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Multiple Evaluations of Use of Digested Slurry from Methane Fermentation of Household Food Waste in Vegetable Growing in Ho Chi Minh City, Vietnam

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Abstract

With the ultimate aim of constructing a recycling loop in Ho Chi Minh City (HCMC) by introducing the source-segregation of household food waste, applying methane fermentation technology to treat it, using the biogas generated as energy and the resulting digested slurry for agriculture, multiple evaluations were made of the use of digested slurry as follows: 1) a physiochemical analysis of the digested slurry obtained by methane fermentation of household food waste in HCMC; 2) a crop growth experiment using the slurry on green mustard; and 3) a simulation of transporting the digested slurry and applying it in agriculture. The digested slurry had a lower ammonia nitrogen content and a smaller ratio of ammonia to total nitrogen than those in previous studies of digested slurries from food waste in other countries. It also had a low harmful contaminant content. The crop growth experiment using the slurry clarified the positive effects of digested slurry on green mustard: plant yield and height, and the width of the biggest leaf produced per seedling, were significantly greater than when no nitrogen was applied. Yield was highly correlated with the ammonia nitrogen application rate, and almost the same fertilization effects as those with chemical fertilizer are expected to be obtained if fertilization design were based on the ammonia nitrogen levels in the digested slurry. No definitive effects of the digested slurry on soil were found. The simulation revealed that the transport and application of digested slurry in the suburbs of HCMC would likely be more efficient than in Japan due to the longer period for application and smaller required storage capacity of digested slurry throughout the year in a climate warmer than that in Japan.

Discipline: Agricultural engineering
Additional key words: ammonia nitrogen, fertilizer effect, resource circulation, transportation and application

Introduction

Appropriate waste treatment is a now global issue in view of worldwide increases in waste generation and a lack of relevant policies, regulations, basic infrastructure and efficient management programs, as well as limited budgets. Especially in developing Asian countries, the quantities of municipal solid waste (MSW) and the problems associated with it are becoming serious, coupled with rapid industrialization, urbanization, economic growth, and a growing population as incomes and standards of living rise (Dhokhikah & Trihadiningrum 2012). In Vietnam, which is representative of these Asian nations, about 7,000 t/day of MSW was generated in Ho Chi Minh City (HCMC)—the country's largest urban area—in 2014 (Verma et al. 2016).

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The rate of MSW generation in HCMC is increasing with population growth, and most of the MSW is disposed of in landfills (Schneider et al. 2017, Verma et al. 2016). Most MSW (currently, more than half; Hitz et al. 2017) is comprised of food waste. Inefficiencies in infrastructure and treatment systems for this kind of waste have led to serious problems, such as greenhouse gas emissions and the contamination of groundwater by leachate in landfills (Verma et al. 2016).

Under these circumstances, an effective solution might be to construct a recycling loop in HCMC by source-segregating household food waste, applying methane fermentation technology to treat it, using the biogas generated as energy, and using the residue—the digested slurry—for agriculture (Hitz et al. 2017). Methane fermentation has the advantage of not only treating waste but also generating renewable energy in the form of biogas, which contains approximately 60% CH_4 (Li et al. 2005). Biogas substitution for fossil fuels can reduce energy-derived CO_2 emissions, and the use of digested slurry as fertilizer can promote resource circulation. In Europe, studies on the agricultural use of digested slurries from food waste have been promoted, and the effectiveness of these slurries has been confirmed (Haraldsen et al. 2011, Odlare et al. 2011, Svensson et al. 2004, Tampio et al. 2016). For example, Haraldsen et al. (2011) found that digested slurry was as good as chemical fertilizer in terms of barley yield and NPK uptake by barley plants when equal amounts of mineral nitrogen were applied. Odlare et al. (2011) reported that digested slurry use resulted in crop yields of nearly 88% of those obtained with chemical fertilizers and higher than those obtained with no fertilization. Further, no negative effects were observed on soil ecosystems after the use of slurry for eight years in crop rotations of oats and barley.

In Vietnam, methane fermentation has mainly been applied to pig manure (e.g., Huong et al. 2014, Izumi et al. 2016, Matsubara et al. 2014, Thu et al. 2012, Vu et al. 2007, 2012), and a few studies have investigated the utilization of digested slurries of pig manure as fertilizer (Nguyen & Fricke 2015, Oritate et al. 2016). However, methane fermentation has rarely been applied to MSW in Vietnam. The only exception is a laboratory-scale experiment conducted by Tran and Le (2015), but that study presented no data on the composition of digested slurry in terms of agricultural use. It is essential to clarify the properties of digested slurry used at a site to determine the appropriate application rate and confirm the safety of the product for agricultural use, because the properties of the slurry will vary with the eating habits of people who produce the food waste and with the manner in which the waste is treated. Moreover, crop growth experiments on the use of digested slurry must be conducted at specific sites, as the fertilization effects of the slurry may differ with changes in such factors as crop type, soil properties, and local climate.

And given the generally low plant nutrient content (especially nitrogen content) in digested slurries at only 0.1% to 0.3% (e.g., Nakamura et al. 2013), which is very low compared with those of chemical fertilizers (with nitrogen content ranging from about 10% to 46%), the required application rate of digested slurry per area is larger than that for chemical fertilizers. The application of digested slurry as fertilizer also requires greater effort by farmers (i.e., more time, more equipment) than with chemical fertilizers. Therefore, it is common in Japan for methane fermentation plants to procure vacuum trucks and slurry spreaders, and provide operators in order to offer farmers services for transporting the digested slurry and applying it (Yamaoka et al. 2016a). To ensure the successful utilization of digested slurry as fertilizer, it is important in the planning phase of methane fermentation to include slurry transportation and application systems, including the numbers of operators and vehicles needed for transportation and application, and the capacity of storage tanks.

The objectives of this study were to: 1) clarify the physiochemical properties of the digested slurry obtained by methane fermentation of household food waste in HCMC; 2) elucidate the effects of the digested slurry on crops and soils through a cultivation experiment; and 3) use the results of 1) and 2) and information on crop growing conditions in suburban HCMC to propose a transportation and application system for the slurry.

Materials and methods

1. Digested slurry from household food waste in HCMC

Digested slurry for the evaluation of agronomic characteristics and use in a crop growth experiment was obtained from a laboratory-scale methane fermentation model called the “Water-needless Two-phase Methanation system” (WTM system) (Hitz et al. 2017) at Van Lang University in HCMC (Fig. 1). The WTM system has the advantage of effectively promoting the total methane fermentation process by combining the use of three independent tanks. The first is the mixing tank that promotes the fluidization of the feedstock by mixing it with digested slurry returned from the drain tank. The second is a thermophilic acidogenic reactor tank that promotes solubilization and acidogenesis of the feedstock at a high temperature (55°C in this system), and the third is the mesophilic methanogenic reactor tank that promotes methanogenesis at a moderate temperature (36°C in this system). The capacity of the thermophilic acidogenic reactor tank was 3 L and that of the mesophilic methanogenic reactor tank was 12 L. The feedstock was food remnants (Table 1) collected from household waste in a residential area of HCMC. The main components of the feedstock were 22.4% total solids (TS), 83.7% volatile solids (VS), 182 g/kg total chemical oxygen demand (T-COD), 6.82 g/kg total nitrogen (TN), and 4.47 g/kg total phosphorus (TP). All items except for TN were analyzed by the Standard Methods for the Examination of Water and Wastewater (Eaton et al. 2005); analysis of TN was based on the National Standard of Vietnam (TCVN, Vietnam's Ministry of Science and Technology). The biogas generation rate gradually increased with the increasing loading rate of feedstock, and reached approximately 0.38 m^3/kg-VS in the stationary state. The seed sludge used in this methane fermentation model was septic sludge from HCMC. The methane fermentation model was in continuous operation from 7 December 2016 to 25 January 2017. The average hydraulic retention time during the operation was 19.5 days. Approximately 5 L of digested slurry was kept in the refrigerator at 4°C in the laboratory at Van Lang University until the fertilization day of the pot experiment (see the next section). The digested slurry was sampled on 9 January 2017 and 8 February 2017, and its physiochemical properties were analyzed. The sampling on 9 January represented a spot sampling to confirm the properties of the slurry during operation of the methane fermentation model. The sampling on 8 February was conducted to determine the properties of the slurry for use in the growth experiment described in the following section; this sample was a composite from the last 16 days of operation of the methane fermentation model. The items analyzed were moisture content, pH, electrical conductivity (EC), total carbon (TC), TN, NH_4-N, P_2O_5, K^+, total potassium (TK), heavy metals (Hg, Cd, Pb, and As), and fecal indicator microbes (*Escherichia coli* and *Salmonella*). All items except for NH_4-N and Hg were analyzed by TCVN; the analysis of NH_4-N and Hg was based on the Official Methods of Analysis of AOAC International (Horwitz & Latimer 2007).

2. Effects of digested slurry on soil and green mustard growth

(1) Pot cultivation experiment

A pot experiment was performed in a net-house with a plastic roof at the Institute of Agricultural Sciences for Southern Vietnam in District 1 of HCMC. Green mustard was selected as the crop because it is popular and widely cultivated around HCMC. The pots used measured 400 mm (width) by 630 mm (length) by 150 mm (height).

The experiment was composed of the following four treatments, each with three replicates: 1) all necessary N supplied as chemical fertilizer in both basal and additional fertilizations (CF); 2) all necessary N supplied as digested slurry in both basal and additional fertilizations (DS); 3)

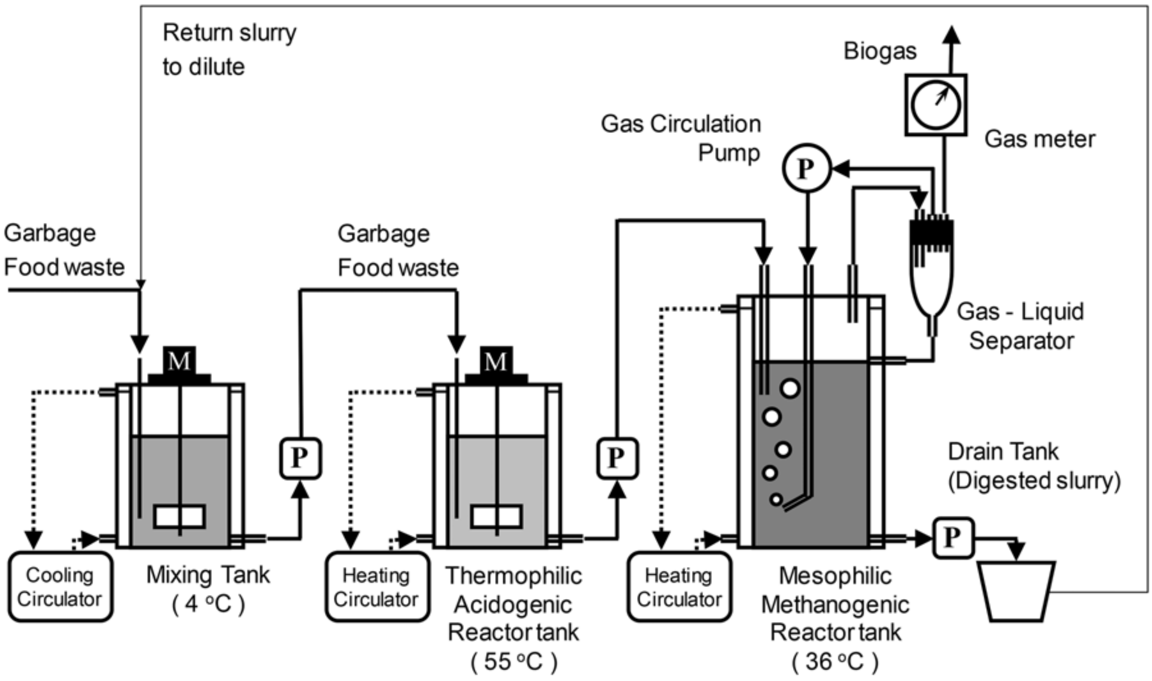


Fig. 1. The laboratory-scale methane fermentation model

necessary N supplied as digested slurry in basal fertilization and as chemical fertilizer in additional fertilization (DSCF); and 4) none of the necessary N fertilizer applied (NF). In all treatments, the necessary P_2O_5 and K_2O were supplied by chemical fertilizers to meet plant requirements. DSCF represented the current

Table 1. Composition of source-segregated household food waste in a residential area of Ho Chi Minh City

Street name in the demonstration area				Alley 25		Alley 7	
				(kg)	(%)	(kg)	(%)
Biodegradable food remnant	Readily biodegradable waste			30.65	55.8	14.00	66.3
	Non-readily biodegradable waste	Hard shell		4.36	7.9	0.14	0.7
		Soft shell		0.98	1.8	0.27	1.3
		Bone	Large bones	0.44	0.8	0.18	0.9
			Small bones	0.98	1.8	0.76	3.6
		Solid OM	Coconut shell	1.54	2.8	0.07	0.3
			Corn cobs	0.57	1.0	0.06	0.3
			Large seeds	0.27	0.5	0.01	0.0
			Small seeds	0.69	1.3	0.17	0.8
		Fibrous OM	Sugarcane bagasse	0.86	1.6	0.48	2.3
			Spices	0.01	0.0	0.05	0.2
		Subtotal		10.70	19.5	2.18	10.3
Other waste	Yard waste	Pruned branches		2.30	4.2	0.80	3.8
		Other		1.14	2.1	0.76	3.6
	Paper	Corrugated board, Used paper		1.01	1.8	0.80	3.8
		Paper beverage containers		0.21	0.4	0.01	0.1
	Nylon	Containers and packaging		1.08	2.0	0.50	2.4
		Others		4.18	7.6	1.37	6.5
	Plastics	Containers and packaging		0.20	0.4	0.04	0.2
		Other		0.59	1.1	0.20	0.9
	Diapers			0.43	0.8	0.04	0.2
	Glass			0.13	0.2	0.07	0.3
	Metal			0.10	0.2	0.07	0.3
	Clothing			0.43	0.8	0.03	0.1
	Timber			0.08	0.1	0.02	0.1
	Rubber, Leather			0.02	0.0	0.00	0.0
	Ceramics			0.12	0.2	0.00	0.0
	Coal ash, Cigarettes			0.02	0.0	0.03	0.1
	Hazardous waste			0.23	0.4	0.06	0.3
	Other	Large waste items		0.00	0.0	0.00	0.0
		Other		0.04	0.1	0.14	0.7
	Subtotal			13.59	24.7	4.94	23.4
Total				54.94	100.0	21.12	100.0

Values are means during the survey from 12 to 19 December 2016 (Hitz et al. 2017). They are expressed by rounding off to two decimal places for weight and one decimal place for the percentage of each weight. Thus, because of rounding errors, there are some small differences between the subtotals or totals shown and the total summed values.
OM: organic material

case of realistic application of digested slurry to large fields, as no method or equipment for additional fertilization with slurry has yet to be developed. The standard method of applying digested slurry to fields involves the use of a slurry spreader. The slurry spreader can be used in fields for basal fertilization because there are no plants in the field at this time, but it cannot be used at the time of any additional fertilizations because plants are present. In contrast, chemical fertilizers are usually applied manually in Vietnam and can thus be used without difficulty for additional fertilizations. DS represented the future case where the use of digested slurry for additional fertilization would have become technically feasible.

(2) Fertilization design

Fertilizers were applied in accordance with recommended application practices at the site by Department of Soil Sciences, Institute of Agricultural Sciences for Southern Vietnam. The application rates of N, P_2O_5, and K_2O for green mustard are 60, 40, and 40 kg/ha, respectively; in addition, 50% of the necessary N and K_2O and 100% of the necessary P_2O_5 are applied as a basal treatment just before transplanting, and 50% of the necessary N and K_2O are applied as additional fertilization 10 days after transplanting. The chemical fertilizers used in the experiment were urea, superphosphate, and potassium chloride.

The necessary volume of digested slurry was based on the recommended N application rate and 50% of the TN concentration in the digested slurry (i.e., 1,200 mg/L). Thus, the volume of digested slurry applied in DS was equivalent to 50 t/ha, whereas that applied in DSCF was equivalent to 25 t/ha. For basal fertilization, digested slurry was applied and immediately incorporated into the topsoil to prevent ammonia volatilization. For additional fertilization, digested slurry was applied at the roots of seedlings. In CF and NF, and in DSCF for additional fertilization, water was applied at each fertilization in the same volume as the digested slurry applied to DS. The pots were arranged in a completely randomized design.

(3) Soil

The soil used for the experiment was a gray degraded soil from a rice field (depth 0 to 20 cm) in the Cu Chi District of HCMC. The soil was sieved to less than 5 mm, and 20 kg of it was used per pot. The physiochemical properties of the soil before the experiment were analyzed, namely, bulk density, pH, EC, TC, TN, NH_4-N, NO_3-N, P_2O_5, exchangeable K_2O, CaO, MgO, cation exchange capacity (CEC), Na^+, Cl^-, particle size distribution, heavy metals, and fecal indicator microbes. After the experiment, the soils were analyzed for the same items as before the experiment, with the exception of bulk density, particle size distribution, MgO, and CaO. Hg, Cd, As, and fecal indicator microbes were also not analyzed after the experiment, given their low levels in the digested slurry. All items except for NH_4-N and Hg were analyzed by using methods based on those of TCVN, and the analysis of NH_4-N and Hg was based on the methods of AOAC (Horwitz & Latimer 2007).

(4) Cultivation

Green mustard seeds were germinated in a seed bed in a net-house for 10 days (from 8 to 17 February 2017) before being transplanted into pots. There were six seedlings in two lines per pot. The spacing between seedlings was 15 cm. Irrigation was conducted with the net-house's automatic drip and spray irrigation system. Twice a day, 300 to 500 mL of water/pot was usually applied. Pesticides or herbicides were not used during the experiment. Seedlings of green mustard were harvested 35 days after sowing on 15 March 2017. All seedlings in each pot were pulled up by the roots and then cut at the roots. The height of the aboveground parts and the width of the biggest leaf of each seedling, plus the fresh weight of all seedlings together in each pot, were measured. After measurement, seedlings were analyzed for TN concentration by using TCVN methods. After the harvest, soil at a depth of 0 to 10 cm was sampled randomly from the surface of each pot, and its physiochemical properties were analyzed.

(5) Data analysis

For the pot cultivation experiment, green mustard yield and height, width of the biggest leaf per plant, and TN content, as well as the soil properties after harvest, are each given as means of three replicate measurements. Significant differences among treatments were analyzed by Tukey's multiple comparisons ($P < 0.05$) using R ver. 3.4.0 (R Development Core Team 2005).

3. Plan for transportation of digested slurry and application to vegetables near HCMC

Yamaoka et al. (2009, 2011, 2012) developed a model for the transportation and application of digested slurry, so as to easily estimate the requirements for these two processes. The model simulates the transportation and application of digested slurry in coordinating both processes, and calculates the numbers of operators and vehicles required, and the capacity of the storage tanks.

The following data were used; the underlined values were input to the model. Some values in the following explanation are expressed using up to three significant digits. Therefore, there are small differences between some of the expressed values and the values obtained in the calculations.

(1) Annual generation rate and nitrogen concentration of digested slurry

The annual generation rate of digested slurry was assumed to be 3.65×10^4 m^3/year based on the planned methane fermentation plant capacity of 100 t/day (Hitz et al. 2017) and operation of 365 days/year. The concentration of effective nitrogen in the digested slurry was assumed to be 0.7 kgN/m^3. The value was assumed here to be for NH_4-N.

(2) Transportation distance of digested slurry

The average transportation distance of the digested slurry was assumed to be 7 km, as follows:

a. The future methane fermentation plant was assumed to be located in the Cu Chi District of HCMC, because MSW in HCMC is treated in this district at present.

b. The area of vegetable fields as a ratio of the total area was estimated at 3.5%, because the total area of the Cu Chi District is approximately 4.35×10^4 ha and that of vegetable fields is 1.52×10^3 ha (Cu Chi District Biomass Town Concept, MAFF).

c. A circle 7 km in radius in the Cu Chi District was estimated to contain 270 ha of vegetable fields (assuming a vegetable field percentage of 3.5% as above).

(3) Frequency, season, and period of application of digested slurry

A survey of local farmers (Hitz et al. 2017) revealed that it is possible to grow six crops of vegetables per year in HCMC. From this, it was assumed that half were grown in the dry season and half in the rainy season. It was assumed that digested slurry was applied as basal fertilization 10 days after sowing (as in our experiment), and the maximum possible length of the application period was set at 13 days, based on the assumption that basal application would take about two weeks with a 5% impossibility of application. The maximum possible working time per day was 7 h in the dry season, and 5 h in the rainy season. These times reflect the weather and working style in HCMC, where there is heavy afternoon rain during the rainy season, and where work typically starts early in the morning year-round.

(4) Application rate and area of digested slurry per crop

The application rate of digested slurry was assumed to be 30 kgN/ha. This was the same as for DSCF, in which digested slurry was used only for basal fertilization. It was based on a consideration of realistic application rates in large fields. The application rate of digested slurry was then calculated as approximately 42.8 m^3/ha from the application rate of 30 kgN/ha and an effective nitrogen concentration in the digested slurry of 0.7kgN/m^3. Considering reports that it is possible to apply 50 t/ha of digested slurry to upland fields of Andosol in Japan (Nakamura et al. 2013), and that 50 t/ha of digested slurry is used as basal fertilization for paddy rice in Japan (Hatanaka et al. 2014), an application rate of 42.8 m^3/ha was not likely to be problematic. The annual application area of digested slurry was calculated as approximately 852 ha/year from the annual generation rate of digested slurry (3.65×10^4 m^3/year) and the application rate of 42.8 m^3/ha, and the application area per crop was calculated at approximately 142 ha in considering the planting of six crops per year.

(5) Other conditions

Other necessary data related to vehicles were prepared (Table 2). These were the default values set in the model (Yamaoka et al. 2014a, 2016b) as a general case in Japan: obtaining these data was difficult, given the lack of research on slurry transportation and application in Vietnam, with the exception of the authors' previous study (Oritate et al. 2016).

Table 2. Dataset for calculations in the model for transportation and application of digested slurry

Item		Value	Unit
Basic conditions	Preparation, clearing of vehicle, and rest	1	h/day
	Running speed of vacuum truck and vehicle for transportation of slurry spreader	25	km/h
Vacuum truck	Minimum number	1	
	Maximum number	6	
	Loading capacity of digested slurry	3.6	m^3/truck
	Loading time of digested slurry	15	minutes/shuttle
	Time to pump digested slurry out to slurry spreader	6	minutes/shuttle
Slurry spreader	Loading capacity of digested slurry	2.5	m^3/slurry spreader
	Application speed of digested slurry	1.5	ha/h
Vehicle to transport slurry spreader	Loading time of slurry spreader	12	minutes/shuttle
	Unloading time of slurry spreader	12	minutes/shuttle

Results and discussion

1. Physicochemical analysis of digested slurry

Table 3 lists the physiochemical properties of the digested slurry. The results for all items analyzed were similar on the two sampling occasions. In the analysis of primary nutrients, TN was approximately 0.24%, NH_4-N was approximately 0.07%, P_2O_5 was 0.09% to 0.12%, K^+ was approximately 0.04%, and TK was approximately 0.05%. In the analysis of items closely associated with crop growth, NH_4-N and its ratio to TN were lower than in digested food-waste slurries in previous studies (Haraldsen et al. 2011, Nakamura et al. 2013, Tampio et al. 2016). In those previous studies, the NH_4-N concentration was more than 1,550 mg/L and the NH_4-N/TN ratio was more than 50%, whereas here they were approximately 700 mg/L and about 30%, respectively. Moreover, PO_4-P concentrations (calculated based on the value of P_2O_5) in this study were higher than in the abovementioned studies, whereas the TK concentration was lower. For example, Nakamura et al. (2013) and Tampio et al. (2016) found PO_4-P concentrations in digested slurry of 35.2 mg/L and 60 to 270 mg/L, respectively, whereas the value in this study was more than 380 mg/L. Previous studies have found TK concentrations greater than 1,000 mg/L, whereas our values were approximately 500 mg/L. These differences may be derived, for example, from differences in dietary habits and food-waste separation systems among the study countries. Notably, the concentrations of heavy metals such as Cd, Pb, As, and Hg in the slurry were below the threshold standards for these heavy metals in commercial fertilizers in Vietnam (MARD-Vietnam 2014). Also, the levels of fecal indicator microbes (*E. coli* and *Salmonella*) were well below the threshold standards for commercial fertilizers in Vietnam (MARD-Vietnam 2014). Together, these results indicated that the use of digested slurry would not negatively affect crops or the environment, at least in the short term.

2. Effects of digested slurry on soil and green mustard growth

(1) Effects of digested slurry on growth of green mustard

Table 4 lists the yield and height, the width of the biggest leaf per plant, and the TN content of green mustard harvested 35 days after sowing. Digested slurry had positive effects on the green mustard, because its use resulted in a yield, height, and biggest-leaf width that

Table 3. Physiochemical properties of digested slurry, and limitation values of heavy metals and fecal indicator microbes in fertilizers, as prescribed in guidance documents issued by the Vietnamese government

Item analyzed	Units	Analysis results		Limitation value 1)
Sampling date		9th January 2017	8th February 2017	
Moisture content	%	94.4	98.7	-
pH		7.87	7.93	-
EC	mS/cm	5.84	7.82	-
TC	mg/L	18,800	16,340	-
TN	mg/L	2,400	2,350	-
C/N ratio		7.8	7.0	
NH_4-N	mg/L	726	702	-
P_2O_5	mg/L	1,200	880	-
K^+	mg/L	417	442	-
TK	mg/L	500	470	-
Cd	mg/L	Not detected 2)	Not detected 2)	5.0
Pb	mg/L	6.0	5.9	200
As	mg/L	Not detected 3)	0.52	10.0
Hg	mg/kg	0.13	0.17	2.0
E. coli	MPN /mL	<0.3	<0.3	1.1×10^3
Salmonella	CFU/25mL	Not detected	Not detected	Not detected

1) Circular No. 41/2014/TT-BNNPTN,T issued by the Ministry of Agricultural and Rural Development on 13th November 2014
2) Method-detection limit is 0.05.
3) Method-detection limit is 1.0.

were not significantly different from those obtained with chemical fertilizer treatment, but were significantly greater than those obtained with no-nitrogen-application treatment. Yield was proportional to the NH_4-N application rate, with a high R^2 value (0.99) indicating a high degree of correlation (Fig. 2). In contrast, the correlation between yield and applied TN was weak. This result indicated that the application rate of mineral nitrogen had a large effect on yield, as was found in previous studies (Haraldsen et al. 2011, Svensson et al. 2004, Tampio et al. 2016). The fertilization design in this study was based on an effective nitrogen level of 50% of TN in the digested slurry, with the expectation that a certain amount of organic nitrogen in the digested slurry would be readily mineralized following application to the soil. The expectation was derived from the result that the ratio of NH_4-N to TN in this digested slurry was less than 30%—lower than that in the abovementioned studies (typically more than 50%). This low ratio of NH_4-N to TN suggested that the organic matter was not fully decomposed in the methane fermentation, and that a certain amount of readily mineralizable organic nitrogen would remain in the digested slurry. However, the results indicated that there was little mineralization of organic nitrogen in the digested slurry; thus, the amount of effective nitrogen in the digested slurry was in fact almost equal to the amount of NH_4-N. It was thus concluded that almost the same fertilization effects would be obtained with digested slurry and chemical fertilizer if the fertilization design were based on the NH_4-N content of the digested slurry.

(2) Effect of digested slurry on soil

Table 5 lists the soil properties before and after the experiment for each treatment. The main characteristics

Table 4. Yield and height, width of the biggest leaf per plant, and total nitrogen (TN) contents of green mustard harvested 35 days after sowing[1), 2)]

Treatment	Yield[3)]	Plant height	Width of biggest leaf	TN in plant
	g/plant	cm	cm	%
CF	40.3 ± 5.4 a	26.8 ± 1.1 a	11.0 ± 0.7 a	2.32 ± 0.15 a
DS	32.3 ± 1.3 a	25.9 ± 0.4 a	10.4 ± 0.1 a	2.26 ± 0.15 a
DSCF	38.1 ± 5.6 a	27.1 ± 0.9 a	11.0 ± 0.5 a	2.35 ± 0.13 a
NF	17.0 ± 1.1 b	20.1 ± 0.5 b	8.1 ± 0.3 b	2.07 ± 0.16 a

1) Values are means ± standard deviations ($n = 3$).
2) Different letters indicate significant differences among treatments by Tukey's test ($P < 0.05$).
3) "Yield" indicates the weight of aboveground parts.

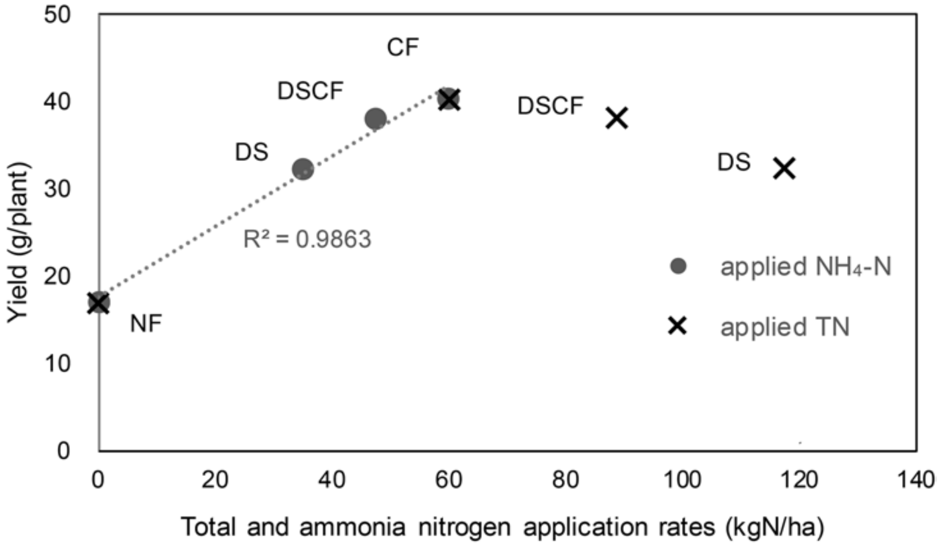


Fig. 2. Correlation between yield of green mustard and each nitrogen application rate
(Note: All nitrogen contents in chemical fertilizer (urea) were calculated as NH_4-N.)

of gray degraded soils (Nguyen et al. 2002)—namely, relatively low organic carbon and nutrient contents—were also observed in this soil. There were no significant differences for almost all items, except for NH_4-N, water-soluble Cl, and pH (KCl), in comparison with the soil amended with chemical fertilizer and that amended with digested slurry. This trend agreed with the results of Odlare et al. (2008), who found few significant differences in soil chemical properties between the application of digested slurry and chemical fertilizers in four years of crop rotation of oats and barley. The current study indicated that NH_4-N in soil fertilized by chemical fertilizer was significantly higher than that in soil amended with digested slurry; the result for water-soluble Cl was the opposite. However, because the values in the NF treatment were similar to those in the slurry treatments, it was difficult to conclude that the abovementioned differences among treatments were derived from fertilization. It was concluded that the application of digested slurry affected few soil properties in this short-term experiment, but that long-term field experiments are needed before digested slurry can be used.

3. Plan for transportation of digested slurry and application to vegetables in HCMC

(1) Number of vacuum trucks for one unit

As a first step for simulation with the model, we calculated the number of vacuum trucks per working unit, which was composed of one slurry spreader and

Table 5. Soil properties before and after the pot experiment

Analysis items		Unit	Before experiment	After experiment1)			
				CF	DS	DSCF	NF
Bulk density		g/cm^3	1.25	-	-	-	-
pH (H_2O)			-	4.39 a	4.52 a	4.41 a	4.42 a
pH (KCl)			4.26	4.36 b	4.41 a	4.38 ab	4.37 ab
EC		mS/m	6.87	5.81 b	6.10 b	6.12 b	9.13 a
TC		g/kg	15.8	17.2 ab	19.7 a	19.1 ab	15.8 b
TN		g/kg	1.0	1.2 b	1.3 b	1.6 a	1.2 b
NH_4-N		mg/kg	3.50	8.97 a	6.93 b	5.70 b	7.23 ab
NO_3-N		mg/kg	2.80	2.82 a	3.50 a	3.10 a	3.03 a
P_2O_5		mg/kg	262	318 a	331 a	319 a	307 a
Exchangeable K_2O		mg/kg	28.9	26.5 b	28.1 ab	21.3 b	37.3 a
CaO		mg/kg	740	-	-	-	-
MgO		mg/kg	520	-	-	-	-
Water soluble Na		mg/kg	21.5	18.4 b	26.5 a	17.5 b	19.7 a
Water soluble Cl		mg/kg	4.44	3.17 b	4.50 a	4.64 a	4.43 a
CEC		$cmol_c$/kg	8.60	4.10 a	4.19 a	4.33 a	4.49 a
Pb		mg/kg	9.00	9.47 a	9.30 a	8.98 a	9.20 a
Cd		mg/kg	N.D.2)	-	-	-	-
As		mg/kg	4.09	-	-	-	-
Hg		mg/kg	0.02	-	-	-	-
Particle size distribution3)	Sand	%	85	-	-	-	-
	Silt	%	8.0	-	-	-	-
	Clay	%	7.0	-	-	-	-
Soil texture			LS	-	-	-	-
E. coli		MPN/g	<0.3	-	-	-	-
Salmonella		CFU/25g	N.D.4)		-	-	-

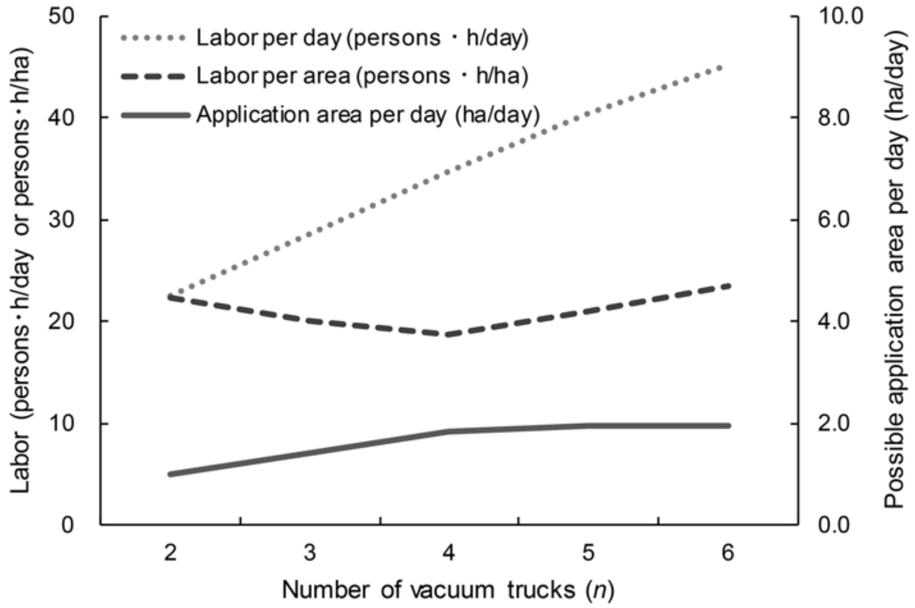
1) Values after the experiment are averages (*n* = 3); different letters indicate significant differences among treatments by Tukey's test ($P < 0.05$).
2) Less than the method-detection limit of 0.05
3) Sand: 0.02 - 2 mm, Silt: 0.002 - 0.02 mm, Clay: < 0.002 mm
4) Not detected

some vacuum trucks. From the model calculation conditions shown in Section 3 of Materials and methods and Table 2, by varying the number of vacuum trucks from two to six, the possible application area per day (ha/day) and the labor required (persons・h/day) to operate one unit were calculated. Then, the labor required per area (persons·h/ha) was calculated (Fig. 3). The minimum labor per area (persons·h/ha) was obtained when four vacuum trucks were used per unit, in both the dry season and the rainy season. This is because as the number of vacuum trucks increased, the labor per day increased proportionally, but the application area per day barely increased with any increase in the number of vacuum trucks beyond four due to the limited nature of slurry spreader operation. Thus, the number of vacuum trucks per unit was chosen as four.

(2) Setting the area of farmland blocks

In the model, a group of farmlands targeted by the

(a) Dry season



(b) Rainy season

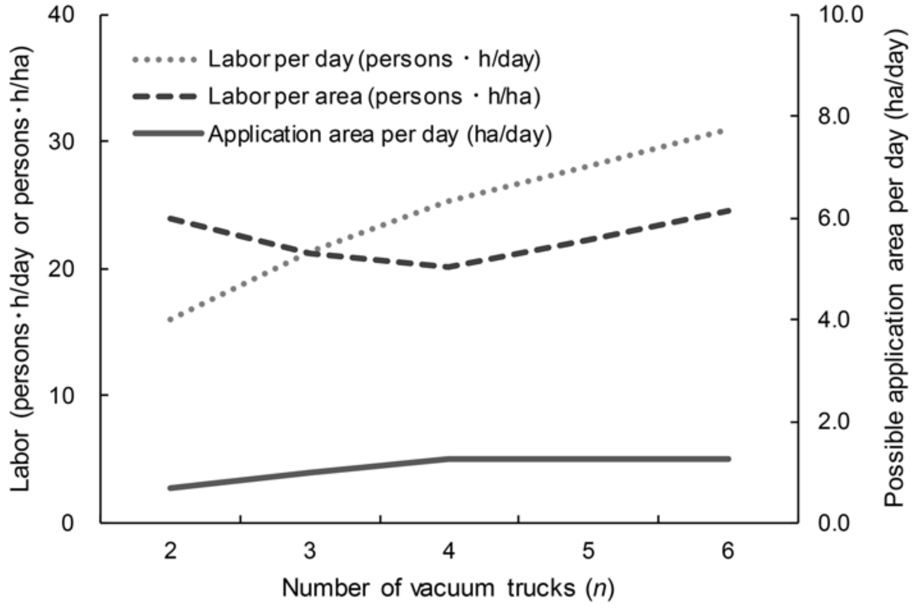


Fig. 3. Changes in labor requirements and maximum possible application area per day
(This information was used to set the number of vacuum trucks required.)

transportation and application of digested slurry by one unit was defined as a “farmland block,” and the transportation distance to, and application area of each farmland block was used in the model calculations. The areas of the farmland block in the dry season and rainy season were set based on the application area for one crop of 142 ha (as shown in Section 3 of Materials and methods) as described below.

Dry season

The maximum possible application area per day using one unit was 1.85 ha (Fig. 3 (a)), and the application area per crop per unit was 24.0 ha (≈1.85 ha × 13 days). The total application area per crop of 142 ha thus needed to be divided into six farmland blocks (142 ha/24.0 ha = 5.92). The area of each of blocks 1 to 5 was calculated as 24.0 ha, whereas that of block 6 was 22.0 ha [142 ha – (24.0 ha × 5 blocks)].

Rainy season

The maximum possible application area per day using one unit was 1.26 ha (Fig. 3 (b)), and the application area per crop per unit was 16.4 ha (≈1.26 ha × 13 days). The total application area per crop of 142 ha thus needed to be divided into nine farmland blocks (142 ha/16.4 ha = 8.66). The area of each of blocks 1 to 8 was calculated to be 16.4 ha, whereas that of block 9 was 10.8 ha [142 ha – (16.4 ha × 8 blocks)].

(3) Application rate per day and storage volume of digested slurry

The transportation and application of digested slurry were simulated by using the model and the calculation conditions obtained in (1) and (2) above (Fig. 4). Approximately 400 m^3 per day of digested slurry needed to be transported and applied during the application period. The required storage tank capacity was thus 4.6 × 10^3 m^3, as the maximum storage volume of digested slurry was, at most, 4.6 × 10^3 m^3 in this case (Fig. 4). This capacity corresponds to 46 days of digested slurry generation. In previous simulation studies with this model in Japan, the tank was required to store the slurry from 173 days of digestion when the slurry was mainly applied to paddy fields, with some being applied to upland fields (“Case A”) (Yamaoka et al. 2014a, b). The tank needed to store slurry from 263 days of digestion when the slurry was applied only to paddy fields (“Case B”) (Yamaoka et al. 2016b). The reason for the need for a slurry storage tank of larger volume in Japan was the long period during which digested slurry could not be applied to the fields due to the weather. This period was extended to approximately 5 months (from 21 November to 14 April the following year) in Case A and 8.5 months (from 1 August to 15 April of the next year) in Case B. In contrast, for farmlands in suburban HCMC, the storage period was much shorter (at about 1.5 months, as shown in Fig. 4). Moreover, in Japan, the transportation and application of digested slurry are concentrated before the transplanting of rice plants in April and May. About 30% of the annual application of digested slurry was applied in this season in Case A, and about 70% in Case B. Both cases were therefore deemed inefficient, given the need to provide the necessary operators and vehicles for a limited season.

This simulation was conducted under limited conditions (six plantings per year and a 13-day application period for each crop), reflecting the conditions in suburban HCMC. However, it can be concluded that, because the warmer climate enables an extension of the growing season in Vietnam, more effective operation is possible than in Japan when targeting the farmlands of

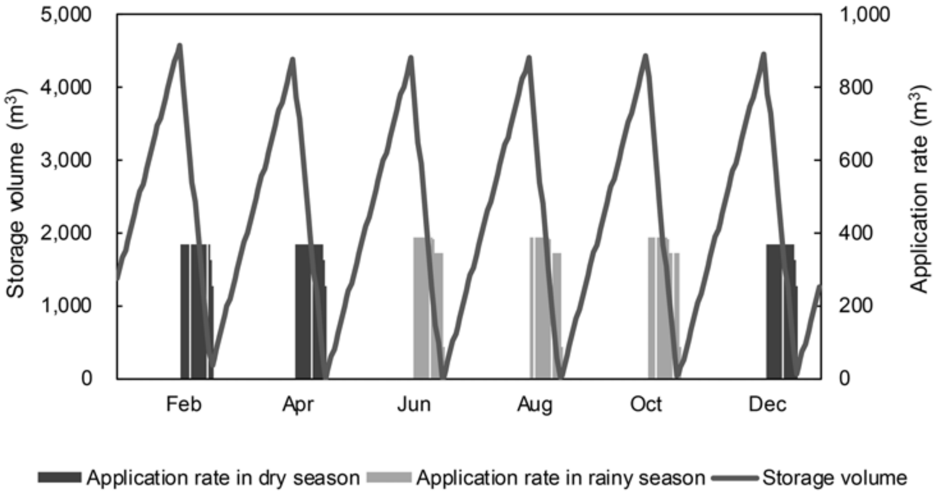


Fig. 4. Annual application rates and necessary storage volumes of digested slurry, as calculated by the model for transportation and application of digested slurry

suburban HCMC. More efficient operation would be achieved by shortening the transportation distance and extending the application period by obtaining more detailed information about farmland locations and cultivation conditions. In particular, shortening the transportation distance could not only increase efficiency but also help reduce greenhouse gas emissions in digested slurry utilization systems, as shown by Nakamura et al. (2014).

Conclusion

The primary nutrient contents in digested slurry of household food waste from HCMC were approximately 0.24% TN, 0.07% NH_4-N, 0.09% to 0.12% P_2O_5, 0.04% K^+, and 0.05% TK. NH_4-N, NH_4-N/TN, and TK were lower than those in digested food-waste slurries in other countries, whereas PO_4-P was higher. The content of harmful components such as heavy metals and fecal indicator microbes was lower than the threshold standards in Vietnam.

The pot experiment using digested slurry clarified the positive effects of digested slurry on green mustard, because yield and height, and width of the biggest leaf per plant of the green mustard produced were significantly higher than when no nitrogen was applied. Yield was proportional to the NH_4-N application rate. These findings indicate that almost the same fertilization effects would be obtained with digested slurry as those obtained with chemical fertilizer if the fertilization design were based on the content of NH_4-N in the digested slurry, as in previous studies. No definitive effects of the digested slurry on the soil were found in this short-term experiment. However, long-term experiments to investigate these issues will be required.

The simulation proposed the use of six units, each composed of one slurry spreader and four vacuum trucks in the dry season, and nine units of the same composition of vehicles in the rainy season to deal with 3.65×10^4 m^3/year of digested slurry on 852 ha/year (142 ha/crop × 6 crops) of farmland. A 4.60×10^3 m^3 storage tank volume was chosen as being suitable to meet the needs of transporting digested slurry and applying it to farmlands in the suburbs of HCMC. The proposed system for the transportation and application of digested slurry in the suburbs of HCMC would likely work more efficiently than in Japan due to the longer growing season in Vietnam. Having detailed information on farmland location and cultivation conditions would increase the efficiency of transportation and application.

The information obtained here will be useful for constructing a recycling loop in HCMC by introducing the source-segregation of household food waste, applying methane fermentation technology to treat the waste, using the biogas generated as energy, and using the digested slurry for agriculture.

The composition of the digested slurry can fluctuate with fluctuations in the composition of the feedstock; therefore, an ongoing investigation is necessary in order to accurately estimate the application rates in commercial situations.

Further investigations, such as growth experiments using digested slurry on different types of soil or on different crops over the long term, along with economic evaluations and the use of detailed site information to plan the transportation and application of digested slurry, remain as tasks for the future.

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