BIOMASS AND BIOENERGY 54 (2013) 260–266

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Life cycle assessment of greenhouse gas emissions of feedlot manure management practices: Land application versus gasification

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ARTICLE INFO

Article history:
Received 8 December 2012
Received in revised form
17 April 2013
Accepted 18 April 2013
Available online 12 May 2013

Keywords:
Feedlot manure
Land application
Gasification
Greenhouse gas emissions
Life cycle assessment

ABSTRACT

Animal waste is an important source of anthropogenic GHG emissions, and in most cases, manure is managed by land application. Nevertheless, due to the huge amounts of manure produced annually, alternative manure management practices have been proposed, one of which is gasification, aimed to convert manure into clean energy-syngas. Syngas can be utilized to provide energy or power. At the same time, the byproduct of gasification, biochar, can be transported back to fields as a soil amendment. Environmental impacts are crucial in selecting the appropriate manure strategy. Therefore, GHG emissions during manure management systems (land application and gasification) were evaluated and compared by life cycle assessment (LCA) in our study. LCA is a universally accepted tool to determine GHG emissions associated with every stage of a system. Results showed that the net GHG emissions in land application scenario and gasification scenario were 119 and -643 kg CO_2-eq for one tonne of dry feedlot manure, respectively. Moreover, sensitive factors in the gasification scenario were efficiency of the biomass integrated gasification combined cycle (BIGCC) system and energy source of avoided electricity generation. Overall, due to the environmental effects of syngas and biochar, gasification of feedlot manure is a much more promising technique as a way to reduce GHG emissions than is land application.

1. Introduction

Greenhouse gases (GHGs) effectively absorb thermal infrared radiation, emitted by the Earth's surface, the atmosphere itself, and clouds. The heat trapping process within the surface-troposphere system by GHGs is called the greenhouse gas effect [1]. Naturally occurring GHGs include water vapor, CO_2, methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) [1,2]. The increase in GHG concentration has been accepted widely as the major cause of current global warming, and animal manure is an important source of GHG [3]. In 2010, CH_4 emissions from manure management represented about 8% of total CH_4 emissions from anthropogenic activities, and manure management also was a small source of N_2O emissions [2].

Land application is the most common way to use animal manure, with the purpose of using manure nutrient as the fertilizer. Around 83% of feedlot manure typically is processed by land application [4]. However, applying feedlot manure to

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http://dx.doi.org/10.1016/j.biombioe.2013.04.011

the surrounding cropland may become unsustainable for large feedlots, as it can exceed the carrying capacity of local ecosystems leading to environmental and health concerns [5]. Gasification is an alternative way to manage animal waste. The principle of gasification is to decompose organic matter into useful energy such as syngas. In order to generate electricity and heat, syngas produced from gasification could be utilized in energy conversion devices, such as boilers and gas turbines. For small-scale power plants, typically syngas is combusted in a stationary IC engine with a generator and provisions for heat recovery. For larger scale operations, integrated gasification/combined cycle (IGCC) technology can be applied to generate electricity and heat [6]. Further, biochar, as the byproduct of gasification, has attracted growing interest globally as a soil amendment [7]. However, the nutrient value of biochar differs considerably due to the variation among the feedstock characteristics and gasifier operating conditions [8].

GHG emissions are a major factor when selecting the appropriate animal waste management practice and life cycle assessment (LCA) is a universally accepted tool to determine GHG emissions due to its "cradle-to-grave" approach [9]. LCA has been adopted to analyze emissions of GHG for different animal waste management systems. For example, Morrie et al. [10] conducted a LCA for anaerobic digesters on small dairy farms. Also, environmental effects of composting dairy manure were evaluated by Hishinuma et al. [11] by means of LCA. Nevertheless, not much information can be found related to feedlot manure management in terms of GHG emissions. Therefore, the aim of this research was to estimate GHG emissions of feedlot manure management systems (land application and gasification) by LCA. In the land application scenario, feedlot manure was collected, stored and applied as fertilizer onto the field. In the gasification scenario, feedlot manure was gasified to produce syngas and biochar, which were used as the power source and soil amendment, respectively.

2. Methodology

2.1. Goal and scope

The goal of this study was to evaluate GHG emissions of two feedlot manure management strategies: land application and gasification. The function unit was one tonne of dry feedlot manure. Emissions of each GHG were converted into carbon dioxide equivalents (CO_2-eq), which were calculated by multiplying their respective global warming potential (GWP) by the specific mass of each GHG. The GWPs of CH_4, and N_2O were 25 and 298 times that of CO_2 on a mass basis, respectively, based on a 100 year horizon [12].

2.2. System boundaries

System boundaries of the two manure management practices are shown in Fig. 1 and 2, respectively. In land application scenario, feedlot manure was collected twice a year (winter and spring), stockpiled and land applied in the fall. The avoided process was the commercial fertilizer utilization due to the manure application. In the gasification scenario, feedlot manure was collected every two months (six times a year). The collected manure was transported to an industrial-scale gasification plant. The technology of biomass integrated gasification combine cycle (BIGCC) was used to generate electricity. Biochar produced from gasification plant was transported back to the field as a soil amendment. Avoided processes were electricity generation from fossil fuel power plant, and fertilizer utilization due to biochar application.

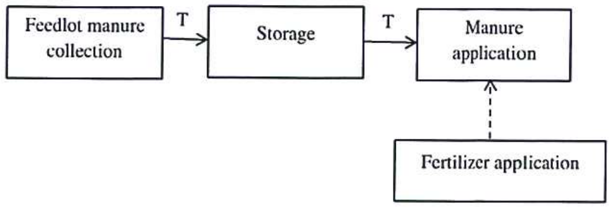

Fig. 1 – LCA boundary of land application system of feedlot manure (T stands for transportation and dashed arrows stand for avoided process).

2.3. Data inventory and major assumptions

To make the industrial-scale gasification plant possible (the feeding rate was 1 tonne of dry manure per hour), assuming the feedlot manure was provided by 10 feedlots, each with 500 animal-units (AU). AU was defined as a 454 kg cow or its equivalent [4]. The inventory data were based on the literature references and GREET Model 2012 (Argonne National Laboratory, USA) [13]. Note that emissions from the manufacture of the transportation tools were out of the consideration in this study. In addition, the biogenic CO_2 emissions were not taken into account, because carbon from biomass is part of the natural carbon cycle. The sections below include detailed information of data sources and assumptions for each life cycle stage.

2.4. Feedlot manure characteristics

Characteristics of feedlot manure vary widely due to factors of climate, diet, feedlot surface and cleaning frequency [4]. The excreted manure is usually high in moisture content and low in ash content. On the other hand, for collected feedlot manure, water concentration drops because of evaporation, and the fixed solid increases due to its incorporation into the soil. Table 1 shows the characteristics of feedlot manure used

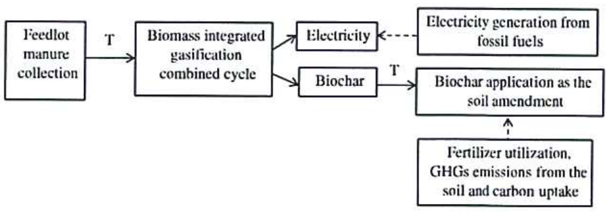

Fig. 2 – LCA boundary of gasification system of feedlot manure (T stands for transportation and dashed arrows stand for avoided process).

Table 1 – Characteristics of feedlot manure per animal unit.

Component	Excreted	Collected	Unit	References
Weight	51.2	7.9	kg d^{-1}	[4]
Moisture	884	450	g kg^{-1}	[4]
TS	5.91	4.4	kg d^{-1}	[4]
VS	5.44	2.2	kg d^{-1}	[4]
FS	0.47	2.2	kg d^{-1}	[4]
N	0.30	0.095	kg d^{-1}	[4]
P	0.094	0.064	kg d^{-1}	[4]
K	0.21	0.014	kg d^{-1}	[4]
C:N ratio	10	13	–	[4]
Higher heating value (DAF)	–	15,000	kJ kg^{-1}	[14]

(Note: TS, VS and FS are total solids, volatile solids and fixed solids, respectively).

in this study, assuming the same characteristics of collected feedlot manure for the two scenarios.

2.5. Manure collection, transportation and land application

In land application scenario, a tractor-mounted front-end loader was used to collect and pile feedlot manure, then the manure was stockpiled, and finally a spreader was used for manure spreading. Heavy-duty trucks were responsible for transportation. The average distance was assumed 5 km from the manure collection site to the storage site, and from the storage site to the designated field [5].

In the gasification scenario, the feedlot manure was collected every two months. The average distance was assumed to be 15 km from the feedlots to the gasification plant [15]. Note that there was no backhaul of trucks, which was used to transport biochar back to the designated field. Based on a feedlot (250 cattle) manure handling system presented by Ghafoori et al. [5], working hours and distance of equipment for one feedlot (500 AU) were adjusted and listed in Table 2. From Table 1, feedlot manure production was 7.9 kg day^{-1} for one AU, the number of heavy-duty trucks (payload = 18,144 kg) also were listed in Table 2. It was assumed that diesel was consumed by the front-end loader, heavy-duty trucks and spreaders, and GHG emissions of those equipment were calculated by GREET Footprint Calculator 2012 (Argonne National Laboratory, USA) [16].

2.6. Manure emissions

GHG emissions from collection, storage and treatment depend on the amount of manure produced, C and N contents, temperature and management method. In general, liquid systems generate relatively more CH_4, while solid systems produce more N_2O [17]. CH_4 and N_2O emissions from annual manure production were estimated by Equations (1) and (2), respectively [4]:

$$\text{Methane emissions (kg year}^{-1}) = VS_{excreted} \times B \times 0.67\ \text{kg m}^{-3} \times MCF \quad (1)$$

where $VS_{excreted}$ = Volatile solids excreted (kg $year^{-1}$), B = maximum CH_4 producing capacity on VS (m^3 kg^{-1}), MCF = CH_4 conversion factor bases on the waste minimization system (%), and 0.67 = CH_4 density at stp (293 K, 101.3 kPa).

N_2O emissions are estimated by Equation (2):

$$N_2O\ \text{emissions (kg year}^{-1}) = 1.57 \times M_N \times MF_{N2O} \quad (2)$$

where M_N = N excretion rate, kg $year^{-1}$, and MF_{N2O} = Nitrous oxide factor.

$VS_{excreted}$ and N excretion rates are shown in Table 1. The estimated values of B, MCF and MF_{N2O} were 0.33, 1.5% and 0.02 [4], respectively.

In the land application scenario, emissions from the feedlot manure occurred in every step, from collection, to storage, to land application. On the other hand, in the gasification scenario, once the feedlot manure was collected every two months for gasification, emissions were prohibited in the gasifier. In this study, manure emissions were based upon manure production from 10 feedlots during one year. Thus, it was assumed that manure emissions from the gasification scenario were 1/6 of the emissions from the land application scenario based on the manure exposure time (2 months–12 months) during one year cycle.

2.7. Avoided fertilizer utilization

In land application scenario, the N, P and K contents of feedlot manure reduced the amount of commercial fertilizer applied to the agriculture system; therefore, GHG emissions related to fertilizer application were avoided. The initial nutrient content of feedlot manure is shown in Table 1. It was assumed that 24% of N was lost to the environment due to volatilization

Table 2 – Manure handling equipment description of two scenarios for one feedlot (500 AU).

Equipment	Working time/ distance for land application scenario	Working time/ distance for gasification scenario	Description
Front-end loader	9 h	3 h	Piling up manure and loading to trucks
Heavy-duty trucks	5 km	15 km	80 trucks and 84 trucks needed for land application scenario and gasification scenario, respectively per year
Spreader	30 min per load	30 min per load	Application of feedlot manure and biochar for land application scenario and gasification scenario, respectively

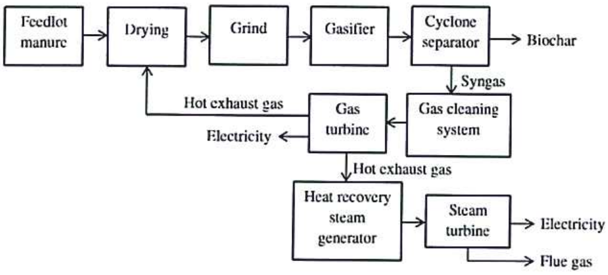

Fig. 3 – Schematic diagram of BIGCC system to process feedlot manure.

Table 3 – Major assumptions of BIGCC system.

BIGCC system	Value	Reference
Capacity factor	0.9	–
Dry matter feeding rate	1 t h^{-1}	–
Moisture mass fraction of feeding manure	15%	–
Efficiency of the dryer	95%	[23]
Latent heat for water evaporating	2.5 MJ kg^{-1}	[23]
Gas turbine power efficiency	28.7%	[24]
Steam turbine power efficiency	15.1%	[24]
Auxiliary power need	3.8%	[24]

of NH_3 and N_2O [18], while no P and K was lost. The emission factors used for each type fertilizer (N, P, or K) were based on the avoided life cycle emissions from fertilizer production. We assumed emission factors of 1 kg N, P, and K were 8.9, 1.8 and 0.96 kg CO_2-eq, respectively [19].

2.8. *Gasification plant*

In the gasification scenario, biomass integrated gasification combined cycle (BIGCC) technology was applied to process the collected manure. The schematic diagram of the BIGCC system is shown in Fig. 3 [20–23]. The basic components included a biomass dryer, a gasifier, a gas cleanup system, a gas turbine, a heat recovery steam generator (HRSG) and a steam turbine. Major assumptions of the BIGCC system are listed in Table 3. Feedlot manure was dried, ground and then fed into the gasifier to generate syngas. A cyclone separator was used to separate the biochar from the syngas. Tar and particles were removed by a gas cleaning system. A gas turbine was used to generate electricity by combustion of the syngas. Part of the hot exhaust gas from the gas turbine was used to dry the feedlot manure and the remaining hot exhaust gas was introduced into HRSG and steam turbine for additional electricity.

Although there were no direct data presented on GHG emissions of gasification system of feedlot manure processing, the reference data of the GHG emissions during thermochemical conversion of wood chips within different thermochemical conversion processes are shown in Table 4. GHGs emissions included plant construction and operation, without direct CH_4 and N_2O outputs from the gasification of wood chips. During biomass gasification, the majority of biomass P was retained by the biochar, while biomass N was mainly converted into biochar, NH_3 and N_2. Thus, a very low level of N_2O in syngas was not taken into account [26,27]. It can be seen that GHG emissions varied from 3 to 9 g CO_2-eq per MJ energy produced. Thus, GHG emissions were assumed to be 6 g CO_2-eq per MJ energy of BIGCC system in this study.

2.9. *Avoided electricity generation*

Since electricity was generated from the feedlot manure through the BIGCC technology, electricity generation from fossil fuels was avoided. However, GHG emissions vary among different energy sources. Table 5 presents GHG emissions of electricity generation from three types of fossil fuels: petroleum, nature gas and coal (GREET Model 2012) [13]. In this analysis, avoided electricity generation was assumed from petroleum.

2.10. *GHG emissions reduction from biochar application*

Biochar composition and yield depend highly on the thermochemical conversion operation and feedstock characteristics. Typically, the order of the biochar yield is slow pyrolysis > fast pyrolysis > gasification [28]. In this study, biochar yield was

Table 4 – GHG emissions for different gasification systems of wood chip [25].

Gasification systems	CO_2 (g MJ^{-1})	CH_4 (g MJ^{-1})	N_2O (g MJ^{-1})	GHG (g MJ^{-1})
Combined heat and power (small scale) by gasification of wood chip from short rotation coppice (option A)	5 ± 1	0.001	–	5 ± 1
Combined heat and power (small scale) by gasification of wood chip from short rotation coppice (option B)	4 ± 1	–	–	4 ± 1
Electricity by gasification of wood chips from forestry residues (large scale)	7	0.003	–	7
Electricity by gasification of wood chips from short rotation coppice (option A)	8 ± 1	0.003	0.001	8 ± 1
Electricity by gasification of wood chips from short rotation coppice (option B)	7 ± 1	0.003	–	7 ± 1

(Note: option A and option B are two different gasification operations from the reference.).

Table 5 – GHG emissions of electricity generation from three types of fossil fuels [13].

	Petroleum	Natural gas	Coal
CH_4 (g MJ^{-1})	0.003	0.0008	0.003
N_2O (g MJ^{-1})	0.001	0.003	0.003
CO_2 (g MJ^{-1})	245.8	125.0	274.2

assumed to be 20% of the dry matter. Biochar effects on GHG emissions reduction can be divided into four aspects: 1) carbon sequestration; 2) N_2O emission reduction when applying biochar in the soil; 3) displacing commercial fertilizer, and 4) enhancement of agronomic efficiency [29]. We assumed that 26% of the biochar was carbon, based on the ultimate analysis of the biochar derived from feedlot manure gasification [30], and 75% of the carbon in biochar was sequestered in the soil [31]. Biochar was transported back by heavy-duty trucks and a spreader was used to apply the biochar in the field. GHG emissions of heavy-duty trucks and the spreader were discussed in previous section. The degree of biochar effects on agronomy depends on a number of factors, including soil properties, geographical attributes, biochar composition, and interactions between these unknown factors [32]. The application rate was assumed to be 5 tonnes per hectare, and ranges of GHG emissions reduction for 1 ha of five different crops are shown in Table 6 [29]. The average value ranges from −0.25 to −1.22 tonne CO_2-eq, and the average medium value of −0.71 tonne CO_2-eq was adopted.

3. Results and discussions

3.1. Net GHG emissions of land application scenario

Detailed GHG emissions from each life cycle stage of land application scenario are show in Table 7. Avoided GHG emissions were derived only from displacing fertilizer utilization, which was 177 kg CO_2-eq per tonne dry feedlot manure. Manure emissions accounted for most of the GHG emissions, which was 98.8%. The net GHG emission was 119 kg CO_2-eq for one tonne of dry feedlot manure.

3.2. Net GHG emissions of gasification scenario

GHG emissions from each life cycle stage of gasification scenario are shown in Table 8. Manure emissions and gasification plant operation, accounted for 63.7% and 31.8% of the total GHG emissions. In addition, avoided electricity generation and carbon sequestration were 76.1% and 20.0% of the total GHG emissions reduction, respectively. The net GHG emissions for one tonne of dry feedlot manure in the gasification scenario were −643 kg CO_2-eq.

3.3. Sensitivity analysis

When building the life cycle inventory, some important assumptions were made. In order to assess the robustness of the result and impacts of parameters on the outcome, a sensitivity analysis was conducted. Results of the sensitivity analysis are presented in Table 9.

One major uncertain assumption in land application scenario was the avoided GHG emissions of fertilizer utilization. Typically, GHG emissions fall in the range of 4.75–13.0 kg CO_2-eq, 0.52–3.09 kg CO_2-eq and 0.38–1.53 kg CO_2-eq for 1 kg of N, P and K fertilizer, respectively [33]. If the highest and lowest fertilizer emission factors were assumed, net GHG emissions decreased and increased by 75%, respectively. That means the results in the land application case are very sensitive to the assumption related to the emission factor of the fertilizer utilization.

Moreover, four uncertain assumptions were made in the gasification scenario. The first uncertainty was the gasification plant emissions. GHG emissions of gasification plant were assumed to be between 3 and 9 g CO_2-eq per MJ energy, resulting in the decrease and increase in the net GHG

Table 6 – GHG emissions for 1 ha when the application rate is 5 tonnes per hectare [29].

Crop	Low (tonne CO_2-eq)	Medium (tonne CO_2-eq)	High (tonne CO_2-eq)
Canola	−0.05	−0.22	−0.39
Broccoli	−0.66	−1.56	−2.57
Wheat (UK)	−0.28	−0.87	−1.49
Maize	−0.19	−0.67	−1.19
Wheat (Australia)	−0.06	−0.25	−0.45
Average	−0.25	−0.71	−1.22

(Note: Negative value indicates GHG emissions reduction).

Table 7 – GHG emissions for every life cycle stage in land application scenario.

Life cycle stage	kg CO_2-eq per tonne dry feedlot manure	%
Manure collection	0.992	0.336
Transportation	0.640	0.217
Spreading	1.90	0.642
Manure emissions	292	98.8
Displacing fertilizer utilization	−177	100
Net emissions	119	–

(Note: Negative value indicates GHG emissions reduction).

Table 8 – GHG emissions for every life cycle stage in gasification scenario.

Life cycle stage	Value (kg CO_2-eq per tonne dry manure)	%
Manure Collection	0.992	1.35
Manure Transportation	1.02	1.38
Manure emissions	46.9	63.7
Gasification plant emissions	23.4	31.8
Biochar transportation	1.03	1.40
Biochar spreading	0.216	0.293
Avoided electricity generation	−545	76.1
Carbon sequestration	−143	20.0
Biochar effects on agronomy	−28.4	3.96
Net emissions	−643	–

(Note: Negative value indicates GHG emissions reduction).

Table 9 – Sensitivity analysis of major assumptions of two scenarios.

Assumptions	Used in this study	Alternative assumptions	GHG emissions change	Alternative assumptions	GHG emissions change
Land application scenario					
Fertilizer emission factor(kg kg^{-1})	8.9,1.8 and 0.96 for N, P and K, respectively	13, 3.09 and 1.53 for N, P and K, respectively	−75%	4.75, 0.52 and 0.38 for N, P and K, respectively	75%
Gasification scenario					
Gasification plant emissions (g MJ^{-1})	6	3	−1.82%	9	1.82%
BIGCC efficiency	40%	35%	18.7%	45%	−18.7%
Avoided electricity generation	Oil-fired power plant	Natural gas fired power plant	41.4%	Coal-fired fired power plant	−9.9%
GHG emissions from biochar (tonne ha^{-1})	−0.71	−0.25	2.86%	−1.22	−3.17%

(Note: Percentage increase indicates an increase in the overall emissions, even where the net GHG emissions remain negative).

emissions of 1.82% respectively. Therefore, it can be seen that net GHG emissions in the gasification scenario is not sensitive to gasification plant emissions. The second uncertainty was the BIGCC efficiency, which varied by the system design and operation. Assuming the efficiency was 35% and 45%, the changes in net GHG emissions increased and decreased by 18.7%, respectively. Thus, the BIGCC efficiency is a major factor influencing the final outcome. The third uncertainty was the energy resource of avoided electricity generation. If the avoided electricity was produced by natural gas and coal, other than petroleum, the net GHG emissions increased by 41.4% and decreased by 9.9%, respectively. The fourth uncertainty was the biochar effects on agronomy. Biochar effects on GHG emissions reduction assumed 0.25 and 1.22 tonnes CO_2-eq per hector, resulting in the final net GHG emissions increased by 2.86% and decreased by 3.17%, respectively. Overall, it can be concluded that the outcome in the gasification scenario is sensitive to factors of BIGCC efficiency and energy sources of avoided electricity generation.

4. Conclusions

In this study, GHG emissions of two feedlot manure management practices (land application and gasification) were estimated by LCA. In addition, a sensitivity analysis was conducted to test impacts of important variables. The net GHG emissions were 119 and -643 kg CO_2-eq per tonne dry feedlot manure for land application scenario and gasification scenario, respectively. From the sensitivity analysis, the replaced fertilizer emissions changed the net GHG emissions up to 75% in the land application scenario. In the gasification scenario, sensitive factors were energy source of avoided electricity and BIGCC efficiency. On the other hand, gasification plant emissions and biochar effects on agronomy did not influence the result much. Our analysis shows that in the gasification scenario, manure emissions were reduced by the gasification process, and at the same time, syngas and biochar, which can be further used as the power source and soil amendment, played an important role in GHG emissions reduction. Consequently, the gasification scenario provides an alternative solution to reduction in GHG emissions.

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