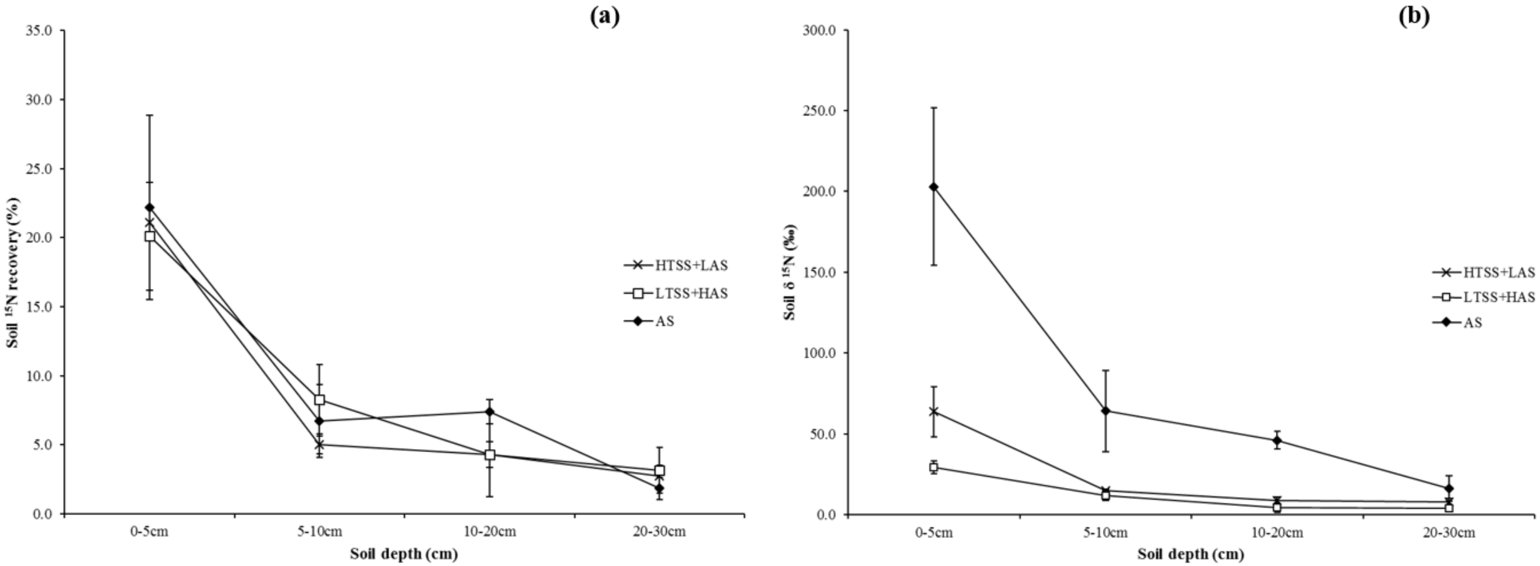
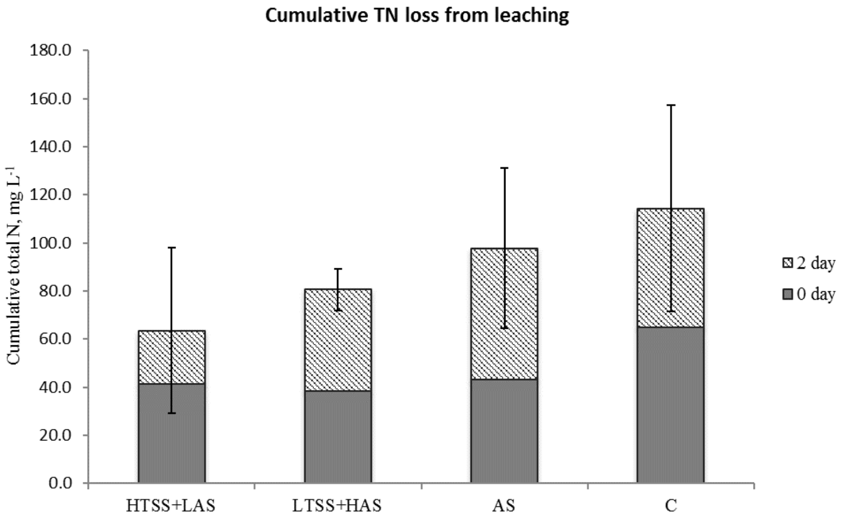


Fig 4.15. Soil ^{15}N recovery (a) and soil δ ^{15}N (b) after an application of treated swine slurry and chemical fertilizer. Error bars represent standard deviations (n=3) of the means of soil ^{15}N recovery and soil δ ^{15}N, respectively.

4.5.4. Nitrogen loss through runoff and leaching

As a result of comparing the amount of leachate collected on the day of rainfall precipitation (0 day) and the amount of leachate collected two days later, the amount of N released from the 0 day was the highest in the control (**Fig 4.16**). The least amount of N loss was occurred in HTSS+LAS treatment (63.6 mg L^{-1}). The N contents of leachate collected two days after the rainfall showed the opposite result in the AS treatment and control compared to the 0 day. The AS treatment showed more N content than the control and increased N content than 0 day. The main reason is that the control has already lost a considerable amount of N at 0 day. In the case of AS treatment, it was confirmed that N loss occurred continuously (rather increasingly) through leaching two days after the rainfall. Therefore, it is considered that the use of TSS in the saturated paddy soils in case of rainfall is a suitable N fertilization practice which can reduce the environmental load due to N loss via leaching. Considering the crop production, the use of chemical fertilizer and TSS together will be an appropriate compromise compared to chemical fertilizer only. The characteristics of N loss through runoff was shown in **Fig 4.16**. The runoff was collected 5 times over a total of 110 minutes of rain. The N tended to decrease over time, but the values were slightly unstable. The amount of N lost through runoff during the rainfall was highest in the HTSS+LAS treatment (24.4 mg L^{-1}). Especially, the rate of N loss of each treatments was increased up to 50 minutes after the start of rainfall and maintained the highest level. In the case of HTSS + LAS and C, it gradually decreased until 110 min. The AS and LTSS + HAS exhibited a slightly unstable N loss characteristic such that the N loss rate increased again in about 90 minutes and decreased to 110 minutes. About 67 to 77% of the annual water used in rice fields (irrigation water + rainfall) was discharged outside the paddy field, and this discharge contained 18% to 35% of the N used in the rice farming (Jang, 2013). However, the amount of N lost in the runoff of this study was smaller than leaching. This is the result of disagreement with the amount N loss via runoff in paddy soils reported by Jang (2013). Paddy soils used in this study were sandy loam or loam. Therefore, it had relatively low runoff and relatively high leaching characteristics (**Fig 4.17**). In sandy soils where leaching can occur relatively easily, it is recommended to reduce TSS use in order to prevent leaching non-point source pollution. In the case of rice farming, it is considered that the use of AS with TSS method can reduce the environmental load due to non-point pollution of runoff N. However, if there is rainfall after two days of fertilizer application, a certain amount of runoff N loss is unavoidable. Therefore, when using TSS, it is necessary to maintain rice paddies to prevent non-point source pollution such as a management of ridge between rice fields, irrigation management, and soil management can be suggested as an additional solution.



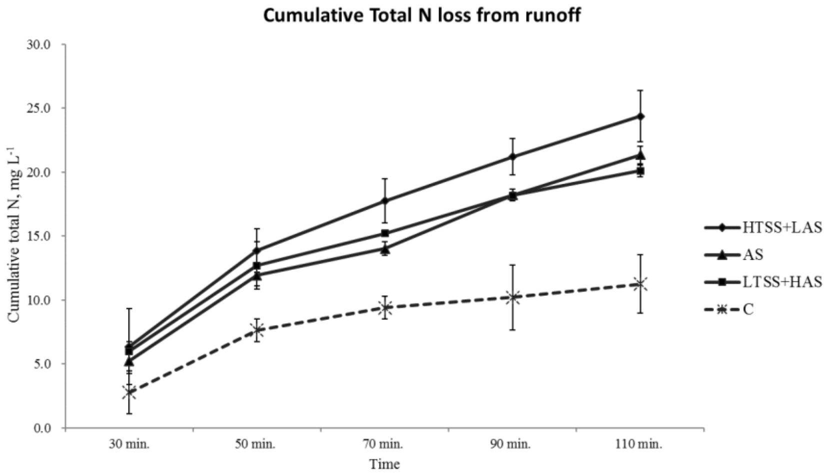


Fig 4.16. Cumulative Total N loss from runoff and leaching. Three rainfall events (June 03, August 10 and September 21) with moderate intensity (9.0 mm hr^{-1}) were applied during the experimental period. Error bars represent standard deviations (n=3) of the means of total N in the water sample

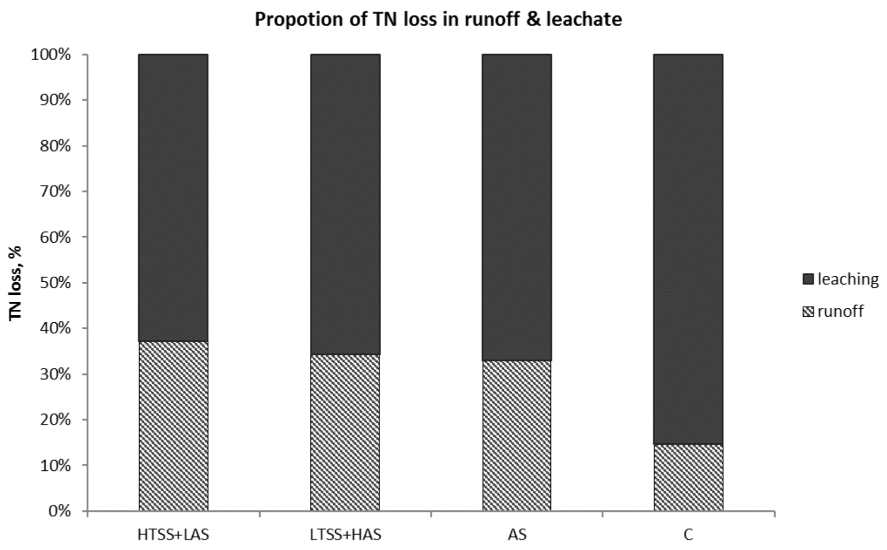


Fig 4.17. Proportion of total N loss (%) in runoff and leaching processes

During the rainfall, the amount of N loss through the leaching seems to be determined by the characteristics of the soil. When TSS was used, the amount of N lost due to leaching was smaller than that of the control. Therefore, it can be interpreted that TSS application plays a role in assisting N adsorption in the soil. Taking the cation exchange capacity (CEC) as an example, the smaller the amount of CEC, the less capacity to hold cations, and in the case of rain, the soil is more likely to flow N ions. In contrast, the CEC of the control was not effective in the adsorption of cations such as NH_4^+ in the soil. CEC has a positive relationship with the amount of organic matter. In other words, the more organic soil, the larger the CEC can be regarded as the loam soil that can provide enough nutrients to the plant. When fertilizers containing cations such as ammonium, potassium, sodium, and copper are used in low CEC soil, they cannot be utilized by plants and are lost in large quantities, adversely affecting the environment. CEC of each treatments showed a relatively low value in chemical fertilizer treatment compared to other treatments (**Fig 4.18**). Thus, it is considered that chemical fertilizer is not suitable for soils with insufficient organic matter. This is supported by the high leachate N content of paddy soils treated with chemical fertilizer only. On the other hand, TSS used treatments (HTSS+LAS and LTSS+HAS) showed higher CEC in the soil due to the organic matter content of the TSS. As is generally known, livestock manure (liquid form in this study) can be interpreted to play a role in making the loam soil. These results are consistent with the EC results (**Fig 4.19**). The EC is generally related to soil salts. The EC value is determined by the amount of water soluble organic components, that is, the amount of cations and anions.

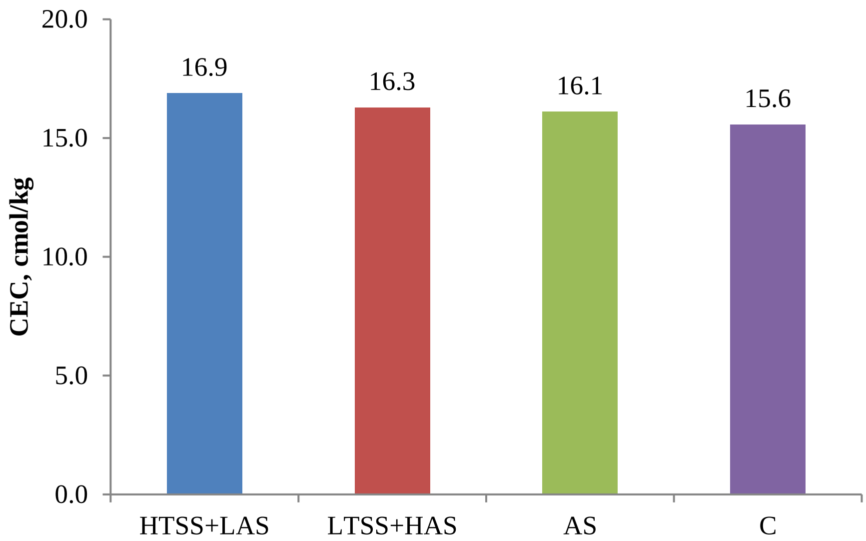


Fig 4.18. Cation exchange capacity (CEC) of each N fertilization practice

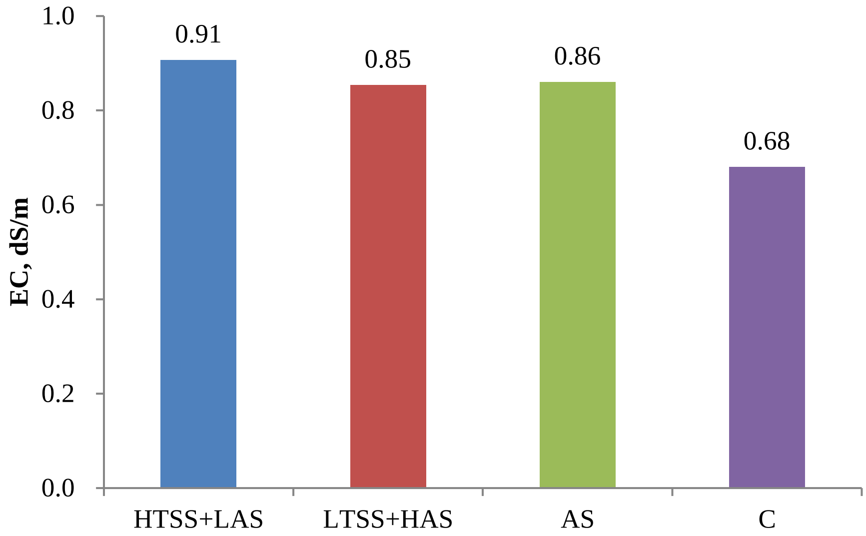


Fig 4.19. The electrical conductivity (EC) of each N fertilization practice

4.5.5. Limitations of the research

i. Although the results of this study are generally observed in similar environments, there were some potential limitations. In general, N use efficiency related to the use of chemical fertilizers and organic amendments is interpreted by converging the results over a long-term period (Pan et al., 2009; Tong et al., 2009; Saleque et al., 2004). The present study is a relatively short period compared to long-term research, only focusing on the period from the vegetative stage to harvest. In addition, the number of treatments (i.e., AS, HTSS+LAS, LTSS+HAS and control) in this study was relatively small. The research should have more treatments at different N levels to generalize the results for an appropriate N fertilization practice. For these reasons, the findings of the present study might not represent the broader rice cropping system based on this study alone. However, the results of the present study could help in determining the chemical fertilizer application rate in the next year through the precise ^{15}N analysis when mixed organic amendment (TSS) and chemical fertilizer were used.

ii. The present study assumed that the bulk density of soil was ranged from 1.1 to 1.3 g cm^{-3} depending on soil depth. In general, the bulk density of clay, silty and sandy soils is known to be about 1.1, 1.4 and 1.6 g cm^{-3}, respectively[18]. The texture of the paddy soil of this thesis corresponds to sandy loam. However, considering the characteristics of paddy soils in which saturated and unsaturated conditions are maintained for a certain period, we tried to make a difference in bulk density by soil layer. The ^{15}N recovery values of this thesis were calculated using soil bulk density. Because the bulk density estimates were used rather than the actual measurements, ^{15}N recovery variation should be considered.

iii. The surface water level of each plot was maintained at 2 cm above the soil surface. The actual height of the water in rice farming seems to be larger than 2 cm. Runoff characteristics should be interpreted to account for the application of low water heights.

4.6. Conclusion

The proper use of N fertilizer is an essential step towards achieving

[18] USDA Natural Resources Conservation Service. Soil Quality Indicators. Bulk Density. 2008.

successful rice farming. The application of chemical N fertilizer with organic amendments (such as livestock manure) has been used to improve sustainability and nutrient use efficiency. The TN uptake by rice for the AS, HTSS + LAS, and LTSS + HAS were 4.06 g m^{-2}, 3.62 g m^{-2} and 3.44 g m^{-2}, respectively. These TN values were partly influenced by the organic fertilizer N, soil N, and chemical fertilizer N. On the other hand, rice ^{15}N recovery (whole plant) only represents the amount recovered from applied chemical fertilizer, and there was a significant recovery difference ($p < 0.05$) between the AS and mixed N fertilization practices. Similar amounts of ^{15}N uptake by rice in the TSS+AS plots were obtained, indicating that the effects of the different quantities of TSS on chemical fertilizer N recovery in rice during the experimental period were not significant.

The soil ^{15}N recoveries of HTSS+LAS, LTSS+HAS, and AS in each soil layer (**Fig 4.15)** were not significantly different. Most of the applied ^{15}N was recovered in the top 10 cm of all N amended soil. We note that those N compounds may be affected by the nitrification processes occurring in the surface paddy soil regardless of the different N fertilization practices. As NH_4^+ is converted to NO_3^- through nitrification in the oxidized paddy soil surface, the increase of soil $\delta\ ^{15}N$ would be obtained because $^{14}NH_4^+$ decreased.

For the HTSS+LAS, LTSS+HAS and AS applications, the total ^{15}N recoveries were 42%, 43% and 54%, respectively. Consequently, a relatively larger amount of unaccounted for ^{15}N was observed for the HTSS+LAS treatment (58%) compared to the other N fertilization practices. Our results showed that HTSS+LAS has a good potential to improve the long-term sustainability of paddy soil-plant systems because the effects of reducing the use of chemical N fertilizer is attributed to enhancing soil quality and cost-effectiveness. When using TSS as a fertilizer source for rice farming, 70 ~ 100kg / ha is suggested as a proper amount based on N (RDA, 2010). Therefore, it is considered that the method of using TN of HTAS + LAS (80kg / ha) through split application (three-fourths of the tillering stage and one-fourth of TN at panicle initiation) is suitable for rice farming. However, N losses, especially through the coupled nitrification-denitrification process, can diminish the benefits that HTSS+LAS offers. A direct measurement of ^{15}N loss pathways (i.e., N_2O and NH_3 volatilization, leaching and surface runoff, denitrification, and immobilization) is required to estimate an accurate N balance in rice paddy soil-plant systems.

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CHAPTER 5. CONCLUSION

The indiscriminate use of chemical N fertilizers causes the long-term depletion of soil organic matter. Thus, the application of organic amendments (such as livestock manure) with chemical N fertilizer has been used as an alternative for chemical N fertilization. Livestock manure generated from swine houses is a good source of organic amendment in South Korea because of its local abundance and high productivity. The number of CAFOs have been increasing throughout the country, particularly in local areas in South Korea. On the contrary, small-scale farms with less than 1,000 pigs are typically unable to control odor complaints (including pig house, livestock manure treatment facilities, and land-application of unmature compost) and treat pig manure and tend to abandon their farm operations. This circumstance makes large-scale pig farms to survive because they can operate expensive odor reduction facilities and swine slurry treatment systems.

However, if the farm is not properly managed, CAFOs can also cause severe ammonia gas production because of the high stocking density of animals. In addition, the high amount of swine slurry production from the CAFOs are not easy to recycle as fertilizer due to physical factor (limited land area) and social factor (distrust of liquid fertilizer performance). Therefore, various livestock manure treatment systems have been tried in South Korea to solve these problems. The biological treatment of swine slurry is essential before it flows into soil-water systems because of its high organic matter (OM) and nutrient contents, which could cause serious environmental problems. These environmental issues have been highlighted, and a movement towards an environmentally friendly treatment system for swine slurry has been initiated. Currently, anaerobic digestion coupled with an aerobic/anoxic reactor is considered a more sustainable swine slurry treatment system to produce treated swine slurry. Although anaerobic digestion has been suggested as an effective solution to treat swine slurry, the anaerobically digested slurry or sludge remaining in the reactor lefts as another negative environmental influence. Thus, the combined anaerobic-aerobic approach is being implemented as an alternative to the conventional anaerobic digestion processes because it can effectively remove OM and N that are present in anaerobically digested slurry.

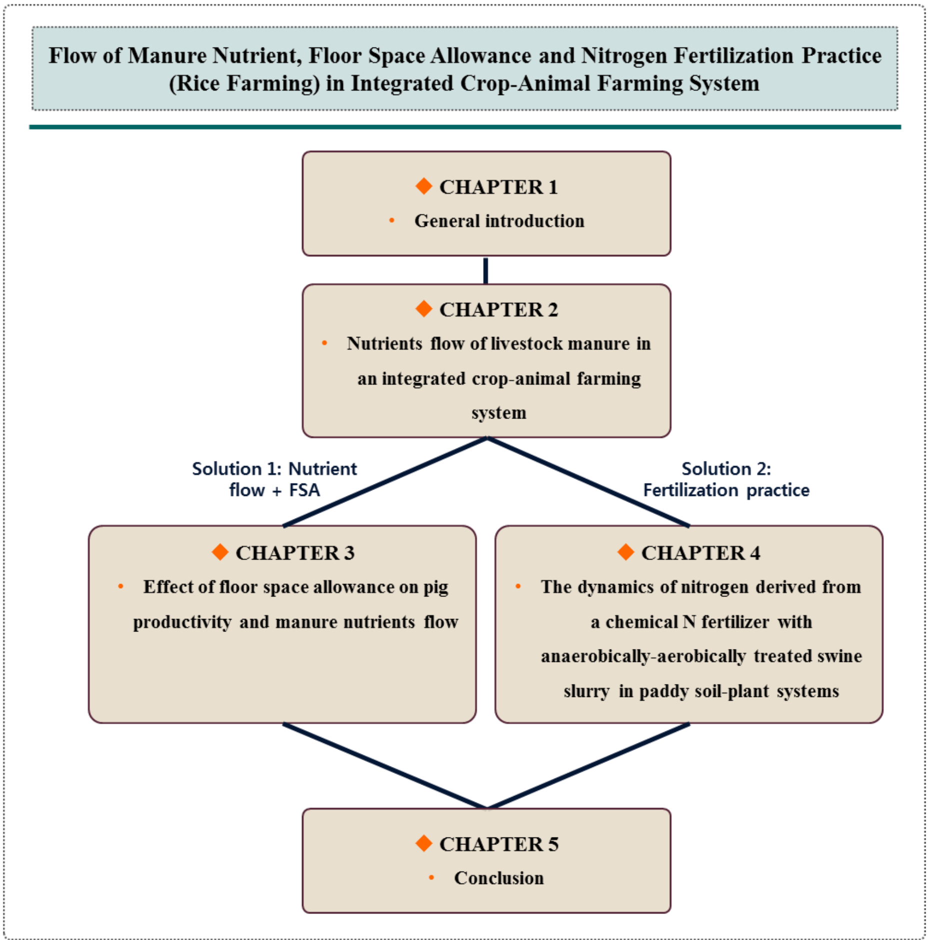

Fig 5.1. The logical flow chart of each thesis's chapters

Understanding the balance of nutrients from the generation of livestock manure to the land-application of soil-crop system is considered to be one of the important factors in establishing the integrated crop-animal farming (ICAF) system. This dissertation analyzed the livestock manure nutrient flow from the livestock manure production to land-application in South Korea (**Fig 5.1**). As a result, the following conclusions were obtained.

First, the ICAF system in South Korea is still inadequate and has been suffering from the disposal of livestock manure and resources in many areas. An investigation of the number of livestock, species, the amount of livestock manure production, the status of livestock manure treatment, urbanization rate and crop species was conducted to propose ICAF models. Jinju and Yeongcheon, where livestock manure has been discharged into the sea after treatment, relatively lacked experience in ICAF system compared to Nonsan and Namwon. As a result, both of the two regions had trouble in recycling livestock manure without treatment facilities like public recycling centers. For Jinju, where the urbanization rate was relatively high, it was considered that a two-track ICAF model would be suitable. This model promotes the use of solid and liquid fertilization facility and waste-to-energy facility together. For Yeongcheon, a decentralized public recycling facility was proposed because livestock industries were concentrated in some *myeon* and large-scale farms with more than 3,000 livestock were equipped with their own purification facilities. This system is a model that involves constructing 3 to 4 medium-sized (about 30 tons) decentralized public recycling facilities in a few *myeon*. Since the certain amount of P were supplied in excess, it is considered that the eutrophication problem of P due to the runoff of the surface water should be considered in the two regions (Jinju and Yeongcheon).

Second, the appropriate pig's floor space allowance (FSA) in terms of productivity was examined in conjunction with the livestock manure environmental problems. The average survival rate (SR) of growing pigs tended to increase with increasing FSA. Generally, fattening pigs in South Korea were being raised in a small space. Therefore, it was found that if the FSA of "0.8 ~ 1.0 m^2 $head^{-1}$" is increased to "1.1 ~ 1.27 m^2 $head^{-1}$", it contributed to raising the average SR. The days at a slaughter weight of 110 kg (d-SW) of fattening pigs also showed a tendency to decrease with increasing FSA. It is considered that the fattening pigs raised in moderately wide space (1.27 ~ 1.54 m^2 $head^{-1}$) were helpful for the increase of the growth rate due to stress reduction. A slight increase in the FSA can have a positive impact on productivity, while also solving environmental problems. As FSA increased, the amount of nutrients (N, P_2O_5 and K_2O) from livestock manure was reduced. In the case of N, 11%, 24% and 35% of N were reduced in 1.1 m^2 $head^{-1}$, 1.27 m^2 $head^{-1}$ and 1.54 m^2 $head^{-1}$, respectively, compared to the N value of 1.0 m^2 $head^{-1}$. Other nutrients (P_2O_5 and K_2O) were also reduced to similar values (ranged from 11% to 36%). According to the nutrient flow calculation method of the four regions (Namwon, Nonsan, Yeongcheon and Jinju), increasing the FSA from 1.0 to 1.54 m^2 $head^{-1}$ resulted in a reduction of surplus N up to 24.4%. In the case of P_2O_5, the surplus P_2O_5 showed a small decrease rate from at least 3.8% up to 6.4% compared with N, and regional variation was not large.

Third, a well-managed chemical N fertilization practice combined with anaerobically-aerobically treated swine slurry (TSS) is necessary to improve sustainability and N use efficiency in rice farming. Therefore, the dynamics of N derived from chemical N fertilizer with and without TSS in paddy soil-plant systems were investigated. The TN uptake by rice for the AS, HTSS + LAS, and LTSS + HAS were 4.06 g m^{-2}, 3.62 g m^{-2} and 3.44 g m^{-2}, respectively. These TN values were partly influenced by the organic fertilizer N, soil N, and chemical fertilizer N. On the other hand, rice ^{15}N recovery (whole plant) only represents the amount recovered from applied chemical fertilizer, and there was a significant recovery difference ($p < 0.05$) between the AS and mixed N fertilization practices. Similar amounts of ^{15}N uptake by rice in the TSS+AS plots were obtained, indicating that the effects of the different quantities of TSS on chemical fertilizer N recovery in rice during the experimental period were not significant. The soil ^{15}N recoveries of HTSS+LAS, LTSS+HAS, and AS in each soil layer were not significantly different. Most of the applied ^{15}N was recovered in the top 10 cm of all N amended soil. We note that those N compounds may be affected by the nitrification processes occurring in the surface paddy soil regardless of the different N fertilization practices. As NH_4^+ is converted to NO_3^- through nitrification in the oxidized paddy soil surface, the increase of soil δ ^{15}N would be obtained because $^{14}NH_4^+$ decreased. For the HTSS+LAS, LTSS+HAS and AS applications, the total ^{15}N recoveries were 42%, 43% and 54%, respectively. Consequently, a relatively larger amount of unaccounted for ^{15}N was observed for the HTSS+LAS treatment (58%) compared to the other N fertilization practices. Our results showed that HTSS+LAS has a good potential to improve the long-term sustainability of paddy soil-plant systems because the effects of reducing the use of chemical N fertilizer is attributed to enhancing soil quality and cost-effectiveness. However, N losses, especially through the coupled nitrification-denitrification process, can diminish the benefits that HTSS+LAS offers. A direct measurement of ^{15}N loss pathways (i.e., N_2O and NH_3 volatilization, leaching and surface runoff, denitrification, and immobilization) is required to estimate an accurate N balance in rice paddy soil-plant systems.

[APPENDIX]

❐ ^{15}N as a tracer of the nitrogen (N) cycle

Stable isotopes of N (^{15}N) have the same atomic number but different masses (= protons + neutrons). The atomic number of N is 7 and the neutron has 7 or 8. Thus, the atomic mass of ^{14}N is 14 and the atomic mass of ^{15}N is 15. Isotope abundance is expressed as atom% or δ scale ($\delta\ ^{15}N$).

- atom % = $100\left(\frac{15N}{15N+14N}\right) = 100\left(\frac{R_{sample}}{R_{sample}+1}\right)$
- $\delta\ ^{15}N$ (‰) =$1000\left(\frac{R_{sample} - R_{standard}}{R_{standard}}\right)$

- R_{sample}: isotope ratio of ^{15}N:^{14}N

- $R_{standard}$: 0.0036765

Atom% abundance is the percent of one isotope (e.g. ^{15}N) contribution to the total number of atoms. The ratio (‰) is to amplify the minute difference (%) between samples to facilitate numerical analysis. Most N stable isotopes exist in the form of ^{14}N (99.6%) and ^{15}N (0.4%). Stable isotope of N (N_2) in the atmosphere is 0 ‰, depending on the source of nitrogen (**Fig A1**). Because the light isotope is small in atomic weight and energy, the reaction happens faster and more. For this reason, the light isotope is enriched in the product of the reaction causing enrichment or depletion. Manure has a relatively large deviation from about 7 to 25‰. The reason for this variation is considered to be the result of external factors such as raw materials of feed and composting/liquid fertilizer method.

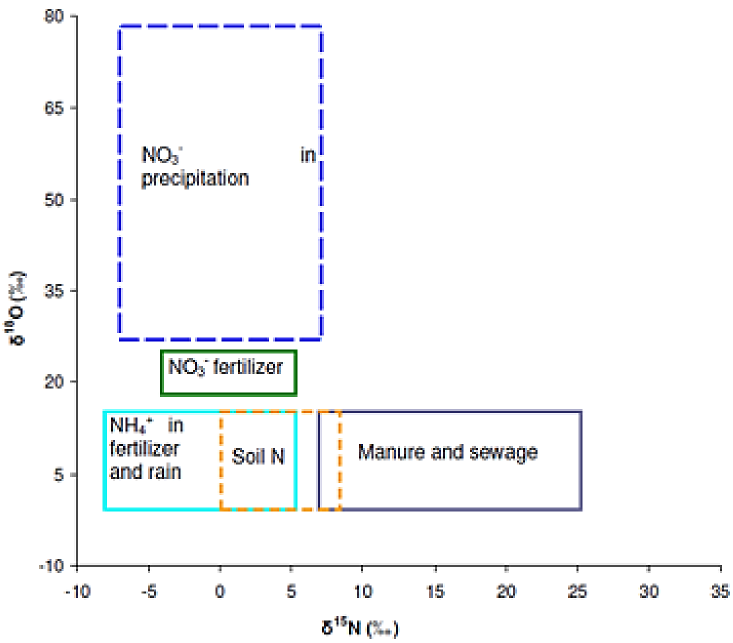

Fig A1. δ ^{15}N **(**‰) value of various nitrogen sources[19] (adapted from Kendall, 1998[20]; Xue et al., 2009[21])

The TN content of crops (rice) showed no significant difference between N fertilization practices. These TN values are the values that were partially influenced not only by artificially introduced N (TSS and AS) in this study but also by endogenous soil N. Therefore, a ^{15}N value is required to accurately determine the effect of fertilizer N (**Fig A2**). Mixed fertilization practice (TSS + AS) showed no significant difference in ^{15}N crop recovery. Compared with the amount of chemical fertilizer (AS) recovered, about 43% ~ 51% of N is considered to be derived from N in soil or TSS nitrogen. When AS and TSS are

[19] The figure is adapted from Nestler A, Bergund M, van Nevel L, Taylor P. Brief introduction into the nitrate isotope methodology and analysis. European Commission.
[20] Kendall C. Tracing nitrogen sources and cycling in catchments, in Isotope Tracers in Catchment Hydrology, edited by C. Kendall and J.J. McDonnell, chap. 16, pp. 519-576. Elsevier, Amsterdam, Netherlands, doi:10.1016/B978-0-444-81546-0.50023-9.
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used together, the absorption of AS N is presumed to be increased, which may be an effect of microbial activation.

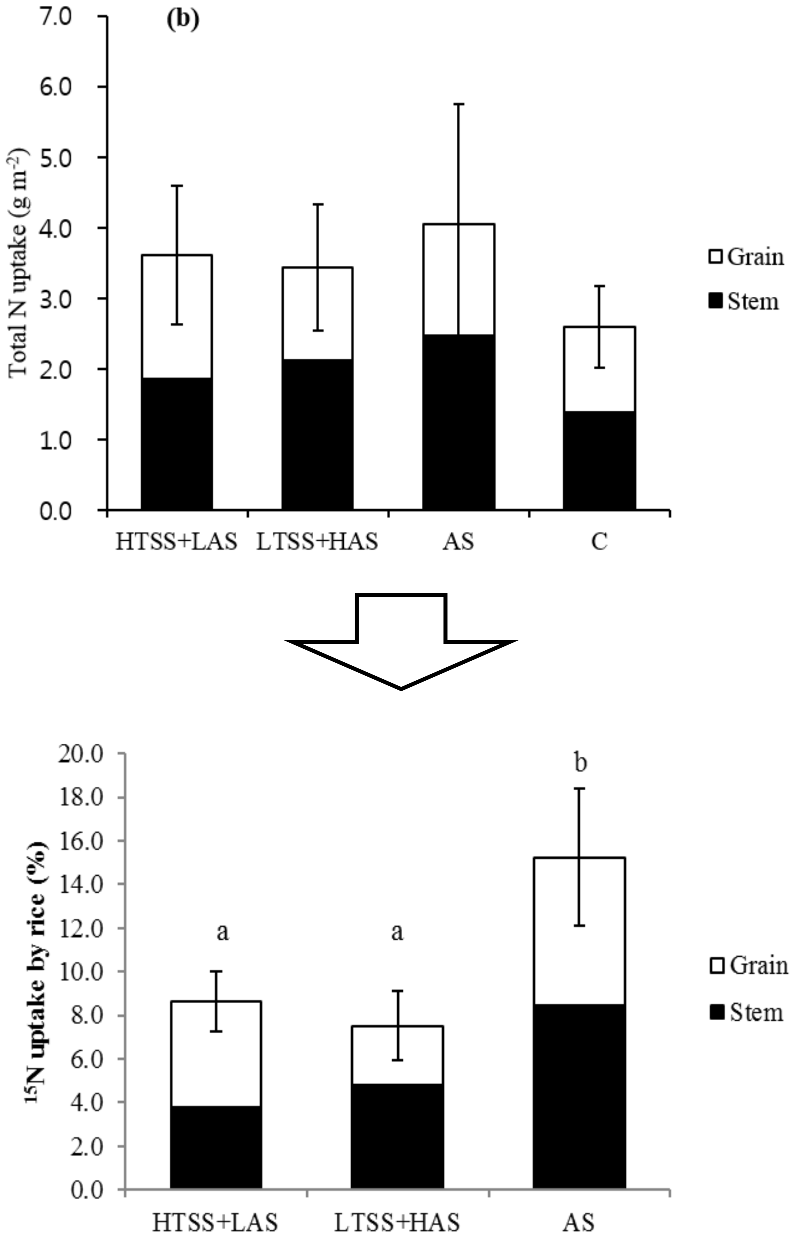

Fig A2. TN uptake by rice (upper) and rice ^{15}N recovery (below) after application of treated swine slurry and chemical fertilizer

❒ Isotope ratio mass spectrometry analysis

The atom % ^{15}N and TN values of the dried soil samples were analyzed via the combustion method using an elemental analyser (EA) linked to a stable isotope mass spectrometer (Isoprime-EA, Micromass, UK). The average isotope ratio measurement begins by placing the sample in a tin capsule. Sample capsules are treated in a combustion furnace, where helium gas acts as a carrier to convert nitrous oxide into N_2 gas. Excess O_2 is removed during this process. In the next step, moisture is removed using a chemical trap. After that, CO_2 and N_2 are separated by gas chromatography (**Fig A3**).

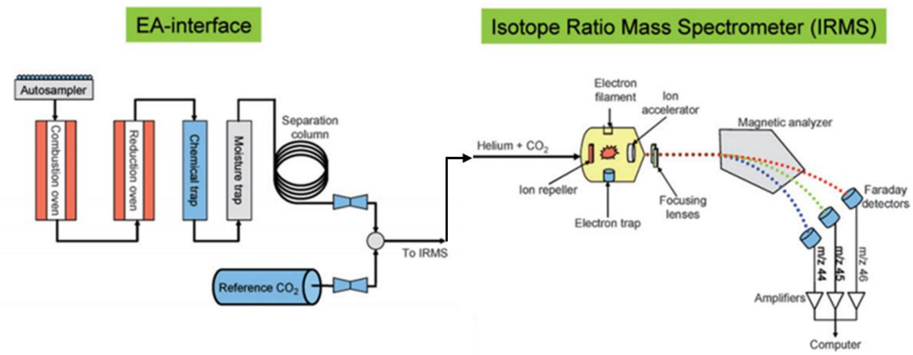

Fig A3. Schematic diagram of EA-IRMS analysis[22] (adapted from Muccio and Jackson, 2009)

Effluent from EA is sent to IRMS. The isotopic ratios were reported in standard notations with respect to atmospheric N gas (N_2) as the working standard (Ozteck, USA; $\delta^{15}N$ value of – 0.22‰). The accuracy (<1.0‰) and reproducibility (<0.5‰) of the measurements were verified using a reference material (IAEA-N3, KNO_3) from the International Atomic Energy Agency.

[22] Muccio Z, Jackson GP. Isotope ratio mass spectrometry. Analyst. 2009; 134: 213-222.

❒ Limitations of rainfall simulator and greenhouse

The large standard deviation of the crop biomass yield is estimated to be due to the inhomogeneous solar incidence received by the lysimeter at the rear of the greenhouse (**Fig A4**). Uneven rainfall occurred due to nozzle clogging in the rainfall simulator. It affected the standard deviation of runoff and leaching data.

Fig A4. The whole view of greenhouse and rainfall simulator (nozzle part)

요약(국문초록)

경축순환농업(ICAF)은 축산농가와 경종농가 사이에서 발생하는 부산물을 농업 시스템 내부에서 다시 활용함으로써 지속가능한 농업환경 및 생태계를 구축하는 관리체계를 의미한다. 가축분뇨의 발생부터 작물-토양 시스템에 환원되기까지의 양분의 균형을 이해하고 활용하는 것은 경축순환농업을 이해하기 위한 중요한 요인 중 하나로 판단된다. 하지만 시스템 내에서는 복잡한 과정이 서로 연계되어 있어 각 요인들의 관계를 이해하고 균형점을 찾아내는 것은 쉽지 않다. 따라서 본 학위논문은 경축순환농업 체계 내 가축분뇨 발생, 처리, 토양환원에 이르기 까지 각 단계별 발생 양분흐름 및 동태를 분석하였다. 이후 생산성을 고려한 적정 사육면적을 제시하여 경축순환농업 체계에서의 적절한 돈분뇨 양분활용 가능성을 알아보았다. 또한 화학비료와 돈슬러리 처리수의 적정 활용방법을 제안하고자 하였다. 그 결과 다음과 같은 몇 가지 결론을 얻을 수 있었다.

첫째, 우리나라의 경축순환농업 체계는 아직 미비하여 가축분뇨 처리 및 자원화에 애로를 겪고 있는 지역을 쉽게 찾아볼 수 있었다. 따라서 상대적으로 활성화된 지역(논산과 남원)의 경축순환농업현황 및 수준을 파악하고 경축순환농업 체계를 면밀히 검토하여 해당 시스템이 부진한 지역(영천과 진주)의 특성을 고려한 경축순환농업 체계 방안 및 모델을 모색할 필요가 있었다. 진주지역은 도시화 비율이 상대적으로 높은 특성이 있어 경축순환농업 모델은 퇴·액비시설과 에너지화 시설을 공동추진하는 two-track 모델이 적합한 것으로 판단하였다. 영천 지역의 경우, 일부 면 단위에 축산산업이 집중되는 현상을 보이고 있고, 3,000두 이상의 규모가 큰 양돈 농장은 정화처리시설을 개별적으로 갖추고 있어 분산형 공동자원화시설을 제시하였다. 하지만 시나리오 예측에 따르면, 해당 지역

의 가축분뇨의 자원화율은 증가했지만 양분의 과잉공급은 줄어들지 않았다. 가축분뇨 작물의 양분요구량과 양분의 토양 환원량을 고려하면 연간 질소 113 kg ha^{-1}과 인산 146 kg ha^{-1}의 과잉공급이 예상되엇다. 진주의 경우 연간 인산 12 kg ha^{-1} 가 농경지에 과잉 공급 될 것으로 나타났다. 이렇듯 지역 특성을 고려한 경축순환농업 시스템이 구축 되더라도 해당지역의 농경지 양분 수용능력을 초과하는 대량의 가축분뇨 발생 및 무분별한 화학비료 사용은 여전히 문제로 남는다.

둘째, 적정수준의 사육면적 관리는 대규모 양축관리에서 가장 중요한 요인 중 하나로 판단된다. 특히, 국내 양돈은 좁은 공간에서 돼지를 되도록 많이 사육함으로써 생산의 극대화를 통한 수익 창출 방식을 선호하고 있다. 결과적으로 농장주(생산자) 입장에서는 일정수준의 생산성을 보장받게 되는 것이 사실이나, 동물, 농장 관리자, 농장 주변의 주민들은 부정적인 영향을 피할 수 없다. 본 학위논문의 연구에서 비육돈은 조사범위 내에서 단위사육면적이 증가함에 따라 비육돈의 평균 육성율도 증가하는 경향을 보였다. 일반적으로 우리나라에서 비육돈은 밀사 관리되고 있어 기존 단위사육면적 기준인 "0.8~1.0m^2/두" 에서 "1.1~1.27m^2/두" 로 넓히면 평균 육성율을 제고(提高)하는데 기여하는 것으로 나타났다. 또한 비육돈의 평균 출하일은 단위사육면적이 증가함에 따라 줄어드는 경향을 보였다. 이러한 현상은 전술한 분석과 일관되는 것으로 적당히 넓은 공간(1.27~1.54m^2/두)에서 사육된 비육돈은 스트레스 감소로 인한 증체율 증가에 도움이 되는 것으로 판단된다. 두당 사육면적을 조금만 늘리면 생산성 증가라는 긍정적 효과를 볼 수 있고, 동시에 환경적 문제점들도 해결할 수 있는 것으로 나타났다. 사육면적을 1.0, 1.1, 1.27, 1.54m^2/두로 넓히면 0.8m^2/두 대비 각각 20%, 27%, 37%, 48%의 질소 저감효과를 보였다. 인과 칼리 역시 비슷한 저감율을 보였다. 가축분뇨 양분흐름 산정법을 4지역(남원, 논산, 영천, 진주)에 적용하여 산정한 결과 1.54m^2/두에서 0.8m^2/두 대비 과잉

질소 약 60%가 저감되었다. 인산의 경우 사육면적이 증가함에 따라 5%~16%의 저감율을 보여 진주를 제외하고 지역별 편차는 크지 않았다. 진주의 인산 저감율은 61%로 가장 높았다. 가축유닛(LU)당 비교적 넓은 경작지 면적에서 영향을 받은 것으로 판단되었다.

셋째, 벼농사에서 적절한 질소비료의 사용은 농사의 성공여부와 직결되는 필수적 요인에 해당한다. 화학비료와 함께 유기질비료(가축분뇨)를 사용하는 질소시비법은 지속가능한 농업의 일환으로 사용되고 있다. 돈슬러리 처리수와 화학비료를 혼용 시비할 경우 화학비료의 혼합비율에 상관없이 일정한 무기질 질소 흡수율을 보이므로 화학비료는 3:1 비율보다 적게 사용하는 것이 바람직하다. 산화된 논토양 표토층은 질산화 과정이 일어나면서 NH_4^+가 NO_3^-로 전환되고, $^{14}NH_4^+$가 감소한 만큼 토양 $\delta^{15}N$ 수치는 증가한 것으로 예측되었다. 총 질소회수율(작물+토양)은 처리수와 화학비료가 3:1 비율인 혼합처리구(HTSS+LAS), 처리수와 화학비료가 1:2 비율인 혼합처리구(LTSS+HAS), 화학비료 단독처리구(AS)에서 각각 42%, 43%, 54%을 보였다. 화학비료 혼합량은 줄이고 돈슬러리 처리수 비율은 높여 사용하는 질소시비법이 지속가능성, 비용절감 측면에서 권장되나 논토양의 질산화-탈질작용에서 기인하는 질소 소실율이 높아질 수 있다는 점을 고려해야 한다.

본 학위논문의 서론에서는 우리나라의 전반적인 축산현황 및 문제점이 기술되었다. 본문에 해당하는 2장에서는 가축분뇨 양분의 동태를 알아보기 위해 개별농가별 경축순환농업을 실행하고 있는 우리나라 지역 두 곳과 (영천과 진주)과 공동자원화시설을 통해 위탁처리하고 있는 두 곳 (남원과 논산)을 선정하여 가축분뇨의 농경지 환원 시 잠재적 양분 공급량 및 작물의 양분 요구량에 관한 관계를 분석하였다. 3장은 2장의 연구내용과 연계하여 생산적 측면과 환경적 측면 모두를 만족시키는 적정 돼지사육면적을 검토하였다. 4장은 2장의 가축분뇨 발생 및 처리공정의 다음 단계에 해당하

는 농경지 환원에 관하여 다루었으며 논토양에서 화학비료+혐기소화 돈슬러리 처리수 혼용 시비법에 따른 질소거동을 알아보았다. 관행 가축분뇨 토양환원 연구가 주로 가축분뇨 퇴·액비의 비료적 가치 및 작물 생산성에 기반을 두었다면 본 논문은 중질소를 활용하여 보다 정확한 토양-작물계의 질소거동을 분석하여 적절한 가축분뇨와 화학비료 혼용시비법을 제안하는 차별성을 지닌다. 특히, 혐기성 발효와 생물학적 수처리공정을 거친 돈분뇨를 논토양에 환원함으로써 가축분뇨의 신재생 에너지화 후속 처리과정에 관한 연구라는 사실 역시 본고의 학문적 기여라 하겠다. 앞으로 본 학위논문의 직/간접적인 연장선상에서 논토양 뿐만 아니라 시설원예, 밭, 과수, 초지 등 다양한 경종분야의 가축분뇨 토양환원에 관한 가이드라인이 만들어 지길 기대한다.

주요어 : 가축분뇨, 양분수지, 사육면적, 경축순환농법, 안정성 동위원소 중질소, 가축분뇨 처리수

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