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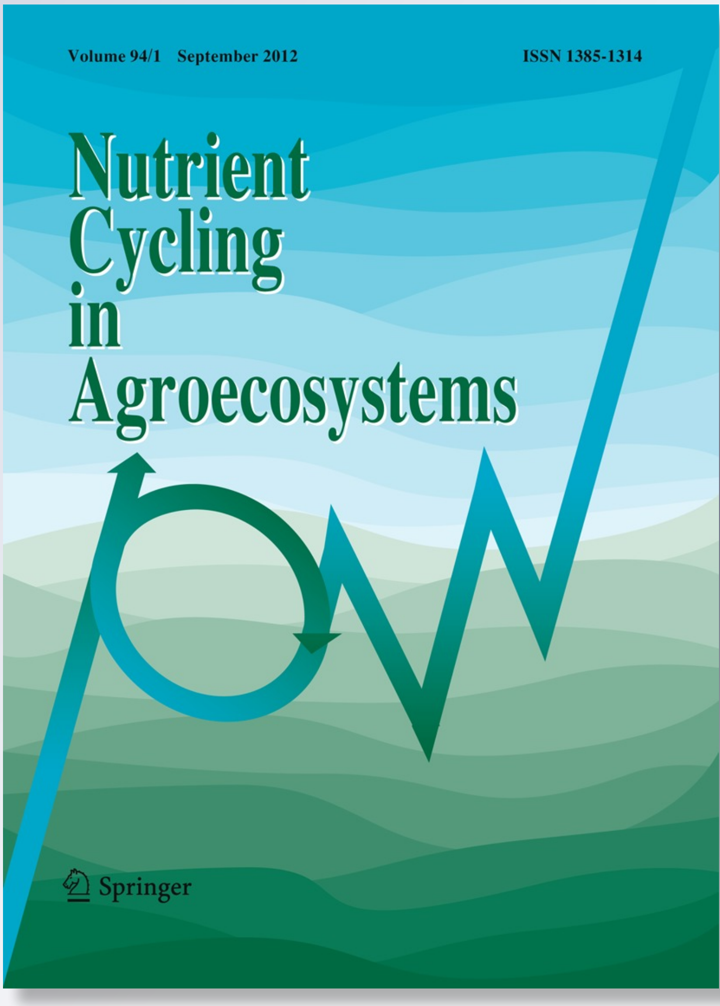

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ORIGINAL ARTICLE

Effect of biogas technology on nutrient flows for small- and medium-scale pig farms in Vietnam

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Abstract Increased demand for meat products has led to increased livestock production in Vietnam, which now risks environmental pollution from inappropriate animal manure management on livestock farms. Biogas technology is generally considered an efficient solution for such farms to produce renewable biofuel for use in the household and to reduce the pollution impact from animal waste. However, with biogas technology, farmers may reduce their use of manure for fertilising crops. This field survey investigated nutrient flows on small- and medium-scale livestock farms with and without biogas in Northern Vietnam, in order to identify existing problems and possibilities for sustainable livestock production. A field survey was conducted on 12 pig farms with biogas and 12 pig farms without biogas in Quoc Oai district, Hanoi city. In general, the non-biogas pig farms used on average 3.8 ton compost and 3.1 ton fresh solid manure ha^{-1} $crop^{-1}$ for each of three crops typically grown per year on their arable land. They discharged on average 16 % of the total manure produced into the environment in liquid form through the public sewage system. On biogas pig farms, the use of fresh solid manure for crops and discharge of liquid manure was lower, as manure was used to produce biogas. However, excessive use of washing water on several of these farms resulted in very dilute slurry (solid manure:water ratio 1:11) entering the biogas digester. This lowered the retention time in the digester (below the optimum range of 35–55 days), leading to low biogas production rates and possible accumulation of sediment. The digestate was also highly diluted and hence difficult and costly to transport and apply to crops, so it was largely (60 %) discharged to the environment. The input volume of washing water should therefore be reduced to a ratio of 1:5. For better sustainability, appropriate technologies are needed to absorb nutrients from the digestate before discharge and to recycle these nutrients to crops.

Keywords Nutrient flow · Biogas technology · Vietnamese pig farm

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Introduction

Livestock production in Vietnam is rapidly changing from small-scale to medium and large-scale production, as in many other agricultural regions of South–East Asia. These changes are usually not accompanied by appropriate adaptations in animal waste management, leading to unnecessary pollution of the environment and inefficient utilisation of the nutrient and energy resources in the waste. For example, Nguyen et al. (2007) reported that mismanagement of fertilisers, including manure and chemical fertilisers, resulted in positive nutrient balances for small-scale peri-urban vegetable farming systems in Hanoi, Vietnam. They found surpluses of 85–882 kg ha^{-1} year^{-1} for nitrogen (N), 109–196 kg ha^{-1} year^{-1} for phosphorus (P) and 20–306 kg ha^{-1} year^{-1} for potassium (K). Similarly, Phong et al. (2011) found that integrated agriculture-aquaculture systems (fish–rice/orchard system) in the Mekong Delta, Vietnam, had average surpluses of 84, 73 and 69 kg ha^{-1} year^{-1} of N, P and K, respectively. Gerber et al. (2004) reported estimated phosphorus overloads of 24 % on agricultural land in South, East and South-East Asia, mainly in eastern China, the Ganges basin and around urban centres such as Bangkok, Ho Chi Minh City, Hanoi and Manila. On average, livestock manure was estimated to account for 39 % of the agricultural P supply in these regions, the remainder being supplied by chemical fertilisers. Thus, these research findings show that intensification of livestock farming often leads to positive nutrient balances, potentially causing pollution of the environment and loss of plant nutrients if manure management is inappropriate.

To solve these problems, simple biogas production technology is often recommended and applied in Vietnam and other parts of South–East Asia. Chinh (2005) and Vu et al. (2007) recommend that environmental problems be mitigated by using a biogas digester on livestock farms and recycling the biogas digestate more efficiently for fish and crop production. Efficient fermentation of manure can also reduce greenhouse gas emissions from animal manure management and, through biogas energy replacing fossil energy, reduce carbon dioxide emissions (Sommer et al. 2004). It can also bring economic benefits for farmers. Møller et al. (2004) concluded that as biogas digestate contains a slowly degradable fraction, it may be useful for soil amelioration and carbon sequestration. Nielsen and Hjort-Gregersen (2002) found that under commercialised, intensive livestock farming conditions in Denmark, biogas energy production is one of the cheapest technologies for reducing greenhouse gas emissions. However, the installation of a biogas plant on a small- or medium-scale livestock farm will produce a digestate slurry which cannot be easily handled with existing technologies, and farmers may choose to discharge a large proportion of the digestate to watercourses in the vicinity. Therefore, the increasing application of biogas technology can increase the environmental and hygiene risk from such discharge or from application of untreated digestate to fresh edible crops.

Unfortunately, relatively little research has been done on the actual changes in manure management practices upon biogas digester installation on these livestock farms and the associated changes in nutrient flows on the farm. We therefore conducted a field survey to investigate manure nutrient flows on small-scale and medium-scale livestock farms with and without biogas in Northern Vietnam. The objectives of the survey were (1) to evaluate and compare nutrient inputs, outputs and internal flows on farms with and without biogas and (2) to identify existing potentials and problems in each of the farm systems with respect to crop production and environmental impact. The overall aims were to provide decision support for policy making and to suggest targeted interventions to achieve sustainable livestock production in Vietnam and similar countries in the region.

Materials and methods

This nutrient flow field survey formed part of a larger field survey in northern and central Vietnam investigating how manure management on small- and medium-scale livestock farms is affected by the introduction of biogas digestion, and what farmers perceive to be the benefits related to introduction of biogas digesters (Thu et al. 2012). That survey was designed to investigate the current situation of manure management on biogas and non-biogas livestock farms (predominantly pig production) in the Hanoi and Hue areas. Information was sought about animal production, animal waste management, utilisation of manure and digestate for crop and fish production, farmers' perceptions of the advantages and disadvantages of the biogas system, etc. The original survey included 281 livestock farms (146 of these with biogas) and was conducted through visiting farm families and interviewing householders in April, 2010. Further details can be found in Thu et al. (2012).

Study site, farms and in-depth interviews

For monitoring nutrient flows as affected by biogas technology, 12 farms with biogas digesters installed and 12 farms without biogas (traditional manure management) were randomly chosen from 96 farms with biogas and 85 farms without biogas included in the larger field survey in Dong Yen and Sai Son communes, Quoc Oai district, Hanoi City (see Thu et al. 2012). These selected farms were subjected to in-depth interviews and sampling of feed, manure and digestate for analyses, as well as quantification of mass flows during April 2010.

The in-depth interviews recorded quantitative information about inflows and outflows concerning the livestock part of the pig farms with and without biogas, such as stock density, the amount of pig feed intake (nutrient input), solid pig manure for the different types of animal, and the relative percentages of excreta and digestate applied in agricultural production (crops and fish ponds) and discharged to the environment (nutrient output).

Sampling and analyses

Feed

In Vietnam, small livestock farms commonly feed their livestock with food residues, maize and a by-product from alcohol production, which is cooked before feeding to e.g. pigs. Medium- and large-scale farms and farms with a lack of labour generally feed commercial animal feeds. However, mixed feed (a combination of traditional and commercial feeds) is often fed by many farmers because it has multiple advantages, such as good resource use efficiency and labour and cost savings.

Feed samples of 500 g (traditional, commercial or mixed) were collected on 2 occasions per day (after the rations had been mixed in morning and afternoon), for three consecutive days. The two samples per day were pooled to one bulk sample and stored at −4 °C. Before analysis (within 1 month of sampling), the samples from the 3 days were thawed and mixed homogeneously to constitute one representative sample. Quantity of feed used was estimated by weighing the feed for different types of pig (piglets, fattening pigs and sows) at the morning and afternoon feeding on each of the three sampling days and calculating the daily average for the 3 days.

Feed samples were analysed in duplicate for dry matter (DM), crude fibre, total N, P, and K at the Laboratory for Feed and Animal Product Analysis at the National Institute of Animal Science, Hanoi, according to standard methods (Association of Official Analytical Chemists 1990).

Manure

Solid manure samples were collected 2 times per day (morning and afternoon) for three consecutive days. The entire amount of manure in individual pig pens (piglets, fattening pigs and sows) was collected by scraping the concrete floors in the morning and afternoon, weighed and then a subsample of 5 % of the total weight was taken. Samples from each day's collection were mixed, transported to the laboratory and kept at −4 °C for 1 month. Before analysis, the samples for the 3 days were thawed and mixed homogeneously to make one representative composite sample.

Liquid manure samples include cleaning water, urine and residual solid manure left on the floor after scraping. On the farms where the liquid manure flowed into a container, liquid samples were collected 2 times a day (morning and afternoon) after stirring the container. On the farms where the liquid manure flowed directly into the sewage system, digester or pond, liquid subsamples were taken every minute during cleaning time and placed in a bucket. Volume of liquid manure effluent was estimated as the volume of water used for cleaning the pig pen, which was measured by installing a flow meter (Asahi GMK 15) attached to the pump or on the water tap. The quantity of urine was not measured, but was estimated to be approximately 15–20 % of the total volume of water used.

Digestate samples were collected 2 times a day from the effluent pipe of the digestate container. The volume of digestate was assumed to be equal to the volume of water used for cleaning the pig pen as measured by flow meter.

For both liquid and digestate, the final liquid sample collected in the bucket was thoroughly stirred and then around 500 mL to 1 L liquid sample were transferred to a plastic bottle. All liquid samples were transported to the laboratory on the day of sampling and stored at −4 °C for 1 week before chemical analysis. Before analysis, the samples for the 3 days were thawed and mixed homogeneously to constitute one representative sample.

The solid, liquid and digestate samples were analysed at the Soils and Fertilizers Research Institute, Hanoi, for the following parameters: Dry matter (for solid sample only, drying at 105 °C for 24 h), pH H_2O (manure:distilled water 1:4 v:v, measured by pH Meter); total N (Kjeldahl method); NH_4–N (extracted by dilute HCl 0.05 N, determined by Bremner distillation); total P (extracted by H_2SO_4:HNO_3 1:1 v:v, measured by the Vanadomodybdophosphoric acid method on a spectrophotometer (Jasko 7800, Japan)); total K (extracted by H_2SO_4:HNO_3 1:1 v:v, measured by flame photometry (Corning 410—UK)).

Calculations and data analysis

Mass flows of N, P and K were calculated using the measured mass or volume of feeds, manures and water used, multiplied by the respective measured concentrations of the elements in each flow.

The amount of nutrients (N, P and K) in meat yield and N losses (urine runoff and seepage between pen washings and ammonia losses in the animal house) for both biogas and non-biogas farms were calculated by subtraction of the nutrient content in collected fresh solid and liquid manure from the nutrient content in the feed intake.

On non-biogas farms, for the proportion of the solid manure which was composted, the amount of nitrogen lost by ammonia volatilisation was assumed to be approximately 30 % of manure N input (Tran et al. 2011).

For the biogas farms, the amount of nutrients retained in the biogas digester (as sediment) was calculated by subtraction of the nutrient content in collected digestate outflow from the nutrient content in excreta entering the digester.

The amount of nutrients applied to different crops, fish ponds or discharged into the environment was calculated for both types of farms from the farm questionnaire information about the proportions of manure used for the different purposes, multiplied by the respective nutrient contents in excreta or digestate. Annual nutrient flows were estimated based on an annual stocking time of 320 days per year, the remainder being used for cleaning and sanitising animal pens and houses.

The mass flow analyses were conducted using a spreadsheet model and the results analysed statistically by one-way analysis of variance, using SAS 9.1 (SAS Institute 1988).

Results and discussion

Characteristics of biogas and non-biogas pig farms

There were no significant differences in average numbers of piglets, fattening pigs and sows between the biogas and non-biogas farms surveyed (Table 1). Similar results were found for the larger populations of biogas and non-biogas farms surveyed by Thu et al. (2012). There was also no significant difference in the total quantity of manure produced between biogas and non-biogas farms.

As the farms with and without biogas were randomly chosen, size of livestock enterprise was not the reason for the farmers to apply biogas technology on the study farms. Rather the in-depth interviews revealed that the reasons for not applying biogas technology on non-biogas farms were lack of money for investment, a preference for using the manure for agriculture production (crops, fruit trees and fish) and lack of information about the advantages of biogas technology. Farmers who used biogas technology stated that the main reasons for this were to obtain gas for cooking and to improve the living environment of humans and animals. Similar findings were made by Thu et al. (2012).

The total amount of manure excreted by the pigs was similar on both the biogas and non-biogas farms surveyed and was on average 6.4 ton of pig fresh solid manure per year (with 320 days of animals on farm). On the non-biogas farms, 50 % of fresh solid manure was composted before use as a crop fertiliser, and 21 % and 13 % of fresh solid manure were directly applied to fish pond and crops, respectively. The remaining 16 % was discharged to the environment through the village sewage system. Thus farms without biogas used an estimated approximately 1.9

Table 1 Average number of pigs (head farm^{-1} in different categories), amount of solid manure produced (kg day^{-1}) and water use for washing (L day^{-1}) on biogas and non-biogas pig farms (Min–Max. values in brackets)

Criteria	Number of pigs farm^{-1}			Solid manure and washing water		
	Non-biogas	Biogas	LSD[a]	Non-biogas	Biogas	LSD
Piglets	7.9 (0–41)	6.8 (0–25)	9.1	4.4 (0–19.1)	3.8 (0–13.6)	4.8
Fattening pigs	12.3 (0–28)	15.4 (6–28)	7.9	11.1 (0–31.1)	13.3 (4.1–44.0)	9.0
Sows	1.8 (0–6)	1.7 (0–7)	1.6	3.5 (0–12.2)	3.1 (0–9.8)	2.8
Total	22.0 (4–43)	23.9 (11–49)	9.2	19.0 (8.3–36.6)	20.2 (7.3–56.4)	9.5
Washing water				183 (54–447)	216 (73–485)	103
Manure:water				1:10 (1:5–1:15)	1:11 (1:5–1:29)	

[a] LSD least significant difference at $p < 0.05$

ton compost for crops (fresh manure weight reduced by 40 % by composting; Tran et al. 2011) and 1.3 and 0.8 ton untreated solid manure for fish and crop production, respectively. Each of the farms had on average 1,700 m^2 cultivated land (Thu et al. 2012) and hence it can be estimated that the farmers used on average 11.3 ton compost and 9.4 ton of fresh solid manure ha^{-1} year^{-1} on their cultivated land. As most farmers grow three crops per year in this region (typically spring and summer rice, followed by either maize or a vegetable crop), this means that on average they apply 3.8 ton compost and 3.1 ton fresh solid manure ha^{-1} crop^{-1}.

According to the biogas programme for the livestock sector in Vietnam (funded by the Dutch government, SNV-VN 2012), 1 kg solid pig manure can potentially produce 40–50 L biogas in a typical farm-scale biogas plant. The biogas farms surveyed in this study should therefore be able to produce 0.8–1 m^3 biogas per day from the 20 kg solid manure produced on average per farm and day. This amount of biogas should be enough fuel for cooking three meals for a household with 5–6 people (Kristoferson and Bokalders 1991). The volume of biogas can be increased by 15–20 % if the volume of urine is also taken into account. The mass loading rate of slurry is one of the main factors deciding yield and quality of biogas. A solid manure:washing water ratio of 1:3 is particularly well suited for the operation of continuous biogas digesters and produces the highest specific biogas yield (Sasse 1988; SNV-VN 2012). However, the amount of washing water used on the farms with and without biogas surveyed here was rather high, yielding an average solid manure:water ratio of around 1:11 on biogas farms. This is probably why the digestate nutrient content (see Table 3) was very low on many of the surveyed farms.

Besides the loading rate of slurry, the retention time of slurry is also considered an important factor for biogas generation efficiency. The hydraulic retention time of slurry was calculated here simply as the ratio between biogas digester volume and substrate (manure and water slurry) loading rate. If the retention time is too short, the degradation of volatile solids and transformation into biogas is not complete. Furthermore, the bacteria formed in the biogas plant are carried out with the digestate faster than they can reproduce, leading to a decline in biogas production. In contrast, if the retention time is too long, the specific biogas production per volume of influent is too small. The retention time should optimally be in the range 35–55 days depending on season (SNV-VN 2012). Singh et al. (1998) stated that the optimum retention time for small-scale biogas plants (6 m^3) should be 50 days. In the current study, the volume of the digesters on the 12 biogas farms ranged from 9 to 28 m^3 and the retention time was on average 64 days, but ranged from 24 to 142 days, i.e. both lower and higher than appropriate for optimal biogas yield as recommended by SVN-VN. In the larger survey (Thu et al. 2012), 55 % of the digesters had a retention time below 20 days. However, in their study the amount of washing water used for cleaning was based on the farmers' own estimates (questionnaire data, average 230 and 380 L farm^{-1} day^{-1} for non-biogas and biogas farms, respectively), whereas in the current study we measured the actual volume of water used, which was found to be somewhat lower than this (183 and 216 L day^{-1}, respectively; Table 1). We carried out the survey during a moderately hot season (April) with above average temperatures, but during the warmest season (May–August) farmers typically use more water for cleaning and especially for cooling the pigs. Therefore, farms with intensive livestock production should be advised to reduce the amount of washing water entering the biogas system, lowering the ratio of manure:washing water from 1:11 to around 1:5, in order to increase the manure retention time to the optimal of approximately 55 days. Farmers could also consider separating the two processes by closing the inlet tank after finishing the first process (pen cleaning) and then continuing with the second process (pig cooling). Other reasons for low biogas yields, e.g. sub-optimal temperature during the winter season, use of chemicals for sanitisation etc. are discussed in more detail by Thu et al. (2012).

Animal feeding practices

On biogas and non-biogas farms, the highest proportion of commercial feed (62–67 %) was used for fattening pigs, with no difference between farm types (Fig. 1). Traditional feed was only used for sows on either farm type, the remainder being fed either mixed or commercial feed, predominantly commercial feed (60 %) on biogas farms. For piglets, a high proportion of farms, 50 % of those with biogas and 75 % of those without, used mixed feed and the remainder used commercial feed. Overall, on non-biogas farms, commercial and mixed feed were the main feed source used for pig production, whereas commercial feed was the main feed source for pig production on biogas farms. In general for Vietnamese pig production, commercial and mixed feeds are more commonly used today than 15 years ago, when traditional feed predominated.

Nutrient content in pig feeds

For both non-biogas and biogas farms, the average N content in commercial feed was higher than that in traditional feed, 31.6 and 30.1 in comparison with 23.1 and 21.9 g kg^{-1} dry matter, respectively, due to the higher and more concentrated protein content of the commercial feed (Table 2). It should be noted that the N (and hence protein) concentration varied greatly for commercial feeds on both farm types, reflecting great differences in feed quality. For both non-biogas and biogas farms, there was no significant difference in P and K content among the three different feed rations used. Together with the patterns of feed type used, this implies that the N content in animal manure could be expected to be higher today, as a consequence of the more widespread use of commercial feed today compared with one or two decades earlier. Therefore appropriate manure management strategies, including regular manure nutrient analyses, are necessary to improve manure nutrient use efficiency for crop production and to protect the environment from nutrient overload impacts.

Nutrient content in pig manures

For both non-biogas and biogas farms, the pH value in piglet manure was 0.5 unit lower than in fattening and sow manure (Table 3). The optimum pH range for anaerobic digestion is 6–8 (SNV-VN 2012), so all

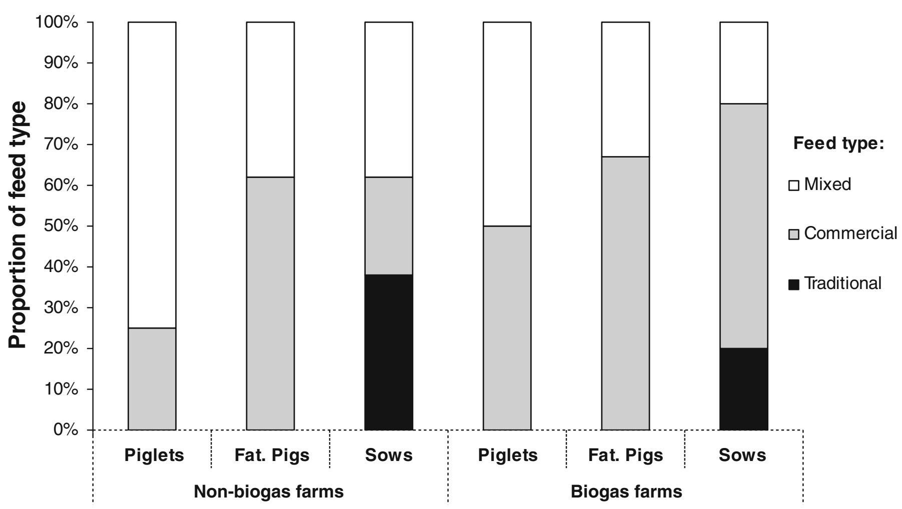

Fig. 1 Proportion of different types of feed used for pigs on biogas and non-biogas pig farms

Table 2 Nutrient content in feed on biogas and non-biogas pig farms

	Non-biogas farms ($g\ kg^{-1}$ dry matter)			Biogas farms ($g\ kg^{-1}$ dry matter)		
	N total	P total	K total	N total	P total	K total
Traditional feed	23.1 (5.3)	9.6 (3.6)	4.0 (0.8)	21.9 (9.0)	5.8 (3.3)	3.8 (1.2)
Commercial feed	31.6 (21.4)	8.4 (3.2)	3.7 (0.9)	30.1 (16.3)	8.7 (3.4)	4.4 (1.1)
Mixed feed	28.4 (15.3)	6.6 (2.7)	4.2 (0.8)	28.1 (4.5)	7.4 (2.7)	3.4 (0.8)

Mean (SD), n = 5–11

Table 3 Chemical properties of different manures on biogas and non-biogas pig farms

Manure type	pH	Total N	N–NH_4	Total P	Total K
Non-biogas farms ($g\ kg^{-1}$ dry matter)					
Piglet solid manure	6.8 (0.3)	29.9 (4.0)	1.6 (1.8)	20.6 (8.5)	6.1 (2.8)
Fattener solid manure	7.6 (1.0)	52.2 (20.9)	3.0 (3.2)	23.2 (6.5)	7.6 (1.8)
Sow solid manure	7.8 (1.0)	36.3 (16.6)	2.1 (1.8)	22.6 (3.6)	7.2 (2.2)
Liquid manure ($g\ L^{-1}$)	7.2 (0.9)	0.8 (0.5)	0.2 (0.1)	0.3 (0.2)	0.2 (0.1)
Biogas farms ($g\ kg^{-1}$ dry matter)					
Piglet solid manure	6.5 (0.3)	33.1 (15.0)	0.5 (1.0)	19.0 (8.0)	7.9 (2.0)
Fattener solid manure	7.2 (0.6)	35.5 (11.8)	4.2 (3.2)	23.7 (7.7)	7.1 (1.6)
Sow solid manure	7.5 (0.9)	39.8 (9.2)	1.6 (1.9)	21.4 (5.2)	8.7 (4.9)
Liquid manure ($g\ L^{-1}$)	7.4 (0.8)	0.7 (0.4)	0.1 (0.07)	0.2 (0.16)	0.1 (0.07)
Digestate ($g\ L^{-1}$)	7.8 (1.4)	1.0 (0.2)	0.6 (0.2)	0.3 (0.2)	0.3 (0.01)

Mean (SD), n = 4–21

were within optimal range, but lower pH decreases the ammonia volatilisation risk with both raw manure and digestates.

The higher N content in fattening pig manure in comparison with piglet and sow manure on non-biogas farms is probably caused by the higher proportion of commercial feed (62 %) used for fattening pigs than for piglets and sows (approximately 25 %). The N content in solid manure from the three kinds of pigs was relatively similar on the biogas farms, probably because they use more or less the same proportion of commercial feed for piglets, fatteners and sows (50, 67 and 60 %, respectively). The P and K content of the different solid manure types were more or less the same for both non-biogas and biogas farms.

The nutrient content in liquid manure and digestate was more or less equal and was far lower than in the solid manure for both non-biogas and biogas systems. This is probably the main reason why the farmers discharged approximately 15 % of liquid manure (on non-biogas farms) and 50 % of digestate (on biogas farms) into the environment instead of using it in crop production.

Nutrient flows on pig farms with and without biogas

There was a large variation in nutrient flows between non-biogas (Table 4) and biogas farms (Table 5), varying up to an order of magnitude for most flows and nutrients. Data on the proportion of manure or digestate discharged to the environment were obtained from farmers in the in-depth interviews and a large number of non-biogas farms indicated no manure discharge, while almost all biogas farms indicated discharge of digestate to the environment.

Data were averaged across farms within the biogas and non-biogas farm groups and nutrient flows expressed relative to feed input to allow the two systems to be compared (Fig. 2).

The total nutrient content excreted (in solid and liquid manure) per pig farm with and without biogas

Table 4 Nutrient flows (kg N, P or K per year) on individual non-biogas (NB) pig farms

Farm#	Nitrogen (N), phosphorus (P) and potassium (K) inputs and outputs per farm (kg $farm^{-1}$ $year^{-1}$)														
	Feed intake			Meat and N losses[a]			Excreta			Excreta applied to crop and fish[b]			Excreta discharged to environment		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
NB1	307	78	46	215	31	26	92	46	20	92	46	20	0	0	0
NB2	196	57	40	144	29	30	53	28	11	26	14	5	26	14	5
NB3	68	30	18	31	5	10	37	24	9	37	24	9	0	0	0
NB4	219	69	49	154	23	28	65	46	21	52	37	17	13	9	4
NB5	237	78	31	114	46	11	123	32	20	123	32	20	0	0	0
NB6	139	41	25	51	15	6	88	26	19	58	20	12	30	6	7
NB7	413	148	74	150	62	32	263	86	41	263	86	41	0	0	0
NB8	350	116	47	250	62	27	99	54	20	99	54	20	0	0	0
NB9	105	64	28	23	8	5	81	56	24	45	37	14	37	18	9
NB10	222	80	34	130	21	16	92	60	18	57	40	8	35	19	10
NB11	518	159	85	361	48	43	157	111	41	109	80	26	48	31	15
NB12	129	42	37	70	1	20	60	41	18	60	41	18	0	0	0

[a] N lost in urine runoff and seepage between pen washings and ammonia losses in the animal house

[b] Applied either fresh or after composting. For average distribution refer to Fig. 2

(Fig. 2) was substantial and represented an important potential source of fertiliser in agricultural production, with (per year): 101 kg N, 51 kg P, 22 kg K on non-biogas farms and 116 kg N, 59 kg P, 22 kg K on biogas farms.

Vu et al. (2010) showed that the N excreted in urine is around 30 % of total feed N intake. Assuming that half the urine is lost in runoff and seepage between pen washings, and that the ammonia lost from urine and fresh solid manure between washings is equivalent to the other half of the urine nitrogen, then approximately 28 and 29 % of N in the feed intake was retained in the pigs as meat produced on biogas and non-biogas farms, respectively. The excretion of P in urine is reported to be around 10 % of total P intake for these pig production systems (Vu et al. 2010) which means that with half of the urine in runoff and seepage, the P retained in the pork meat produced by the farms with and without biogas was 41 and 32 %, respectively. The feed nutrient use efficiency of the pigs was thus in the same range or a little higher than previous results, for instance, Tamminga et al. (2000) found that N retention in pork meat varied from 24 to 34 %, IAEA (2008) reported N and P retention in pork meat of 29 and 28 %, respectively, and Hedlund et al. (2003) retention of 37 and 20 %, respectively.

On the non-biogas pig farms a significant proportion of the manure was applied to cultivated land either directly or after composting. On average, 16 % of the total amount of manure (mainly liquid) was discharged directly into the environment, e.g. ponds and rivers, through the village sewage system. The remaining manure (84 %) was distributed between crops, fruit trees and fish production (but only 18 % of farms had a fish pond). Of this, approximately two-thirds of the solid manure was composted before application to crops and the remainder used directly for agricultural production. Assuming N losses during composting to be approximately 30 % of manure N input, as shown by Tran et al. (2011), total nutrient losses to the environment for non-biogas farms were 32 kg N (half as ammonia to the atmosphere, Fig. 2 left), 8 kg P and 4 kg K $farm^{-1}$ $year^{-1}$. In comparison, the non-biogas farms studied by Hedlund et al. (2003) produced 187 kg N, 84 kg P and 101 kg K ha^{-1} $year^{-1}$ in manure, of which 91 kg N, 70 kg P and 32 kg K were used for crops, 32 kg N, 5 kg P and 26 kg K were used for fish production and the remaining 64 kg N, 9 kg P and 43 kg K $farm^{-1}$ $year^{-1}$ were discharged into the environment.

On the biogas pig farms, 116 kg N, 59 kg P and 22 kg K $year^{-1}$ in excreta were fed into the digester

Table 5 Nutrient flows (kg N, P or K per year) on individual biogas (B) pig farms

Farm #	Nitrogen (N), phosphorus (P) and potassium (K) inputs and outputs per farm (kg $farm^{-1}$ $year^{-1}$)																							
	Feed intake			Meat and N losses[a]			Excreta applied directly to crop and fish			Excreta entering biogas digester			Retained in biogas digester			In digestate			Digestate applied to crop and fish			Digestate discharged to environment		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
B1	262	75	38	205	42	26	5	3	1	52	30	12	23	20	4	29	10	8	14	8	6	14	5	4
B2	121	47	19	80	16	7	0	0	0	42	31	13	20	17	2	22	14	11	0	0	0	22	14	11
B3	130	54	25	60	18	7	0	0	0	70	37	17	1	3	2	69	33	15	35	17	7	35	17	7
B4	108	48	21	41	15	4	0	0	0	67	33	16	2	3	2	64	31	14	32	15	7	32	15	7
B5	296	86	37	177	20	13	0	0	0	119	65	24	63	39	6	55	26	19	28	13	9	28	13	9
B6	130	48	34	83	24	24	20	11	3	26	13	6	1	1	1	25	12	5	20	10	4	5	2	1
B7	496	308	153	197	150	100	0	0	0	299	158	53	160	106	1	140	52	51	0	0	0	140	52	51
B8	248	61	39	125	13	19	0	0	0	123	48	20	24	5	0	99	43	20	0	0	0	99	43	20
B9	733	253	124	403	167	76	0	0	0	330	87	48	142	61	4	189	25	44	189	25	44	0	0	0
B10	168	90	59	63	29	35	0	0	0	105	62	23	40	30	1	65	31	22	20	9	7	46	22	15
B11	542	212	63	438	104	38	0	0	0	105	109	24	51	78	10	54	30	15	0	0	0	54	30	15
B12	231	61	35	168	22	21	7	6	2	56	32	12	11	11	1	45	22	11	9	4	2	36	17	9

[a] N lost in urine runoff and seepage between pen washings and ammonia losses in the animal house

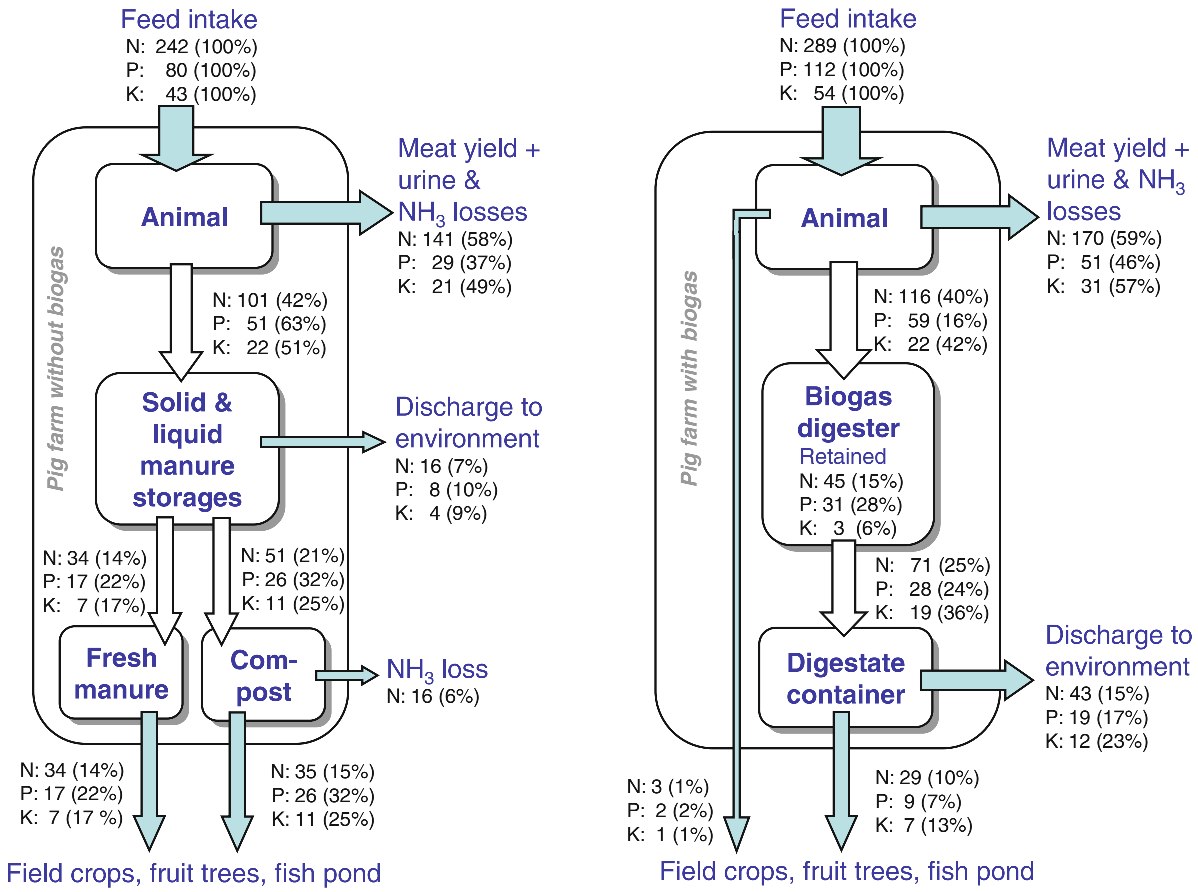

Fig. 2 Average N, P and K flows quantified on non-biogas pig farms (*left*) and biogas pig farms (*right*). All values are given in kg farm^{-1} year^{-1} (320 production days) and as a percentage of feed input in brackets. Width of *arrow* indicates magnitude of flow

where microorganisms degraded the manure to produce biogas (carbon dioxide and methane). The by-product of biogas production, the digestate, had a nutrient content of 71 kg N, 28 kg P and 19 kg K year^{-1}. A significant proportion of this digestate (on average 60 % of the total amount produced) was discharged directly into the environment, transferring on average 43 kg N, 19 kg P and 12 kg K year^{-1}, and the remaining 29 kg N, 9 kg P and 7 kg K year^{-1} were used for fertilising crops, fruit trees and fish production. The remaining fraction of nutrients (45 kg N, 31 kg P and 3 kg K year^{-1}) appeared to be retained in sediment within the biogas digester. This high proportion (representing 39, 53 and 14 % of N, P and K inputs to the digester, respectively) was a little surprising, but was partially caused by two farms with high retention, B7 and B9 (Table 5), which were special for several reasons. First of all, both these farms had relatively intensive pig production levels, amongst the highest of all farms in the study, with rather high N and P in both feed intake and digestate output, and there was a fairly strong positive correlation between the intensity of pig production on the farm (expressed as feed N intake), and the amount of N retained in the biogas digester (Fig. 3a). Although the volume of the digester on biogas farms in the current study ranged from 9 to 28 m^3, many biogas digesters on livestock farms are in the size range 11–15 m^3 (Thu et al. 2012). Intensive livestock production leads to higher loading of the digester, which in turn decreases retention time and hence also volatile solids conversion into biogas, leading to increased sedimentation of solids. Furthermore, the biogas digesters on farms B7 and B9 in the present study were relatively new (built in 2009 and 2008, respectively) and hence equilibrium between sedimentation and degradation had probably

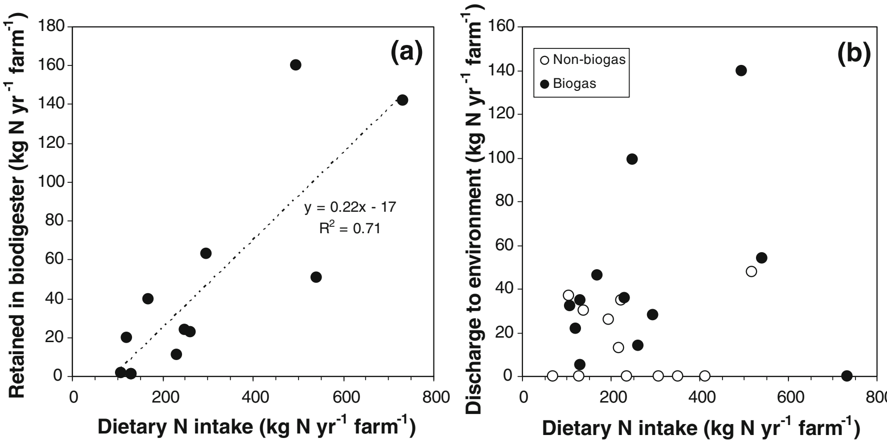

Fig. 3 Influence of farm size (expressed as total dietary N intake) on **a** N retained (accumulated) in the biogas digester and **b** manure and digestate discharge into the environment for non-biogas and biogas farms, respectively

not yet established fully. The question is whether it ever will, as the high loading rates may eventually lead to overaccumulation of solids, impeding efficient operation and functioning of the digester and necessitating troublesome excavation of sediment. The fact that retention of K was quite low compared with N and P confirms that the mass balance is correct, since K is mainly present in a dissolved state and does not form precipitates or become assimilated into organic forms.

Comparing the biogas and non-biogas pig farms, twice as much manure was discharged into the aquatic environment on biogas farms (15 % compared with 7 %; Fig. 2). This is a waste of nutrients and may also cause environmental problems such as eutrophication of surface waters or groundwater pollution. Farmers generally opt to discharge the liquid digestate because of its low nutrient content (see Table 3), as well as its large volume and hence high transportation cost. The amount of nutrients applied to crops, fruit trees and fish ponds on biogas farms was therefore less than half that applied on non-biogas farms. However, on the non-biogas farms, 40 % of the solid manure used for fish and crop production was applied fresh, potentially posing health risks for farm workers and eventually for consumers if applied inappropriately to vegetable crops. This risk could probably be eliminated by composting all the manure or by introducing biogas technology on these farms. However, if such a high proportion of the liquid digestate is discharged as was found in the current study, this would just create other, perhaps more significant, problems. The high proportion of liquid manure discharged into the environment should be controlled by the implementation of new official regulations for livestock production facilities to reduce the risk of environmental pollution and to save nutrients for agricultural production. Overall, our data showed that many livestock farms with biogas do not discharge more nutrients than those without biogas (Fig. 3b), so the main reason for the higher average discharge from biogas farms was the few farms with intensive pig production and discharge of all digestate and the higher proportion of biogas farms which discharge. Hence, new regulations should target these two issues.

In general, the nutrient content of liquid digestate was approximately 15 times lower than in manure, (N, P and K concentrations of 0.1; 0.03; 0.03 % for digestate and 1.5; 0.6; 0.2 % for manure, respectively). Therefore it is important to find a way to remove water from the liquid digestate in order to lower the volume and increase the nutrient concentration. Advanced separation technology such as centrifugation is difficult to apply for small livestock farmers under Vietnamese conditions. However, simple technologies, e.g. rice-straw filtration (Sommer et al. 2003a, b), could potentially retain the nutrients and create a higher fertiliser value product. This would involve relatively low costs and would be easy to implement, since it utilises an abundant crop residue in the countryside. In addition, composting the rice straw together with the accumulated digestate after filtration would potentially reduce the hygiene and health risk through the high sanitising temperature usually achieved for several days during composting (60 °C).

The manure and digestate nutrients were distributed to different types of crop production on the farms or discharged to the environment (Fig. 4). For non-biogas farms, a large proportion of manure (approximately

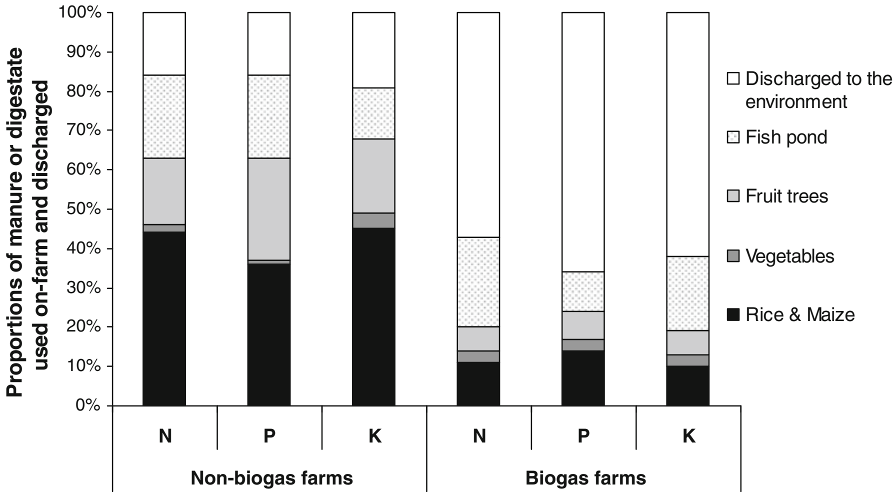

Fig. 4 Manure or digestate use and discharge on biogas and non-biogas pig farms

40 %) was applied to stable food crops (rice and maize) owing to the higher area cultivated of these crops and their important role in household food security. For the biogas pig farms, a large amount of digestate was discharged to the environment (50 %) or used in fish ponds (near digestate source) to avoid high transportation costs.

Conclusions and recommendations

There were no significant differences in animal density or total amount of manure between the biogas farms and non-biogas pig farms studied here. The two groups of farms were therefore considered directly comparable.

For both biogas and non-biogas farms, commercial and mixed feed were the dominant feed sources. This means that the nutrient content of manure has increased compared with previous decades and appropriate manure management and technology are therefore needed more than ever.

The high loading rate of dilute slurry (manure:washing water ratio 1:11) to the farm biogas digesters was too high to comply with best management recommendations. For optimal operation and performance of biogas digesters, this should be adjusted to a ratio of 1:5. For the most intensive livestock farms, this would increase the digester retention time to a more appropriate range and decrease sediment accumulation in the digester. In general, non-biogas livestock farms discharged 16 % of total manure (16 kg N, 8 kg P and 4 kg K year^{-1}) into the environment in liquid manure form through the village sewage system. On biogas livestock farms, almost all fresh manure was used to produce biogas. In addition to producing a valuable biofuel for household consumption, replacing coal or propane gas, it also has the potential to reduce the environmental pollution risk arising from discharge or mismanagement of fresh manure. However, the biogas livestock farms in our study discharged a much higher proportion of nutrients (43 kg N, 19 kg P and 12 kg K year^{-1}) into the environment instead of using it for crops as a consequence of the low nutrient content and high transport cost of the digestate. This wastes nutrients and leads to eutrophication of recipient waters. Because of the low retention time in many biogas digesters due to overdilution, there is also a risk of pathogenic bacteria, viruses and parasites persisting and being discharged with the digestate. It is therefore essential to develop appropriate technology to separate water from digestate and to eliminate pathogens by composting the digestate before use as a fertiliser.

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