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Life Cycle Assessment of Three Manure Treatment Modes in Large-scale Pig Farm

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Abstract: With the rapid development of China's livestock breeding industry, it is very important to efficiently deal with the pollution caused by livestock and poultry manure. In this study, the life cycle resource consumption and pollutant emission inventory of a large-scale pig farm were analyzed by life cycle assessment (LCA). The environmental impact potentials of three different modes of livestock and poultry manure treatment were analyzed, including aerobic composting, anaerobic fermentation and black soldier fly larvae (BSFL) treatment. Results showed that the environmental loads of BSFL treatment and anaerobic fermentation were much smaller than those of aerobic composting in the life cycle process of pig manure treatment. The environmental impacts of aerobic composting process were in the order of environmental acidification, eutrophication, and global warming; while the environmental impacts of anaerobic fermentation treatment and BSFL treatment process were in the order of global warming, environmental acidification, and eutrophication. It is recommended to strengthen the emission of CO_2 and NH3 in the pig manure treatment process to reduce their environmental impacts.

Keywords: Swine manure; Life cycle assessment; Composting; Black solider fly; Anaerobic fermentation.

1. Introduction

With the continuous development of intensive farming, China's livestock and poultry manure production has been on the rise in recent years, but the comprehensive utilization rate of livestock and poultry manure in China is less than 60%. A large number of nitrogen and phosphorus compounds in livestock and poultry manure (if not properly handled) will flow into the natural ecosystem, exacerbating global warming, acidification effects, and eutrophication of water bodies and other global environmental problems.

At present, there are two main types of livestock manure treatment: aerobic composting and anaerobic fermentation. These two modes of manure treatment can play a certain role in realizing the resourcefulness of manure, but the treatment process may cause nutrient loss, leading to global warming, soil acidification, and a series of secondary pollution problems. The use of BSFL to treat manure is an emerging mode of manure treatment. A BSFL is a kind of insect that lives in putrefaction and has the characteristics of large biomass, strong reproduction ability, and high transformation efficiency. The treatment of feces by BSFL can greatly reduce the concentration of N, P, and other elements in the excreta and reduce the threat to the environment.

Different modes of livestock manure treatment differ significantly in terms of resource consumption, economic costs, and environmental friendliness. Therefore, it is necessary to carry out a life cycle assessment (LCA) of the three modes, namely aerobic composting, anaerobic fermentation, and BSFL treatment, to identify the environmental impact potential of the three manure treatment modes to optimize the production process. Life cycle assessment (LCA) is the evaluation of the economic benefits, output emissions, and potential environmental impacts of a product system over its life cycle, and its main process can be divided into four interrelated steps: objective and scope determination, inventory analysis, environmental impact assessment and interpretation of results.

This thesis investigates modern farms and consults relevant information [1-3], determines the system boundaries of life cycle assessment, obtains life cycle emission data of different treatment modes of livestock and poultry manure, including pollution emission and energy input and output, and carries out inventory analysis and impact evaluation of different treatment modes to explore a more optimal manure treatment pathway.

2. Scope and System Boundaries

A large-scale pig farm with a stocking capacity of 10,000 heads is selected, and its annual fresh pig manure production can be up to about 15,000 t [4], and the dry manure method used to deal with pig manure, i.e., the animal's feces and urine are shunted immediately after they are discharged, and the dried feces are collected, swept, and transported, while the urine is directly drained away.

The Functional unit (FU) selected for the life cycle assessment was 1t of fresh pig manure, and all other energy inputs and outputs, pollutant emissions, etc. were based on the corresponding amount of 1t of pig manure processed [5]. The physicochemical properties of the manure were 70% moisture content, 32.6 g/kg TN, 17.4 g/kg TP, and 330 g/kg TC.

The system boundaries of the three treatment modes are shown in Fig. 1. The system boundaries of aerobic composting include the collection of manure, mixing of manure pre-fillers (composting stage), turning process, and waste treatment stage [6-7]. The main pollutant emissions are CO_2, CH_4, and NH_3, and in the composting stage, CO_2 emissions account for about 30%, and NH_3 reaches 3.26 $kg \cdot FU^{-1}$. The total power consumption in the turning stage is equivalent to 3.38 $kWh \cdot FU^{-1}$, and its emissions of CO_2 are 1.07 $kg \cdot kWh^{-1}$, SO_2 is $9.93 \times 10^{-3} kg \cdot kWh^{-1}$, CH_4 is $2.60 \times 10^{-3} kg \cdot kWh^{-1}$. The emission factors of NO_X, CH_4, and CO_2

produced during the final wastewater treatment stage were 0.38kg·FU^{-1}, 0.0123kg·FU^{-1}, and 25.43kg·FU^{-1}, respectively.

The system boundary of anaerobic fermentation includes the fermentation phase, the biogas generation phase, and the digestate treatment phase [3], and the gas production rate of swine manure during the fermentation phase is 0.42 m^3·kg^{-1}TS and the equation (1) for gas production per FU of swine manure is as follows.

$$Q=1000\times TS\times 0.42 \qquad (1)$$

Q——Gas production from pig manure, unit (of measure) (m^3·FU^{-1})

TS——Dry matter content of pig manure, unit (of measure) (m^3·kg^{-1})

1000——1000 kg of pig manure.

After calculation, the polluted gas emission Q from pig manure is 75.6 m·FU^{-1}. i.e. the amount of biogas produced from pig manure is 75.6 m^3. CH_4 accounts for about 60% of the biogas, CO_2 accounts for about 35%, and the rest of the components are negligible. Under the standard condition, the density of CH_4 is 0.714g·L^{-1}, and the density of CO_2 is 1.977g·L^{-1}. Then the following formula (2) can be used to calculate the amount of CH_4 produced by swine manure Q_1 (kg·FU^{-1}).

$$Q_1=65\%\times Q\times \rho_1 \qquad (2)$$

Q_1——CH_4 emissions per ton of pig manure (kg·FU^{-1})

Q——Biogas production per ton of pig manure (m^3·FU^{-1})

ρ_1——Density of CH_4 at standard conditions (g·L^{-1})

60%——CH_4 as a proportion of biogas.

From this, we can calculate the emission of CH_4 per ton of pig manure, Q_1, as 32.38 kg·FU^{-1}. Similarly, we can use equation (3) to calculate the emission of CO_2, Q_2 (kg·FU^{-1}).

$$Q_2=35\%\times Q\times \rho^2 \qquad (3)$$

Q_2——CO_2 emissions per ton of pig manure (kg·FU^{-1})

Q——Biogas production per ton of pig manure (m^3·FU^{-1})

ρ_2——Density of CO_2 at standard conditions (g·L^{-1})

35%——CO_2 as a proportion of biogas.

This gives a CO_2 production Q_2 of 52.31 kg·FU^{-1} during the fermentation phase.

The methane produced during the biogas generation phase of the process i.e. in the fermentation phase is 32.38 kg·FU^{-1} and according to the methane combustion equation, it can be calculated that the CO_2 emission during the process is 89.05 kg·FU^{-1}.

The emission coefficients of CO_2, CH_4, SO_2, and NO_X in the biogas and digestate treatment stages were 1.07 kg·kWh^{-1}, 2.60 × 10^{-3} kg·kWh^{-1}, 9.93 × 10^{-3} kg·FU^{-1}, and 6.46 × 10^{-3} kg·FU^{-1}, respectively.

As for the BSFL treatment model, the system boundary is divided into the use of organic fertilizer for returning to the field after BSFL treatment and the sale of insect protein[8-9]. In the BSFL treatment process, the main gases are CO_2 and NH_3, of which CO_2 emission is 63.78kg·FU^{-1} and NH_3 emission is 0.15kg·FU^{-1}, and CH_4 production is 1.1kg·FU^{-1}.

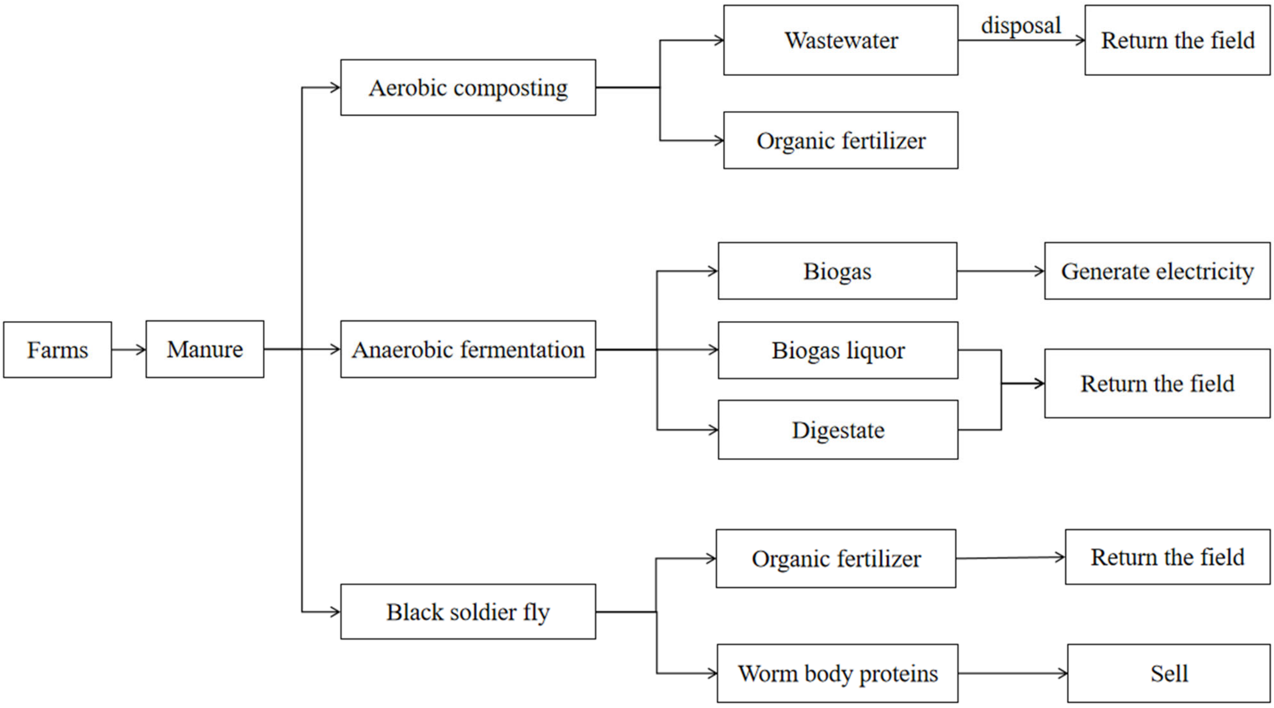

Figure 1. Three treatment modes system boundaries

3. Life Cycle Inventory Analysis

3.1. Characterization

One of the design aims of characterization is to synthesize the application of many different levels of environmental pressures and impact relationships [10], applying them to a generic environmental framework for study [3]. Based on the atmospheric pollutants such as volatile gases (CO_2, CH_4, and NH_3, etc.) emitted from these different treatment modes, their impacts on three environmental impacts such as soil eutrophication potential (GWP), global environmental warming potential (EP), and groundwater acidification potential (AP) are assessed.

Equivalency factors were chosen to convert a class of pollutants to the environmental impact potential of the corresponding baseline pollutant. That is, one pollutant is selected as the baseline pollutant, and the environmental impact of pollutants released during treatment is assessed by converting other pollutants to units of the baseline pollutant using equivalence factors, as shown in Table 1.

Table 1. Equivalent coefficients for main impact factors

Type of impact	Global warming	Environmental acidification	Eutrophication
CO_2	1	-	-
CH_4	25	-	-
NH_3	-	1.88	0.35
N_2O	298	-	-
SO_2	-	1	-
NO_x	-	0.7	0.13

In this study, CO_2, NH_3, and SO_2 were selected as baseline pollutants, and the characterization results were calculated according to equation (4).

$$E_{P(X)}=\sum E_{P(x)i}=\sum [Q_{(x)i}E_{F(X)i}] \quad (4)$$

where $E_{P(X)}$ denotes the potential of the system for the Xth environmental impact in kg (pollutant) eq./t, $Q_{(X)i}$ denotes the emission of the ith coercive factor in kg/t, and $E_{F(X)i}$ denotes the equivalence factor of the impact of the ith coercive factor on the Xth impact in g (pollutant) eq./t.

3.2. Characterization inventory analysis

The order of magnitude of each treatment model in terms of environmental impact potential is global warming, environmental acidification, and eutrophication. By analyzing the emission inventory data, it is possible to identify the gases that have an impact on the environment and to propose corresponding countermeasures to reduce pollution to optimize the production process and reduce gas pollution and emissions [11-15]. The specific data are shown in Table 2.

Table 2. Environmental impact potential of aerobic composting process

Type of impact	Pollutants	Impact potential	Sum
Global warming ($kgCO_2eq./t$)	CO_2	30.73	169.44
	CH_4	13.55	
	N_2O	125.16	
Environmental acidification ($kgSO_2eq./t$)	SO_2	0.03	5.53
	NH_3	5.48	
	NO_X	0.02	
Eutrophication ($kgNH_3eq./t$)	NH_3	5.48	5.50
	NO_X	0.02	

Table 3. Potential environmental impacts of anaerobic fermentation processes

Type of impact	Pollutants	Impact potential	Sum
Global warming	CO_2	141.93	142.43
	CH_4	0.5	
Environmental acidification	SO_2	0.03	0.031
	NO_X	0.001	
Eutrophication	NO_X	0.001	0.001

Table 4. Potential environmental impacts of the BSFL treatment process

Type of impact	Pollutants	Impact potential	Sum
Global warming	CO_2	63.78	91.28
	CH_4	27.5	
Environmental acidification	NH_3	0.28	0.28
Eutrophication	NH_3	0.05	0.05

3.3. Standardized analysis

The purpose of the standardized research process is to provide relatively mature and reliable criteria for assessing the potential human impact of environmental factors such as global atmospheric warming, acidification of environmental media, and environmental eutrophication. At the same time [7], this also provides an objective basis for international environmental assessment activities. In this paper, the average per capita annual integrated environmental impact of countries around the world is used as a benchmark for China's overall environmental impact statistics. The calculation of the standardization can be done using equation (5).

$$Rx=EP_{(x)}/S(1990) \qquad (5)$$

Rx is the normalized result for the Xth potential impact.

EP(X) is the result of the characterization of x potential impacts.

S (1990) is the standard human-equivalent baseline for global environmental impact potentials.

The per capita equivalent of this is 8700 $kgCO_2^{-eq}$ for global warming, 35 $kgCO_2^{-eq}$ for environmental acidification, and 59 $kgCO_2^{-eq}$ for eutrophication For the farms in this study, each pig emits an average of 3 tonnes of pig manure per day, giving a total of 30 tonnes per day for a 10,000 pig scale farm, or 10,095 tonnes of pig manure per year.

The standardized results of the three modes can be calculated by substituting the characterization data of the three modes as well as the data in the standardized human equivalent of the potential environmental impacts into Equation (5) and are shown in Table 5. After standardization, it is found that the values of the BSFL treatment mode in terms of acidification of the environment as well as global warming are significantly larger than those of the aerobic composting mode and the anaerobic fermentation mode. This is because more nitrogenous compounds and carbon dioxide are produced in the BSFL treatment mode.

Table 5. Results of standardization of environmental impacts under three models

Type of impact	Aerobic composting	Anaerobic fermentation	BSFL treatment
Global warming	196.608	164.687	122.88
Environmental acidification	1595.01	8.941	80.76
Eutrophication	941.059	0.171	8.6

3.4. Weighted assessment

Normalization of the data indicates the extent of possible environmental impacts. To compare the consequences of impacts, a weighted evaluation of the data is required. Equation (6) was used to weigh the standardized data.

$$EI=WxRx \qquad (6)$$

EI is the weighted environmental impact potential.

Wx is the weight of the Xth potential environmental impact.

Rx is standardized data for environmental impact type x.

The weights are 0.83 for global warming, 0.73 for environmental acidification, and 0.73 for eutrophication, and the impact potentials of the weighted assessment are obtained by substituting the normalized data and the weights into the formula, and the impact potentials of the three models are shown in Table 6.

Table 6. Weighted assessment values for the three treatment modes

Type of environmental impact	Aerobic composting	Anaerobic fermentation	BSFL treatment
Global warming	163.245	136.691	101.1
Environmental acidification	1164.358	6.526	58.96
Eutrophication	686.973	0.079	6.3
Total (environmental load)	2014.576	143.296	166.36

It can be seen that after a weighted assessment of the data (Table 6), aerobic composting mode and BSFL treatment mode have the main impact on the environment, which is environmental acidification; while anaerobic fermentation contributes more to global warming. Through weighting, the severity of the environmental impact of each mode can be effectively reflected, and further weighted data need to be added and processed that is, the environmental impact load (EI), after calculating the BSFL treatment (166.36) and anaerobic fermentation (143.296) of the environmental load is significantly lower than aerobic composting treatment (2014.576). From the point of view of environmental impact, the environmental impacts of aerobic composting treatment were environmental acidification, eutrophication, and global warming, while the environmental impacts of anaerobic fermentation and BSFL treatment were global warming, environmental acidification, and eutrophication, in that order.

4. Summary

This paper draws the following conclusions from a life-cycle assessment of three treatment processes (aerobic composting, anaerobic fermentation, and BSFL treatment) for swine manure, as well as an analysis and evaluation of the potential long-term environmental quality impacts with characterized, standardized, and weighted integrated assessment results.

(1) In terms of environmental impacts: the environmental impacts of the aerobic composting process are environmental acidification, eutrophication, and global warming in order; the environmental impacts of the anaerobic fermentation process and the BSFL process are global warming, environmental acidification, and eutrophication in order.

(2) By comparing the environmental loads, the environmental loads of the anaerobic fermentation as well as the BSFL treatment modes were much smaller than those of the aerobic composting mode, and the gap between the BSFL treatment mode and the anaerobic fermentation mode was smaller.

(3) It is recommended to strengthen the emission of CO_2 and NH_3 in the pig manure treatment process to reduce their environmental impacts.

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