Greenhouse gas emission from the total process of swine manure composting and land application of compost

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HIGHLIGHTS

- The GHG emission factors of swine manure compost & land application were developed.
- The GHG emission factors of this case study are lower than that of IPCC.
- The GWP was dominated by CH₄ in the composting, land application emitted most N₂O.

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ABSTRACT

Greenhouse gas (GHG) emissions from animal manure management are of great concern in China. However, there are still great uncertainties about China's GHG inventory due to the GHG emission factors partly used default values from the Intergovernmental Panel of Climate Change (IPCC) guidelines. The purpose of this study was to use a case study in Beijing to determine the regional GHG emission factors based on the combination of swine manure composting and land application of the compost with both on-site examination and a life cycle assessment (LCA). The results showed that the total GHG emission factor was 240 kgCO₂eq tDS⁻¹ (dry solids), including the direct GHG emission factor of 115 kgCO₂eq tDS⁻¹ for swine manure composting and 48 kgCO₂eq tDS⁻¹ for land application of the compost. Among the total GHG emissions of 5.06 kgCH₄ tDS⁻¹ and 0.13 kgN₂O tDS⁻¹, the swine manure composting contributed approximately 89% to CH₄ emissions while land application accounted for 92% of N₂O emission. Meanwhile, the GHG emission profile from the full process in Beijing in 2015 and 2020 was predicted by the scenario analysis. The composting and land application is a cost-effective way for animal manure management in China considering GHG emissions.

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1. Introduction

The intensive livestock industry in China sharply increased pig output by 60% from 2000 to 2010 (Ministry of Agriculture of China, 2011), and the amount of animal waste produced increased consequently. According to the National Census on Pollution Sources (Environmental Protection Agency of China, 2010), the total amount of animal waste produced was 243 million metric tons in 2007, and part of the discharged water pollutants accounted for 42% of the total COD_{Cr} (Chemical Oxygen Demand) and 22% of total nitrogen (TN) of wastewater nationwide. Moreover, cattle and swine manure are

among the major contributors to greenhouse gases (GHG) and global warming potential (GWP). The Second National Communication on Climate Change (2013) revealed that CO₂ equivalents from livestock manure management in China in 2005 were 4.34 times more than the emission estimate of the year 1994 (National Development and Reform Commission, 2004). However, there is still great uncertainty about the national GHG inventory derived from waste management in China. On one hand, the GHG emission factors from animal waste management used in the inventory analysis of China were based on default values recommended by the IPCC, whose data were from a few literature sources (IPCC, 2006a). On the other hand, GHG emission factors from animal waste management based on on-site observations in China was lacking.

As a cost-effective way to treat and reutilize organic wastes such as animal waste (Kumar, 2011), composting and compost land

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Fig. 1. The technical roadmap of windrow composting at the farm scale.

application for agriculture is encouraged and promoted in China, e.g., a policy of technological control for livestock and poultry pollution (Ministry of Environmental Protection of China, 2011) was officially issued in 2011. Of the total farm fields in China, 12% were vegetable fields, which were generally applied with fertilizer or compost (Ministry of Agriculture of China, 2011). Organic fertilizer such as manure compost, which is low in N content and high in organic matters, was widely used as a soil conditioner to amend the soil structure and complement organic matter. It is estimated that the potential organic fertilizer resources of 3.05 million metric tons of N, 1.40 million metric tons of P_2O_5 and 2.95 million metric tons of K_2O like compost (Li, 2011) could possibly make up the gap of imported inorganic fertilizer of 0.44 million metric tons per year (Ministry of Agriculture of China, 2011). Although 74% of N_2O emissions in China were due to direct emission from agricultural activity (National Development and Reform Commission, 2013), compost land application was also considered as a temporary reserve for GHG. The application of compost to agricultural land has been reported to increase soil carbon (C) content, and is regarded as a means of C sequestration (Smith et al., 1998).

GHG emissions from composting of manure (Czepiel et al., 1996), other organic wastes (Recycled Organics Unit, 2006; USEPA, 2002), and land application of compost (Whalen et al., 2008) had been widely studied. However, these studies paid little attention to their global warming potential. Many greenhouse gas emission calculations were oriented towards fuel combustion by facilities and machines (Suh and Rousseaux, 2002), but the composting pile has a greater emission potential for climate change (Butler and Hooper, 2010; Kumar, 2011). The GHG emissions from fertilization practices in crop production were influenced by the key factors of N uptake efficiency (Novak and Fiorelli, 2010) and the enhancement of soil organic carbon (SOC) remediation (Smith et al., 1998). However, current research on GHG calculation combining composting operation and land application of compost is rare, whereas existing research that draws on field tests has been mostly focused on rice paddies, wheat and maize rather than vegetable fields (Pei et al., 2011).

Another fact leading to the great uncertainty over the GHG inventory from waste management in China is extremely lack of on-site GHG observation data. Most of the relevant research was conducted at pilot scale (Fukumoto et al., 2003; Hao et al., 2001; Jiang et al., 2011) rather than at large scale. Moreover, few studies undertake integrated analysis of the total process of animal manure composting and land application of the manure compost, including mechanical operation and power supply as a whole system (Thelen et al., 2010). Therefore the purpose of this study was to determine GHG emission factors from the total process of swine manure composting and land application of compost through on-site observations and a life cycle assessment using a case study in Beijing,

China. Both uncertainty and scenario analyses related to the case study's GHG emissions were conducted.

2. Materials and methods

2.1. Field test

An animal manure composting plant and a vegetable field applied by manure compost from an intensive swine farm were investigated in this study. The animal manure composting plant, which has an area of 1.34 ha, annually produces about 4.0 thousand metric tons of manure compost (25% of moisture content) using windrow composting technology as shown in Fig. 1. The composting plant operates in a typical mode with a total of 24 windrows, each of which is 75.00 m long, 2.00 m wide and 0.90 m high (50 t of treating capacity per windrow). The windrow composting period usually includes a thermophilic stage (2–3 weeks) and a maturity stage (nearly one month). The manure compost product is sold as an organic fertilizer for soil amendment.

In this study, the investigation of the entire process of animal manure composting and land application of the compost included 53 days of swine manure composting from May to July in 2011 and 68 days of land application of the compost in a lettuce (*Lactuca sativa* L.) field from December 2011 to February 2012, respectively. The manure was collected in daily routine from the hogpen, while the mushroom residue was transported from the mushroom plant nearby. The experimental windrow composting pile had a capacity of 25 t with a size of 35.00 m × 2.00 m × 0.90 m (L × W × H). The manure and the mushroom (Table 1) were mixed at a ratio of 2:1 (v/v) by a front loader (LW160, Xugong, China). The raw manure was representative due to similar characteristics to studies of manure composting in Beijing (Table S1). The windrows were then built up by a front loader and

Table 1
Characteristics of main raw materials of swine manure composting.

Characteristics	Composting			Land application	
	Swine manure	Mushroom residues	Mixture (Initial)	Compost	Background soil
pH	8.11	6.21	7.27	9.79	8.67
Moisture content (%)	72.02	45.00	47.80	22.58	15.94
Bulk density ($kg\ m^{-3}$)	993.10	190.21	—	—	960.51
TC ^a (g kgDS ⁻¹)	331.42	395.28	223.62	202.86	25.50
TN ^a (g kgDS ⁻¹)	25.98	22.55	20.63	21.84	1.99
TP ^a (g kgDS ⁻¹)	12.01	4.69	16.77	18.45	1.66
C:N ratio	12.75	17.53	14.86	9.29	12.78

TN – Total Nitrogen; TP – Total Phosphorus.

^a Measured based on dry matter.

Fig. 3. Fluxes and cumulative emissions of N_2O and CH_4 during composting.

moisture content, turning frequency, and compost application rate. Therefore, a Monte-Carlo simulation was carried out to minimize the overall uncertainty and to determine the variance of the GWP resulting from the input parameters. By defining the range and randomly generating the values of input variables from a Gaussian distribution in Gabi® 4.4 over 400 times, the GWP values were computed with a relative standard deviation distribution (RSD) based on around the GWP results derived from our case study. Twelve input variables (Table S3) were considered in the uncertainty analysis, of which the minimum, maximum and deviation values were used from this study's results. Literature data (Table S4 and Table S5) relevant to on-site GHG emission factors from composting and land application of compost were selected to define the variations in GHG emission factors.

2.5. Scenario analysis

The GHG emission scenario analysis of swine manure composting and land application of compost in this study was simulated for the next 5–10 years, and this time frame will be a primary concern for both the livestock industry and composting facilities to maintain their sustainability.

As expressed in Equation (1), H represents the number of output pigs (10 thousand heads) as shown in Equation (2) of Section 3.2.3, reflecting the agricultural development and population growth. R (%) is the composting treatment rate of animal manure, and the potential GHG emission factors (EF , $kgCO_2eq\ tDS^{-1}$) come from the Monte-Carlo simulation. DC is the manure discharge coefficient for fattening output pigs ($660.65\ kg\ head^{-1}\ year^{-1}$, wet weight) from the national database (Dong et al., 2011; Environmental Protection Agency of China, 2010), and $100\% - w_{H_2O}$ is the solid content of manure (%).

$$GHG_{\text{scenario}} = H \times R \times EF \times DC \times (100\% - w_{H_2O}) \quad (1)$$

There are several assumptions made for this scenario analysis: 1) the solid content of raw swine manure is 30% (Chinese Agricultural University, 1997); 2) R was assumed at three levels (10%, 30%, and 50%) as different treatment scenarios based on the current treatment scale (Lian, 2010); 3) 100% of the compost was applied to the land as its end use; and 4) the baseline year was set in 2011.

2.6. Life cycle cost analysis

The cost-benefit analysis of this case study, including energy consumption, freight, rent, labor and net profit from the compost product, was carried out by a life cycle-based cost method (LCC). Due to inadequate access to the capital costs of constructing the composting plant and greenhouses, only the operational costs were considered in this study. In addition, the vegetable cultivation within the composting plant was a low-cost endeavor. Therefore, five parts of the LCC analysis in this study are energy and fuel consumption, freight costs for trucks, rent for the leased tractor, labor costs and packaging. The power was supplied at a cost of US\$ $0.11\ (kW\ h)^{-1}$ (US\$ 1 = RMB 6.366). The fuel price was referenced to the current diesel price of US\$ $1.46\ L^{-1}$. The freight cost consisted of raw materials (US\$ $23.56\ t^{-1}$) and compost (US\$ $6.28\ t^{-1}$) transportation by trucks. Rents for tractors were paid on time at US\$ 47.12 per hour. The annual salary of a worker (10 workers in the factory) was US\$ 3768. Each package of the compost costs US\$ 0.25 ($50\ kg\ package^{-1}$). A government subsidy was provided at US\$ $18.85\ t^{-1}$ compost (moisture content at 25%).

3. Results and discussion

3.1. GHG emissions

3.1.1. Composting of swine manure

Windrow composting is done by setting up long rows of biodegradable wastes subject to decomposition with aeration by periodic turning (Shi et al., 1999). As shown in Fig. 3, the first thermophilic stage lasted 23 days, when N_2O flux decreased from a flux peak of $230\ \mu gN\ m^{-2}\ h^{-1}$ on the first day, but steadily rose afterward as did levels of CH_4 . The major contribution to GHG production occurred during the last 30-day of maturity stage, when the peak values of CH_4 and N_2O emerged on the final day (day 53) at $535\ mgC\ m^{-2}\ h^{-1}$ and $224\ \mu gN\ m^{-2}\ h^{-1}$, respectively. The cumulative N_2O and CH_4 emissions in this maturity stage accounted for 73% and 93%, respectively, of the total accumulated emission amount. The emission factors for CH_4 and N_2O were $4.51\ kgCH_4\ tDS^{-1}$ (dry manure) and $6.26 \times 10^{-3}\ kgN_2O\ tDS^{-1}$, respectively. Even though the GWP of N_2O (298 times the equivalent amount of CO_2) is 12 times more than that of CH_4 (25 times the equivalent amount of CO_2), the CO_2 equivalents of N_2O were minimal and amounted to only 1.6% of the total CO_2eq .

In this study, the total accumulated C and N losses in the form of GHG emissions were 16.90 kgC (0.58% of the initial TC of the compost mixture, TC_{ini}, dry basis) and 19.93 gN (less than 0.01% of initial TN of compost mixture, TN_{ini}, dry basis), respectively. Though a higher TN content resulted in low C:N ratio, the lower pH value might result in a relatively lower N₂O emission loss (Law et al., 2011). Other studies also took N₂O emission in concern (Huang et al., 2010; Wu et al., 2012). N₂O was detected in the early and maturity stages of windrow composting in a pilot scale of 7.70 m in length (Hao et al., 2001) with C and N losses of 0.81% TC_{ini} and 0.019% of TN_{ini}, respectively. Two other manure windrow systems (straw-rich and wood-chip mixture) in Hao's study (2004) showed comparatively higher emission losses (CH₄–C: 2.7% of TC_{ini} for straw-mixture and 2.0% of TC_{ini} for woodchips; N₂O–N: 0.39% of TN_{ini} for straw and 0.68% of TN_{ini} for woodchips-mixture). A comparable loss of 2.12% of TN_{ini} in the N₂O–N form was from an 11 m long manure windrow composting compared to a 1.53% N-loss from an aerated static system of sewage sludge composting (Czepiel et al., 1996). Meanwhile yard waste and sludge windrow reported a 0.1%–2.2% of total N loss due to N₂O (Barton and Atwater, 2002). However, these measured values of direct GHG emissions were lower than the published default values (10 kgCH₄ tDS^{−1} and 0.6 kgN₂O tDS^{−1}) from the IPCC (2006b). And most of the GHG emission factors from literature of animal manure composting listed in Table S6 were higher than those of this study.

3.1.2. Land application of swine manure compost

GHG emissions during a 2-month cultivation of *L. sativa* L. applied with swine manure compost are shown in Fig. 4. The CH₄ flux rose sharply after day 26 when the moisture content of the soil decreased to its average level of 26%, and the flux of N₂O steadily fell off from the beginning of cultivation. In the first growth stage (26 days) of *L. sativa* L., 73% of N₂O–N and 3.2% of CH₄–C were lost. The total N and C loss due to GHG emissions from the land application of swine manure compost were 732 mgN (0.2% of TN in compost, dry basis) and 3604 mgC (0.1% of TC in compost, dry basis), respectively, and N₂O surpassed CH₄ as the key contributor to GHG emissions. Hence the GHG emission factors from the vegetable cultivation were calculated at 0.50 kgCH₄ tDS^{−1} and 0.12 kgN₂O tDS^{−1}, respectively. Addition of compost promoted the N₂O while the soil moisture content regulated the CH₄ emission. Borken et al. (2006) explained that the moisture content of the soil may increase CH₄ uptake by methanotrophs, which are sensitive to water stress, and CH₄ absorption was significantly reduced by drier conditions with limited methanotroph activity (Liu et al., 2008). This would possibly result in the CH₄ emission peak due to drying soil.

A similar result for N₂O emission from a greenhouse vegetable system in northern China (Pei et al., 2011) was reported with 0.27–0.30% N loss of the nitrogen input, of which 57–94% was from N₂O emissions in the initial growth stage. Another greater loss of 0.73% N₂O–N was observed from a Nanjing vegetable field due to humid weather (Xiong et al., 2006). However, the default N₂O emission factors for agricultural soils applied with organic additions or livestock excretion deposits are 1% and 2% of TN input, respectively, in the national inventory guidelines (IPCC, 2006c). These values are 3–6 times higher than the N₂O emission factors in this study (0.34% of TN input), which would not be applicable in case of GHG inventory calculation.

3.1.3. Mass Balance of CH₄ and N₂O

The GHG emission factors in CO₂ equivalents base were 115 kgCO₂eq tDS^{−1} from swine manure composting (4.51 kgCH₄ tDS^{−1} and 6.26 × 10^{−3} kgN₂O tDS^{−1}) and 48 kgCO₂eq tDS^{−1} from land application of the compost (0.50 kgCH₄ tDS^{−1} and 0.12 kgN₂O tDS^{−1}). With the application of manure compost, the organic matter, TC and TN content in soil rose from 10.38%, 2.55% and 0.20% to 15.69%, 3.06% and 0.27%, respectively, which resulted in 14.12%, 2.91% and 0.25% remained in the soil after the reap of *L. sativa* L.

Compost and manure additions could raise the soil's carbon level and improve N use efficiency (Novak and Fiorelli, 2010). The potential benefits of integrating livestock and cropping systems had been considered to enhance the net GHG remediation of −784 gCO₂eq m^{−2} year^{−1} by corn–soybean bioenergy production and soil carbon sequestration, compared to 52 gCO₂eq m^{−2} year^{−1} for non-manure amended check (Thelen et al., 2010).

3.2. Life cycle assessment

3.2.1. Life cycle inventories and global warming potential

The major input and output mass and energy reference flows of each subprocess during the full process were listed in Table 2 as the life-cycle inventory. As shown in Fig. 5, the transportation section contributed the most to diesel consumption and the rolling engine used in greenhouse was dominant in power consumption. In terms of the GHG emissions, 56% of fossil CO₂ was from diesel consumption by vehicles, 89% of CH₄ was from the swine manure composting process, and 92% of N₂O was created by the land application of compost.

According to the inventory result, the total GHG emission factor of the complete process in this study was 240 kgCO₂eq tDS^{−1} with contributions by CH₄ (53%), fossil CO₂ (31%), and N₂O (16%), respectively. The largest GHG emission contributions of subprocesses were

Fig. 4. Fluxes and cumulative emissions of N₂O and CH₄ from the land application of compost.

Table 2

Life cycle inventory of the full process of swine manure composting and land application of compost.

Parameter	Transportation	Composting operation	Composting pile	Land application	Power grid	Diesel supply	Total
Main input							
Materials (kg tDS ⁻¹) ^d	3574 kg Raw Manure + 342 kg Mushroom residue	3916	3916	2610	—	—	—
Diesel (kg tDS ⁻¹)	8.91	3.89	0.00 ^a	0.00 ^a	0.00 ^a	0.00 ^a	12.80
Electricity (kJ)	0.00 ^a	1370	0.00 ^a	58,800	0.00 ^a	0.00 ^a	601,700
Main output							
CO ₂ (kg tDS ⁻¹)	40.85	10.45	0.00 ^b	0.00 ^b	16.39	5.25	72.94
CH ₄ (kg tDS ⁻¹)	4.04E-04	5.55E-05	4.51	0.50	0.00 ^c	5.48E-02	5.06
N ₂ O (kg tDS ⁻¹)	8.06E-04	4.71E-05	6.26E-03	0.12	0.00 ^c	9.02E-05	0.13
Percentage of CO ₂ eq (%)	17	4	48	20	7	3	100

^a No diesel or electricity was assumed to be consumed during the process.^b Biogenic CO₂ was not addressed in this case.^c According to baseline emission factors of the regional power grid (Department of Climate Change and National Development & Reform Commission of China, 2011), CH₄ and N₂O were excluded.^d Materials calculated at a 2:1 ratio of swine manure; mushroom (v/v) on the basis of 1 ton dry swine manure; for the moisture content and bulk density of swine manure and mushrooms, please see Table 1.

from swine manure composting (48%) and land application (20%) followed in order of transportation (17%), the power grid (7%), the composting operation (4%), and the diesel supply (3%).

Due to the large GHG emission potential of composting, many research have been carried out to control and mitigate GHG emissions. Jiang et al. (2011) conducted a lab-scale manure composting mixed with cornstalks to investigate operational coefficients like C/N ratio, aeration rate, and initial moisture content. Their total value of CO₂eq emission ranged from 324 to 743 kgCO₂eq tDS⁻¹ (aeration power included), and a lower C/N ratio was considered to be the effective factor in CH₄ and NH₃ reduction. The results also indicated that the aeration rate reduced the GHG emission from 747 kgCO₂eq tDS⁻¹ to 546 kgCO₂eq tDS⁻¹, however the GHG emission due to power consumption (which increases) rose from 5% to 23% of the total CO₂eq emission. Park et al. (2011) compared CH₄ and N₂O fluxes using four manure composting forms mixed with sawdust (forced aeration, wire mesh, turning, and no aeration). Among these techniques, the turning system had the highest GHG emission factor of 155 kgCO₂eq tDS⁻¹, similar to that in this study (115 kgCO₂eq tDS⁻¹). Another large scale case based on composting of household organic waste and green waste in Italy showed a net GHG emissions at 130 kgCO₂eq per ton of the original bio-wastes (Blengini, 2008) with CO₂ compensated by the avoidance of fertilizers (48 g kg⁻¹ mixed waste) and CO₂ sequestration (48 g kg⁻¹ mixed waste).

3.2.2. Uncertainty analysis

The result of uncertainty analysis was shown in Fig. 6. The GWP simulation results ranged from −20% to +90% RSD of the obtained

GHG emission factor at 240 kgCO₂eq tDS⁻¹ (0% RSD) in Gauss distribution. A percent of 88% of all the simulated values were higher than the 0% RSD, and the mean value was 300 kgCO₂eq tDS⁻¹ ± 13% RSD as discussed below in the scenario analysis.

3.2.3. Scenario analysis

In the scenario analysis of this study, two key factors should be considered as the composting rate of swine manure (R) and the number of output pigs (H). Three composting rate levels of 10%, 30% and 50% were assumed in the years 2011, 2015, and 2020 respectively. Due to the difficulty of predicting the future of the livestock and poultry industry, e.g., the outbreak of foot-and-mouth disease abruptly cut the number of output pigs between the years of 2005 and 2007 (Beijing Municipal Bureau of Statistics, 2006), a linear function was extrapolated from 2007 to 2010 ($R^2 = 0.895$) based on the population in Beijing (P , 10³ persons) and agricultural GDP (GDP_{agri}, million US\$) using the multi-variant linear regression method in SPSS® 18.0. As a result, the number of output pigs (H , 10⁴ heads) is expressed as Equation (2).

$$H = 129.874 + 0.67 \times P + 6.69 \times \text{GDP}_{\text{agri}} \quad (2)$$

Although the growth rate of the residential population (P) was expected to be controlled within 1% annually in the 12th Five-year Plan of Beijing (Beijing Municipal Commission of Population and Family Planning, 2011), the average population growth rate reached 5.07% per year from 2006 to 2011, and the GDP_{agri} rate increased by 9.0% (Beijing Municipal Bureau of Statistics and NBS Survey Office in Beijing, 2012). The results of the scenario analysis showed that the 2011 GHG emissions of 2.47×10^3 tCO₂eq at $R = 10\%$ will increase to 7.42×10^3 tCO₂eq and 12.4×10^3 tCO₂eq at $R = 30\%$ and $R = 50\%$ levels, respectively. These GHG emission values will chronologically increase by 21% in 2015 and 50% in 2020, respectively, compared to the benchmark value in 2011. This soaring increase rate of GHG emission requires more attention to GHG reduction.

Optimistically, the SOC input by compost additions was deemed to enhance carbon sequestration (Whalen et al., 2008), offset GHG emissions from biofuel agriculture practices (Thelen et al., 2010) and substitute for N fertilizer (Gajalakshmi and Abbasi, 2008) through reductions in the GWP. However, they were conservatively not considered in this study to calculate the direct emissions. One study using the DNDC (Denitrification and Decomposition) model (Wang et al., 2012) simulated the 45-year exchange of GHG emissions in a crop field beginning from a baseline year of 2009 in China. The results revealed that manure additions would help to increase the SOC in soil, compared to the inorganic fertilizer treatment

Fig. 5. Major input and output reference flows of each subprocess.

Fig. 6. Frequency distribution of global warming potential based on relative standard deviations from Monte-Carlo simulations.

(700 kgN ha⁻¹ yr⁻¹), by attenuating net GWP from 5853 to 5203 kgCO₂eq ha⁻¹ yr⁻¹ and enhanced the grain yield and SOC sequestration rate at the same time.

3.3. Life cycle cost-benefit analysis

As shown in Fig. 7, the operational cost of swine manure composting was US\$ 25.32 t⁻¹ compost (wet weight, moisture content at 25%), which could be divided into freight costs (37%) followed by labor costs (31%), packaging (20%), energy costs (11%), and tractor rental fees (0.9%). The selling price of the swine manure compost at US\$ 26.39 t⁻¹ compost (wet weight, moisture content at 25%) was much cheaper than the price of urea at US\$ 314.15 t⁻¹ (China Fertilizer Network, 2012). Although the main role of the compost acted as the soil amendment with abundant organic matter, the cost in inorganic nutrient form at 5% (25% of moisture content) was US\$703.73 t⁻¹, while the urea was higher at US\$ 930.81 t⁻¹ (inorganic nutrient rate at 45%, 25% of moisture content). With government subsidies of US\$ 18.85 t⁻¹ compost, the gross profit of compost was US\$ 45.23 t⁻¹ compost for a net profit of US\$ 19.92 t⁻¹ compost, which was largely composed of government subsidies. Although there was a vast resource, huge amount and geographical proximity of farmyard organics in China (Li, 2011), the prospects of manure compost still lay in economic feasibility and market competitiveness. With an increasing loss in soil organic matter due to excessive fertilization (Zhang et al., 2010), the compost application would be more popular among farmers according to the

governmental promotion and subsidy (Ministry of Agriculture of China, 2012) to supplement the organic humus in soil.

Illinois State University (Livestock and Urban Waste Recycling Research Team, 2004) examined the operational costs of two windrow composting processes that treated swine manure at a capacity of 2500 and 4500 tons year⁻¹, respectively. The average operational costs for the small and large capacities were US\$ 31.69 and US\$ 17.60 per ton of compost (moisture content not given), respectively, with their selling price ranging from US\$ 10 to US\$ 40 per ton of compost. These results were similar to those of this study, which showed that it would be profitable for the composting industry. Obviously, the marginal cost will be reduced with increased compost production scale, and the profit will be affected greatly by the price gap of between nitrogen-based chemical fertilizers such as urea and organic fertilizers. The land application of compost should therefore be encouraged because the compost is more cost-effective than chemical fertilizers in terms of GHG emission and support from government subsidies.

4. Conclusions

Using on-site observations and an LCA analysis, the integrated GHG emission of swine manure composting and its land application in Beijing, China was investigated for the first time. The direct GHG emission factors for swine manure composting and land application of manure compost were 115 kgCO₂eq tDS⁻¹ (99% as CH₄) and 48 kgCO₂eq⁻¹tDS⁻¹ (74% as N₂O), respectively. Considering the energy consumption, the total GHG emission factor of the entire life cycle was 240 kgCO₂eq tDS⁻¹, including 48% from the direct GHG emission during swine manure composting and 20% from land application of the compost. The results of uncertainty analysis showed that the mean GHG emission value (300 kgCO₂eq tDS⁻¹ ± 13% RSD) was 26% RSD higher than the observed GHG emission factor (240 kgCO₂eq tDS⁻¹). The scenario analysis predicts increases in GHG emission by 21% and 50% in 2015 and 2020, respectively, compared to that in 2011. The life cycle cost analysis showed that swine manure composting and land application of compost would be a cost-effective method for animal manure management in China when considering GHG emissions.

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Fig. 7. The result of the life cycle cost-benefit analysis.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at doi:10.1016/j.atmosenv.2013.08.048.

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