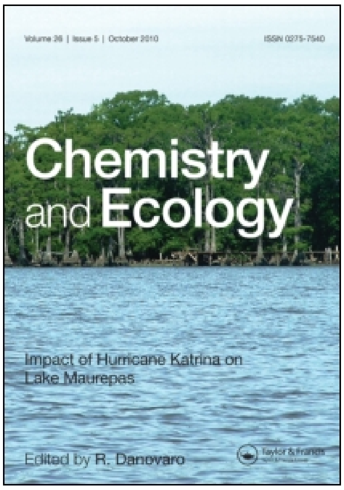

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Effects of anaerobically digested pig slurry application on runoff and leachate

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Effects of anaerobically digested pig slurry application on runoff and leachate

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Land application of the effluent of anaerobically digested pig slurry is becoming common practice in integrated crop and livestock farming. However, the loss of nutrients, in particular nitrogen and phosphorus, within the water bodies is still a main concern of this practice. The objective of this study was to evaluate nitrogen and phosphorus losses in runoff and leachate for four application rates of anaerobically digested pig slurry (25.0, 70.1, 140.2, and 210.3 kg N ha^{-1}) for Chinese cabbage grown in lysimeters. Simulated rainfall events, occurring one week after slurry application, were used to generate runoff. The yields of nutrients, biochemical oxygen demand and chemical oxygen demand in runoff and leachate increased linearly or logarithmically with slurry application rates. A combination of long rainfall duration (90 minutes) and lower rainfall intensity (33.3 mm hr^{-1}) induced higher nutrient concentrations in the runoff, but lowered the nitrogen concentration in the leachate. The application doses of anaerobically digested pig slurry before sowing, nutrient supplementation and fertilisation time management are the key factors in reducing nutrient contamination of water courses.

Keywords: anaerobically digested pig slurry; nutrients loss; runoff; leachate; rainfall simulator

1. Introduction

The worldwide swine industry has been developing rapidly over the last two decades. The industry consisted of a population of 798 million pigs in 2007 and produces approximately 1090 million tons of pig slurry per year [1]. The cost of disposal of pig slurry, however, continues to increase, and is becoming a large problem for the swine industry. One solution that is gaining popularity is the processing of pig slurry in an anaerobic digester for biogas. In addition to its popularity, the anaerobically digested pig slurry (ADS) has been shown to be an effective nitrogen source for crop production [2]. However, ADS should be managed on the basis of its nutrient value to maximise its fertiliser efficiency and to avoid negative environmental impact. Adequate ADS application can help to achieve satisfactory crop yields. As with raw pig manure and mineral fertilisers, nitrogen, phosphorus and even organic pollutants in ADS can be washed out by rainfalls to surface water, and/or can leach out of the crop root zone, thereby contaminating the ground water. Several

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studies have investigated the potential pollution threat of land application of raw pig slurry [3–5], but only a few studies have examined environmental pollution due to ADS application. Little information is available concerning nutrient availability for crops, ammonia and odour emission, or soil property changes with ADS land application [6–8]. Nonetheless, valuable information can be obtained by examining the effects of ADS application on runoff and leachate.

However, it is challenging to estimate the pollution potential of ADS application, because the processes involved in nutrient and pollutant movements are sensitive to management practices, soil properties, and climate characteristics. In particular, the rainfall intensity plays an important role on nutrient transport in water [9]. Rainfall intensity can significantly affect surface runoff generation, as well as the concentrations of nutrients in the runoff [10]. A large and growing body of research has made use of small plots subjected to simulated rainfall to assess the influence of source factors on nutrients in surface runoff [11,12]. These studies have provided a quantitative insight into the role of individual source variables (soil P, applied manure, and mineral fertiliser P) in nutrient transport via surface runoff. However, there is limited information available about the interaction between rainfall intensity and nutrient loss from anaerobically digested pig slurry application.

The objective of this study was to investigate the effects of three ADS application rates and two rainfall intensities (typical storms in summer and autumn) on cabbage yield, and the transport of nutrients and pollutants to runoff and leachate.

2. Materials and methods

2.1. *Experimental design*

The experiment was conducted in 2007 at the experimental swine farm of Seoul National University, South Korea, using eight drainage lysimeters (Figure 1) of 1.44 m^2 in area and 0.6 m in depth. Lysimeters were filled with sandy loam soil (637 g kg^{-1}sand, 290 g kg^{-1} silt, 73 g kg^{-1} loam); the soil properties are given in Table 1. Lysimeters were successively cropped with Chinese cabbage for two years before the beginning of this experiment. Four treatments were designated with two replicates each. The amount of ADS applied was 41.7 Mg ha^{-1} for treatment ADS1, 83.3 Mg ha^{-1} for treatment ADS2, and 125.2 Mg ha^{-1} for treatment ADS3. In the ADS0 treatment, the amount of ADS applied was 14.9 Mg ha^{-1} before plant seeding and with no side-dressing fertilisation.

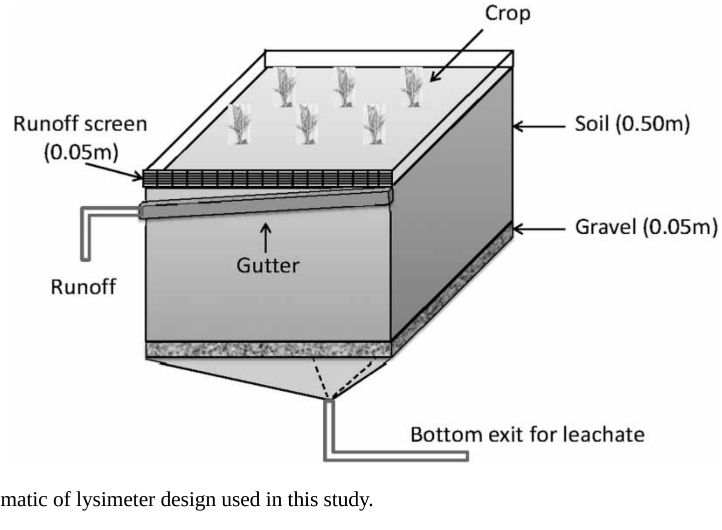

Figure 1. Schematic of lysimeter design used in this study.

Table 1. Upland soil properties.

Characteristics	Value
Texture	Sandy loam
Sand (g kg^{-1})	637
Silt (g kg^{-1})	290
Loam (g kg^{-1})	73
pH (soil : water = 1 : 5)	6.95
Total N (g N kg^{-1})	0.72
Total P (g P kg^{-1})	0.51
Organic matter (g kg^{-1})	23.5

The anaerobically digested pig slurry was obtained from an anaerobic digester operated for biogas production located on the same swine farm as the experiment was conducted. The pig slurry was anaerobically digested for 30 days under mesophilic anaerobic conditions, and collected as the effluent from the digester. The physicochemical properties of ADS and the ADS application rate are presented in Tables 2 and 3, respectively.

The ADS2 rate of 140.2 kg N ha^{-1} was chosen to evaluate the effect of a single ADS application that satisfied the nitrogen requirement of Chinese cabbage. This amount of N is greater than the recommended N fertilisation rate, but it is the normal rate applied by farmers in the field. The ADS0 rate of 25.0 kg N ha^{-1} was selected for evaluation of the basal fertiliser application rate. The ADS1 rate of 70.1 kg N ha^{-1} was selected to evaluate the application of ADS in spring before plantlet transplantation. The higher rate of 210.3 kg N ha^{-1} in ADS3 was selected to evaluate potential detrimental environmental effects when fields are used as waste disposal landfills for ADS effluent in areas located with large scale anaerobic digesters.

Table 2. Physicochemical properties of anaerobically digested pig slurry.

Characteristics	Value
Specific weight, g L^{-1}	1.018
pH	7.35
Dry matter, g DM kg^{-1}	7.48
Organic matter, g OM kg^{-1}	5.25
Ammonium N, g N kg^{-1}	1.06
Total N, g N kg^{-1}	1.68
Total P, g P kg^{-1}	0.26

Table 3. Fertilisation rate and measured runoff/leachate ratio (R/L) for each treatment.

		Fertilisation			
		Basal	Side-dress	Total	
Treatments	Nutrients		(kg ha^{-1})		RL
ADS0	N	25.0	0	25.0	1.1
	P	3.8	0	3.8	
ADS1	N	25.0	45.1	70.1	0.9
	P	3.8	6.9	10.7	
ADS2	N	25.0	115.2	140.2	0.9
	P	3.8	17.6	21.4	
ADS3	N	25.0	185.3	210.3	1.1
	P	3.8	28.3	32.1	

To study the soil with high percolating ability, a target runoff/leachate ratio (R/L, defined as the ratio of the amount of runoff water to that of leaching water) of 1.0 was selected for all of the treatments. The measured R/L in the experiment period ranged between 0.9 and 1.1 for the four treatments.

Anaerobically digested pig slurry was uniformly spread by a water sprayer. Chinese cabbage was transplanted two weeks after the basal fertiliser application at a density of 83,000 plants ha^{-1}.

2.2. *Rainfall simulation*

The rainfall simulator, designed by the Animal Environment and Bio-Engineering Laboratory of Seoul National University, was set up to conduct a series of rainfall simulations. The source water for the simulation was tap-water, which was stored in a 2.0 m^3 tank for two weeks before rainfall application to remove hypochlorite. Three rainfall events (shown in Table 4) representing storms in July, August and September, the rainy months in South Korea, were applied in this experiment. The first rainfall event was conducted one week after the first application of ADS on 25 October. The rainfall duration was 90 minutes, with a high intensity of 50.0 mm hr^{-1}. Two weeks later, by which time the soil moisture had decreased to the initial level, the second rainfall event was conducted with the same intensity of 50.0 mm hr^{-1} for 90 minutes. After another two weeks, the last rainfall event was scheduled on 22 November, with a lower intensity of 33.3 mm hr^{-1} for 90 minutes.

2.3. *Sampling and sample analysis*

The plants were harvested on 7 December 2007, and three whole plants were taken from each lysimeter for the analysis of total nitrogen and total phosphorus by the Kjeldahl method and ammonium molybdate spectrophotometric method [13], respectively.

The soil was sampled on 27 September 2007 (before basal fertilisation), and 7 December 2007 (after harvesting). Three samples per lysimeter were taken at 0∼20 cm depth. To examine the effect of ADS application on nutrient concentrations in surface soil, nitrate nitrogen and bio-available phosphorus were analysed by Subbiah and Asija's method [14] and Olsen's method [15], respectively.

Runoff was collected through a gutter attached to the down-side of the lysimeter (Figure 1). Leachate was collected in a 200 litre plastic container that was connected by a tube to the bottom exit of each lysimeter. The volumes of runoff and leachate were measured after each rainfall event, and runoff and leachate samples were taken for analysis of nutrient concentrations. Runoff water samples from each lysimeter were collected two hours after the rainfall event, and leaching water samples were collected four days after rainfall application. The water samples were analysed for biochemical oxygen demand (BOD$_5$), chemical oxygen demand (COD$_{Cr}$) and nutrients including total nitrogen, nitrate nitrogen, ammonium nitrogen, total phosphorus, and dissolved reactive phosphorus [13].

Table 4. Three simulated rainfall events.

	1st	2nd	3rd
Date	25 Oct	8 Nov	22 Nov
Intensity (mm hr^{-1})	50.0	50.0	33.3
Duration (minute)	90.0	90.0	90.0
NO_3^--N (mg l^{-1})	1.3	1.2	1.3
PO_4^{3-}-P (mg l^{-1})	0.03	0.03	0.03

2.4. *Data analysis*

Mass loads of nutrients, BOD_5, and COD_{Cr} in runoff and leachate were calculated by multiplying water volume with the corresponding concentration. Analysis of variance (ANOVA) was conducted for BOD_5, COD_{Cr} and nutrient yields to determine the treatment effects. When the ANOVA indicated a factor, e.g. N fertilisation rate, was significant ($p < 0.05$), for a specific rainfall event, responses were regressed against this factor.

3. Results and discussion

3.1. *Nitrate N and available P in the surface soil*

The average nitrate concentration of the soil across all treatments for the $0 \sim 20$ cm depth was 26 mg NO_3^--N kg^{-1} at the beginning of the experiment. At the end of the cropping period, there were significant differences among treatments, as indicated in Table 5. After harvest, the NO_3^--N concentration decreased to 15 mg NO_3^--N kg^{-1} in the ADS0 treatment due to ammonia emission from the reduction of nitrate and nitrite, crop N uptake and nitrate leaching. Although the difference was not significant between ADS1 and ADS2 treatments, both treatments produced higher nitrate concentrations in the soil than ADS0. The highest NO_3^--N concentration was found in the soil of the ADS3 treatment. Application of high nitrogen rates resulted in producing higher nitrate concentration in the surface soil at the end of the crop season. In the study of Daudén et al. [16], however, the nitrate contents in the soil were not significantly different between treatments in which different rates of pig slurry were applied. Possible reasons for these conflicting results may be the different experiment periods (6 months in Daudén et al.'s study vs 3 months in our study) and different crop types (corn vs Chinese cabbage).

Before crop transplantation, available P among the treatments in the $0 \sim 20$ cm depth soil was 59 mg P kg^{-1} on average. At both dates of transplant and harvest, there were no significant differences in ADS0 treatment, and ADS1 treatment as well. But the available P concentrations increased 13, 25 mg P kg^{-1} in ADS2 and ADS3 treatments respectively. Esteban and John [17] also found that application of anaerobically digested swine slurry increased the available P in soil.

Table 5. Soil NO_3^- N concentration in the $0 \sim 20$ cm depth.

		Nitrate-N (mg NO_3^--N kg^{-1})	
Treatments	Fertiliser rate (kg N ha^{-1})	Before transplant	After harvest
ADS0	25.0	25a[a], A[b]	15a, B
ADS1	70.1	26a, A	32b, B
ADS2	140.2	23a, A	35b, B
ADS3	210.3	28a, A	51c, B
		Available P (mg P kg^{-1})	
	Fertiliser rate (kg P ha^{-1})	Before transplant	After harvest
ADS0	3.8	58a[a], A[b]	59a, A
ADS1	10.7	60a, A	67b, A
ADS2	21.4	58a, A	71b, B
ADS3	32.1	59a, A	84c, B

Notes: [a]At the same sampling date, the numbers in the column followed by similar lowercase letters indicate no statistically significant difference among the treatments at the 0.05 level. [b]At the same treatment, the numbers in the row followed by similar uppercase letters indicate no statistically significant difference among the treatments at the 0.05 level.

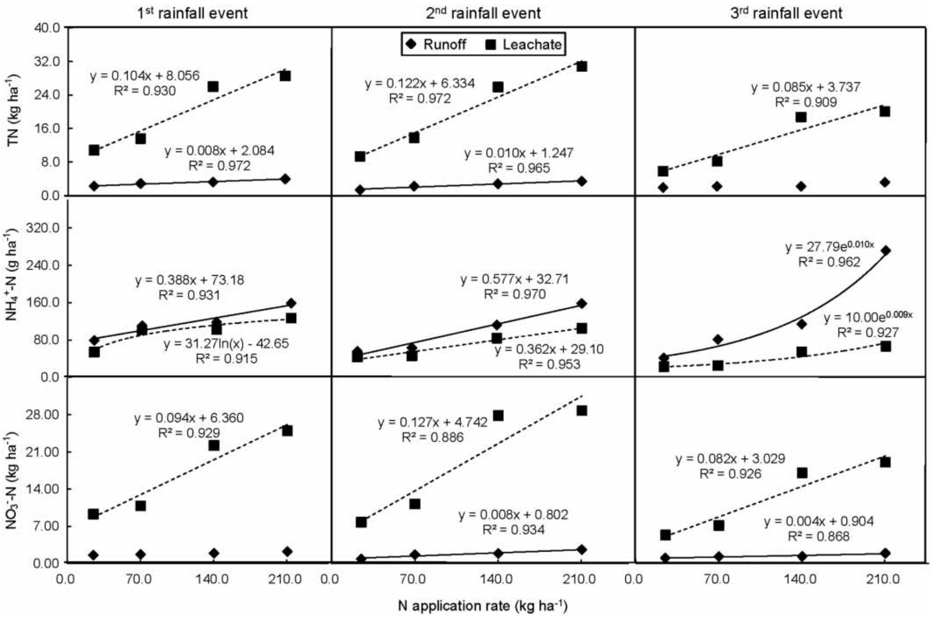

Figure 2. The contents of TN, NH_4^+-N and NO_3^--N as a function of N application rate for each rainfall event. Statistical significances for treatment effects are indicated in Table 6. Significance for the regression fit was set to the 0.05 probability level.

3.2. *Nitrogen in the runoff and leachate*

To evaluate nitrogen loss, total nitrogen (TN), nitrate-nitrogen (NO_3^--N), and ammonium nitrogen (NH_4^+-N) were evaluated in the runoff and leachate. The results are shown in Figure 2, with the statistical significance of treatment effects given in Table 6. The differences of nitrogen contents between rainfall events could be attributed to several factors, including rainfall intensities, soil conditions and crop conditions. In all three rainfall events, the effect of ADS application rate was significant, with the exception of NO_3^--N content in the 1st rainfall event and TN in the 3rd event. Before the 1st event, the soil was dry and freshly tilled and the soil surface was disturbed. This was expected to increase the dissolution of nitrate in the runoff under heavy rainfall conditions, and thereby reduce differences in the nitrate content among the treatments. The low rainfall intensity might reduce differences of the contents of TN among all of the treatments in the 3rd rainfall event. The regression equations (when significant) were fit to the fertiliser N rate responses. In the runoff, significant linear relations were established between the contents of TN, NO_3^--N, NH_4^+-N and N application rate, except NH_4^+-N content in the 3rd rainfall event, which was exponentially related with the N application rate. A result similar to this was reported by Mihara and Suzuki [18]. In Mihara and Suzuki's study, the ammonium nitrogen concentration in the runoff also increased after several rainfall events. Gangbazo et al. [19] also found that NH_4^+-N loss increased from autumn to winter, while the 3rd rainfall event occurred in winter in our study. These results suggest that changes in temperature and moisture conditions of soil enhance ammonification and leaching of nitrate nitrogen, thereby affecting the concentration of ammonium nitrogen in surface runoff.

In the leachate, the contents of TN and NO_3^--N were much higher than those in the runoff. Many studies [20,21] also reported that nitrate concentration in leachate was higher than that in the runoff. Because there is little tendency for the NO_3^- anion to be absorbed by soil colloids, nitrate becomes susceptible to diffusion and mass transport with soil water [22]. In this study, the

Table 6. Partial ANOVA for significance of ADS application rate on the contents of TN, NO_3^--N, NH_4^+-N, TP, DRP, BOD_5 and COD_{Cr} in the runoff and leachate.

Water qualities		1st rainfall	2nd rainfall	3rd rainfall
		p value		
Runoff	TN	0.007	<0.001	0.024
	NO_3^--N	0.099	<0.001	<0.001
	NH_4^+-N	0.006	<0.001	<0.001
	TP	<0.001	<0.001	0.006
	DRP	0.003	0.001	<0.001
	BOD_5	<0.001	0.139	<0.001
	COD_{Cr}	<0.001	<0.001	0.478
Leachate	TN	<0.001	<0.001	<0.001
	NO_3^--N	<0.001	<0.001	<0.001
	NH_4^+-N	<0.001	<0.001	<0.001
	TP	0.313	0.324	0.079
	DRP	0.023	0.028	0.017
	BOD_5	<0.001	<0.001	<0.001
	COD_{Cr}	0.007	0.005	0.003

runoff/leachate ratio was 1.0, and the nitrate concentration in the leachate was 3–8 times higher than that in the runoff. Nitrate was the predominant form of nitrogen in the leachate and accounted for 80 $\sim$ 90 % of total nitrogen, making the TN content of the leachate higher than that in the runoff. However, the NH_4^+-N content in the leachate, which was only 0.013 $\sim$ 0.127 $kg\,ha^{-1}$, was lower than that in the runoff (0.032 $\sim$ 0.277 $kg\,ha^{-1}$). Ammonium is unlikely to be leached from soil because of adsorption and fixation processes in the soil [22]. Furthermore, NH_4^+ was generally not present in the soil solution of soil samples tested under laboratory conditions [23]. In this study, the NH_4^+-N content was almost 1% of the nitrate content in the leachate. Interestingly, however, the NH_4^+-N content was greatly affected by the rainfall events: in the 1st rainfall event, the NH_4^+-N content in the leachate increased logarithmically with the applied fertiliser NH_4^+-N content; in the 2nd event, this relationship became linear; while in the 3rd event, the relationship became exponential. Thus, after several rainfall events, the NH_4^+-N content in the leachate became more sensitive to the fertilisation rate.

3.3. *Phosphorus in the runoff and leachate*

Total phosphorus (TP) and dissolved reactive phosphorus (DRP) were analysed in the water samples of runoff and leachate. Figure 3 shows the results of phosphorus and Table 6 includes the statistical significance of the treatment effects. DRP accounted for 20% and 85% of TP in the runoff and leachate respectively. Both TP and DRP contents in the runoff showed a significant treatment effect for all three rainfall events, but this did not hold true for the TP or DRP contents in the leachate. P in the runoff was linearly related with the P application rate. As P transport through surface runoff from agriculture is affected by soil P status [24], and the soil available P was significantly affected by the P application rate (Table 2). Therefore, P loss in runoff increased from ADS0 to ADS3 treatment. Because of high P sorption capacity in subsoil [25], the treatment effects on P losses in the leachate were negligible.

The TP and DRP yields in runoff were the greatest in the 1st rainfall event among all treatments. The surface soil was loosened during the transplantation which made the soil more susceptible to being removed via runoff. This effect, coupled with the highest runoff volume, resulted in the 1st

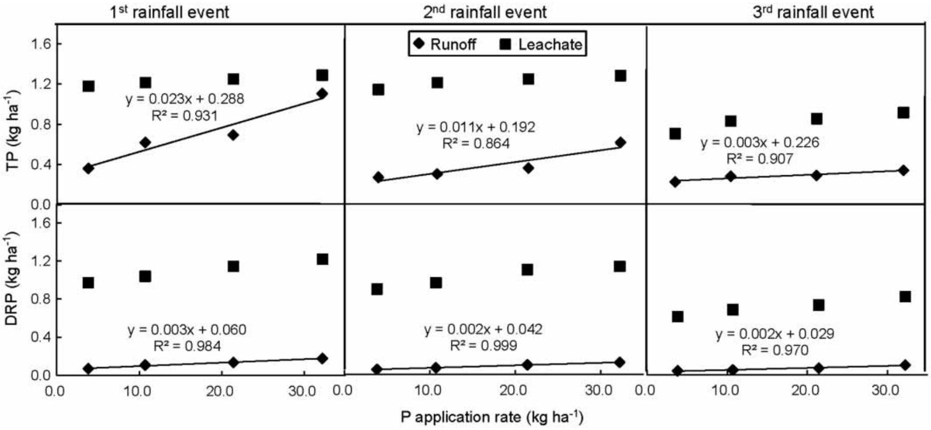

Figure 3. The contents of TP and DRP as a function of P application rate for each rainfall event. Statistical significances for treatment effects are indicated in Table 6. Significance for the regression fit was set to the 0.05 probability level.

rainfall event producing the greatest TP and DRP yields. The TP and DRP yields in the leachate were the lowest in the 3rd rainfall event due to the lower rainfall intensity of the 3rd event compared to the first two rainfall events; this is consistent with the finding that P leaching loss was closely linked to water management [24]. In summary, the 3rd rainfall event resulted in the lowest TP and DRP yields in the leachate.

3.4. ***BOD_5 and COD_{Cr} in the runoff and leachate***

BOD_5 increased linearly as the application slurry BOD_5 rate increased (with the exception of the runoff at the 2nd event), while COD_{Cr} increased logarithmically as the application slurry COD_{Cr} rate increased (with the exception of the runoff at the 3rd event) (Figure 4). The BOD_5 content in

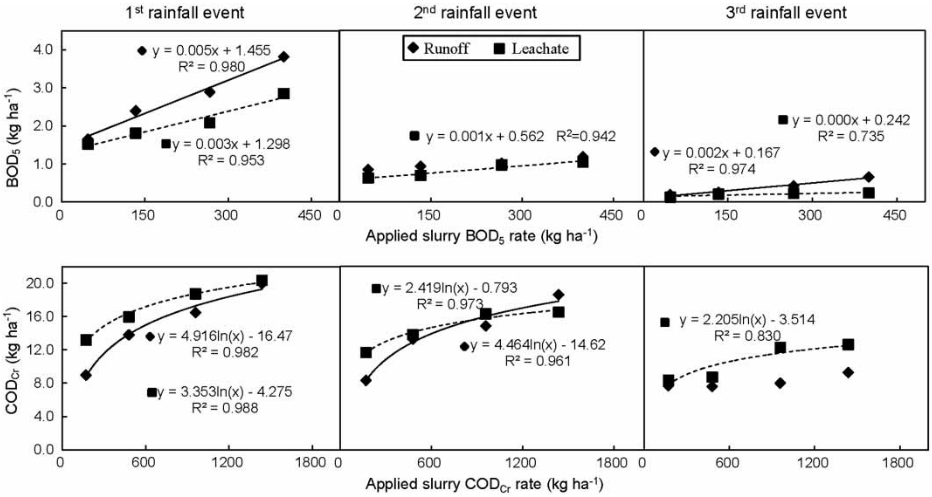

Figure 4. The contents of BOD_5 and COD_{Cr} as a function of BOD_5 and COD_{Cr} application rates respectively, for each rainfall event. Statistical significances for treatment effects are indicated in Table 6. Significance for the regression fit was set to the 0.05 probability level.

the runoff was very different between treatments in the 2nd event. This may be because the fast growing period for crops was before the 2nd event, and it was likely that the organic matter in ADS, which might be one of the main contributors of BOD_5 in the runoff, was quickly decomposed by micro-organisms in the soil and then used by the crops. Lower rainfall intensity reduced the soil erosion [26], and, as shown in our study, also reduced the treatment effect on COD_{Cr} in runoff at the 3rd event.

Comparing the rainfall events, the effects of rainfalls and soil conditions were evident in the contents of BOD_5 and COD_{Cr}. As expected, BOD_5 decreased from the 1st rainfall event (event mean: 2.7 $kg\,ha^{-1}$ in the runoff, 2.1 $kg\,ha^{-1}$ in the leachate) to the 3rd event (event mean: 0.7 $kg\,ha^{-1}$ in the runoff, 0.3 $kg\,ha^{-1}$ in the leachate). Rainfall-induced consolidation and sealing effects could reduce the soil erodibility [27], which may explain why BOD_5 content in the water was reduced after several rainfalls.

In this study, the rainfall intensity mainly determined the flow path of water through the soils, which was a very important factor for the content of organic matter in runoff [28]. The result

Table 7. Nutrients (N and P) uptake by crop and using efficiency.

	Nutrients uptake by crop		Nutrients using efficiency[a]	
Treatments	N	P	N	P
ADS0	17.8	2.6	0.71	0.68
ADS1	34.7	5.6	0.50	0.52
ADS2	43.8	7.6	0.31	0.36
ADS3	34.0	4.9	0.16	0.15

Note: [a] Nutrient using efficiency was defined as: the amount of nutrient (N or P) uptake by the crop relative to the amount of nutrient applied.

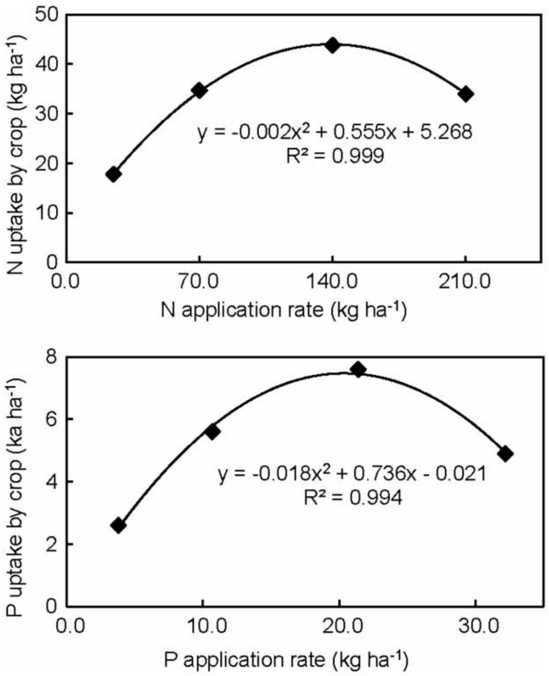

Figure 5. Nutrient (N, P) uptake by crops as a function of nutrient (N, P) application rate over the entire crop season.

indicated that lower rainfall intensity did reduce the BOD_5 and COD_{Cr} contents, both in the runoff and leachate.

Transplantation disturbed the soil surface, and it not only affected the N and P losses in runoff, but also contributed to the highest BOD_5 and COD_{Cr} loading in runoff during the 1st rainfall event.

3.5. *Nutrient uptake by crop*

At the first fertilisation, the high ADS dose applied in ADS3 treatment resulted in emergence problems, and some cabbage plants were re-transplanted. This was probably due to ammonium toxicity [29]. Total N uptake (Table 7) by cabbages ranged between 9.7 kg N ha^{-1} (ADS0) and 43.8 kg N ha^{-1} (ADS2), while total P uptake ranged between 1.8 kg P ha^{-1} (ADS0) and 7.6 kg P ha^{-1} (ADS2). The optimum rates of N and P fertilisation for the target $RL = 1.0$, estimated by the binomial regression using nutrient uptake data (Figure 5), were 139.1 kg N ha^{-1} (99% confidence interval $= 136.2 \sim 142.0$ kg N ha^{-1}), and 20.7 kg P ha^{-1} (99% confidence interval $= 18.7 \sim 21.9$ kg P ha^{-1}). These estimated optimum rates would indicate that ADS0 and ADS1 treatments were under-fertilised, the ADS3 over-fertilised, and that ADS2 can be included in the well-fertilised range.

4. Conclusions

The environmental effects of anaerobically digested pig slurry application were evaluated in this lysimeter study. In general, higher dose ADS applications resulted in higher nitrogen and phosphorus contents in surface soil, runoff and leachate as well. However, the phosphorus in leachate was the exception.

The low and moderate ADS rates were able to completely cover the N and P needs of cabbage and to produce the optimal yields in this East Asian environment. However, the ADS rate above the N crop requirement (210.3 kg N ha^{-1}, ADS3) did not increase cabbage yield. In contrast, the high ADS application rate had the highest risk of environmental pollution to water resources due to higher nutrient concentrations and loads in the runoff and leachate.

Although the moderate ADS application rate (ADS2) was optimal for crop development, nutrient losses were high during high intensity rainfalls. It is important in a rainy environment to adapt N applications to crop extractions. The application of lower ADS doses before sowing complemented with side-dressing fertiliser application (mineral or ADS) and consideration of weather conditions before any fertiliser or slurry application would reduce nutrient losses in crop development.

Rainfall intensity did have a big effect on nutrient movement to the runoff and leachate. In Korea, the rainy season is the cabbage growth season. To improve N and P use efficiency and to diminish N and P contamination (reduce exported N and P loads) in these areas, good water management as well as fertilisation schedules including lower application rates of basal fertiliser, harvesting of rainfall water and avoiding fertiliser application in heavy rainy periods, are key factors.

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